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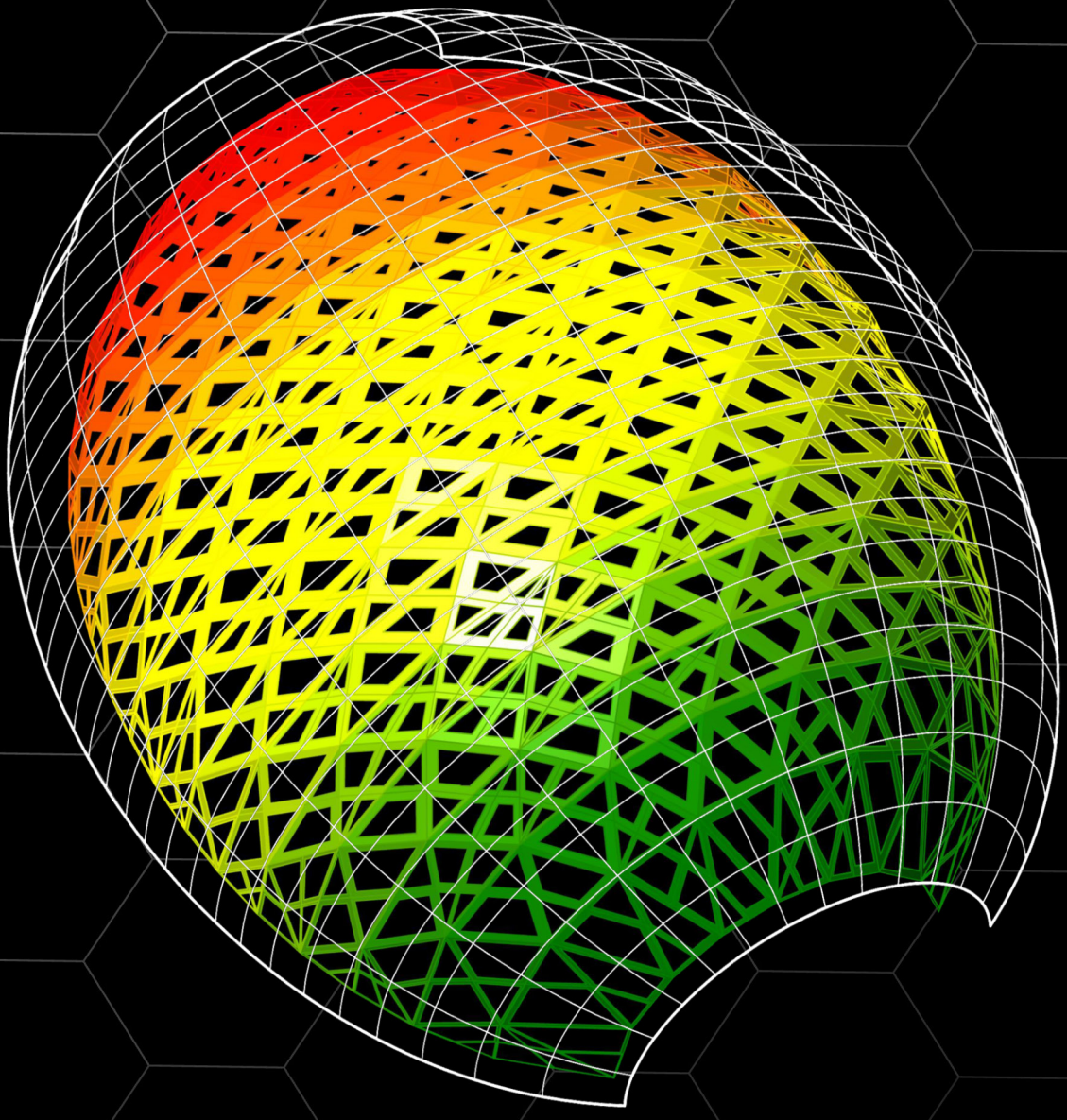
DIGITAL TECHNIQUES APPLIED TO DESIGN PROCESS



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Programa de Pós-graduação em Ambiente Construído

DOMVS
LABORATÓRIO DE INVESTIGAÇÃO EM ARQUITETURA E URBANISMO

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INTRODUCTION

FERNANDO LIMA
MARCOS BORGES
FREDERICO RIBEIRO COSTA

From the second half of the XX century until today, there is a huge evolution on the context of design methods and tools that bring the building sector to a moment that can be considered as a second paradigm change since the introduction of CAD in the last century sixties. Many authors argue that design and representation can be viewed as indissociable parts of the same process, and in that sense, this evolution is changing the ways architects and designers think, work and are educated. Algorithmic-parametric approaches to the design processes is now a reality and it can be found in areas from mechanical design to urban planning, including architectural and product design. Concepts of generative systems, evolutionary algorithms, evolutionary computing, parametric design, among others, are more and more part of the professionals working environment. These approaches aren´t new to designers in a broad sense. Actually, they can be found in ancient Greece as has been reported by Mitchel (1977).

Recently, Oxman (2017) presents the Parametric Design Thinking (PDT) concept as a schema formulated from the intersection of three knowledge directions: (a) cognitive models of a typological and topological design in architecture; (b) process models of digital design, and; (c) tectonic order of material fabrication design (MFD). These three knowledge areas reflect the evolution of design methods approaches since it started to be more deeply investigated by researchers in the second half of the last century. The technologic evolution of nowadays personal computers and software have enabled the implementation of those concepts more efficiently than a decade ago. However, this evolution of methods and tools stills needs to be investigated and experimented.

In this context, this book addresses the implementation of various digital approaches aimed at supporting design processes tasks. In this sense, this work is organized by researchers from the Post-graduation Program of Built Environment (PROAC-UFJF) and DOMVS Laboratory of investigation in Architecture, Urbanism, and Landscape and consists of a collection of works by authors from several institutions in three countries (Brazil, Portugal, and France).

The first chapter presents a research elaborated by Ricardo Gago, from Lisbon School of Architecture, that deals with the development of architectural structures, following the geometrical qualities of the biologic morphology. More specifically, his research aims to develop a geometric design tool of geometric essence able to transfer this morphological identity to architectural structures. The main idea is to demonstrate relations between the morphological patterns from biological structures and to achieve their structural and material optimization through self-supported structures.

In the second chapter, Victor Calixto and Gabriela Celani, from Campinas University, present a literature review that seeks to identify processes, experiments and designs that used evolutionary

algorithms as a method to solve space planning problems. In this research, the hypothesis consists in the affirmation that the new tools for architectural design support (Computer Aided Architectural Design-CAAD) are helping in the dissemination and in the approximation of architects to computational design methodologies and that they could help to spread Space Planning methods.

The third chapter consists in the work of Deborah Macedo dos Santos, Thiago Bessa Pontes (both from Federal University of Cariri) and António Menezes Leitão, from Lisbon School of Architecture. In this work, the authors present a programming case-study for generative design, through the development of a practical application that uses textual and visual programming languages (Python and Grasshopper). In this chapter, the authors highlight that to learn an adequate use of computational thinking (CT) is as important as the use of programming languages.

In the fourth chapter, Gonçalo Castro-Henriques, from Federal University of Rio de Janeiro, deals with the application of responsive architecture. The author points that there are no established processes for creating and managing responsive architecture and that the creation of responsive systems requires meta-systems and the use of computation to construct a formal model that can approach a probabilistic model used in physics. In this chapter, the author analyzes and synthesizes contributions, seeking operational concepts for the development of responsive architecture.

In the fifth chapter, Marcos Martins Borges, from Federal University of Juiz de Fora, reports some undergraduate teaching and learning experiences in Engineering Design Graphics (EDG), linked to the Product Design Process context (PDP). For that, the author presents (a) a brief historical description of digital design aids from the first attempts to the present paradigm of parametric modeling; (b) a brief overview of engineering design methodologies evolution, and; (c) a discussion that links the EDG to PDP from a teaching and learning perspective. In this sense, this chapter presents the structure of a parametric modeling tool and its relation to Computer Aided Engineering (CAE) resources, using some didactic examples to illustrate the concepts. Finally, the author reports and illustrates some partial results from his experiments.

In the sixth chapter, Maria Aparecida Steinherz Hippert, Orlando Celso Longo and Adriano Castro Moreira, from Federal University of Juiz de Fora and Fluminense Federal University, reports the application of a logical model for the management of maintenance information. Conceptually, the model makes use of Web Orientation technologies using Content Management Systems (CMS) and identification tags (RFID). The authors emphasize that this combination enables easy, fast, decentralized and hierarchical access to information through mobile connection technologies such as laptops, smartphones and tablets, supporting building maintenance teams. In addition, it allows designers to confirm the fulfillment of a user's maintenance needs. One contribution of this work is the continuity of research in the field of intelligent tagging.

In the seventh chapter, Fernando Lima, Nuno Montenegro, Rodrigo Cury Paraizo and José Ripper Kos, from Federal University of Juiz de Fora, Lisbon University, Federal University of Rio de Janeiro and Federal University of Santa Catarina; describe and evaluate the implementation of CityMetrics: a computational system that articulates performance evaluation metrics and algorithmic-parametric

resources, in order to analyze and optimize the degree of efficiency and the possibilities of operation of geometric and algebraic configurations of urban areas. The work uses computational resources and algorithmic tools specifically designed to assess the performance of urban areas, from the perspective of objectively measurable principles of Transit Oriented Development (TOD), an urban development model aimed at more autonomous and sustainable cities. More specifically, this research aims at verifying how TOD's measurable, geometric and algebraic (and therefore programmable) attributes can be implemented through a computational model that uses optimization methods to support decision making in urban design processes. Thus, CityMetrics is intended to provide support to decision making in urban design tasks related to the organization of neighborhoods and cities, as well as to contribute to the improvement of analysis and proposition possibilities in urbanistic contexts.

In the eighth chapter, Leonardo Sanches, José Gustavo Francis Abdalla and Klaus Chaves Alberto, from Centro de Ensino Superior de Juiz de Fora and Federal University of Juiz de Fora, explores the use of a digital tool, specifically parameterization and generative systems, as support methods on the decision-making process in architecture. At their research, a practical approach was adopted, through the development, application and analysis of algorithms in three distinct levels of design: architectural detail, architecture and urban occupation. With an emphasis on fire safety regulation and on Juiz de Fora/MG city's building code, the studies showed that it is possible to create digital tools aiming the automation of the repetitive tasks related to legal constraints. Besides from architectural objects and details, it was also possible, to use the models for simulating urban occupation. Thereby, the authors noted the potential on the use of a digital tool as support on space analysis and creation, pointing that constraints based parameterization tools and generative systems could lead to better and more efficient processes since design solutions can be developed and tested seemingly on real time.

In the ninth chapter, Raphael Augusto de Andrade, Marcos Martins Borges and Fernando Lima, from Federal University of Juiz de Fora, explore the concepts and knowledge that surround the BIM platform (Building Information Modeling). This design methodology has been adopted around the world due to its ability to optimize the AECO industry's design processes. Among the benefits already evidenced with the advent of this platform were the increase in productivity, compatibility, collaboration and improvements in coordination between project agents, followed by reduction of expenses, time, rework and waste during the entire building lifecycle. However, such benefits are only achieved by making profound changes in the AECO industry, ranging from changes in the design process to the emergence of new work structures and responsibilities. Because of this, the implementation of BIM has many challenges to be solved for the full use of its benefits.

In the tenth chapter, Aline Calazans Marques, Leopoldo Eurico Gonçalves Bastos and Luc Adolphe, from Federal University of Juiz de Fora, Federal University of Rio de Janeiro and *Institut National des Sciences Appliquées de Toulouse*, explore the growing process of integrating digital environmental analysis tools into the Building Information Modeling (BIM) system. It is recognized as a result of three-dimensional modeling, the potential of parameterization between geometry/ information and interoperability between software and actors. This chapter deals with the dynamics

of environmental analysis when integrated with the BIM system and proposes the investigation of the decision-making strategies immersed in this environment during the design phases of the architectural design. So how to deal, with a multidisciplinary approach, with the conformation of the building elements – in the digital environment – to allow an adequate environmental performance of the architectural object? The results focus on decision-making issues facing the complexity of the environmental analysis variables, inferring the relationship between geometry and information regarding the modeling, parameterization and interoperability of the BIM system.

In the eleventh chapter, Jorge Alcântara Filho and Letícia Mendes from the Federal University of Pernambuco, explore the techniques of digital fabrication and rapid prototyping as consistent technologies and increasingly present in the fields of design and construction. The significant presence of Computer Aided Design and Computer Aided Manufacturing systems in designing the most varied artifacts has been a subject of much discussion in the various fields of the creative industry. Parallel to this discussion, the introduction of the parametric design approach has great importance in obtaining new perspectives and innovation in design. Thus, in order to associate the potential of rapid prototyping and digital fabrication tools and a generative design system, this chapter describes the development of a furniture design — an exhibition panel and tool organizer — through the detailed documentation of the processes and procedures carried out for its completion.

Finally, in the twelfth chapter, Ana Moreira and Francisco Serdoura from Lisbon School of Architecture, address the relationship between public household units built in the early 60's with underprivileged resident's lifestyles of the late 70's. The study focuses on the differences between initial household designs and the 'new' layouts, a product of accommodation needs of occupant families as a result of their distinct lifestyles. This analysis allows for the determination of dwelling tendencies. The intent is also to understand the extent to which some of society's attributes contributed to redefining families' social behavioral patterns, particularly their way of life and use of housing spaces, so to determine their impact in apartment's layout. Examples of public housing in Lisbon, and their respective layout adjustments were analyzed, based both on the original designs and on the renovations carried out by users in the late 70's. The results of the research are supported by syntactic measures (integration and depth), to better understand how the renovations made by the families to their households best served their lifestyles. Apartment layouts were analyzed by recurring to justified graphs and visual graph analysis, both used as a comparative assessment in the validation of attained results. It is argued that the original dwellings were not adequate to disadvantaged families' household necessities and lifestyles and that in most of the analyzed households the renovations performed by the residents were seemingly well-adjusted to their daily living requirements.

Thus, this book aims to present a small compendium of digital approaches (or techniques) applied to design processes. More related to the Luso-Brazilian scientific context, this work, published in English, aims to reach an international audience, specifically interested in issues related to the application of digital resources in creative processes.

CHAPTER 01

ARCHITECTURE BIO-GEOMETRICALLY INSPIRED

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ARCHITECTURE BIO-GEOMETRICALLY INSPIRED

RICARDO MASSENA GAGO

ABSTRACT

This research is in the biological design field, more specifically it deals with the development of architectural structures following the geometrical qualities of the biologic morphology. The biologic structures are the human main reference in the ecological design field. Their ecological performances are directly related with their morphology. However, this morphology carries an identity. It allows identifying the biological structures whatever their shapes. If that happens it means that they have to share a morphological pattern, i.e., the ecological shape uses a specific geometry. So, this research aims to develop a design tool of geometric essence able to transfer this morphological identity to architectural structures. For that purpose, a geometrical pattern is defined and decoded using the geometric and algebraic language of shapes grammars. The decoded pattern is organized through parametric rules. The generative quality of this drawing tool allows generating shape diversity with the same morphological identity through a random combination of the same rules. So, the design tool allows designers and architects to experience spatial design through a biological perspective. The idea is to show the morphological pattern with which the biological structures integrate spontaneously their shapes in the environment and achieve their structural and material optimization through self-supported structures.

INTRODUCTION

In the last decades several ecological design strategies have been emerged in the architectural field. However, the ecological purpose is not clear in most of them. The solutions developed do not reveal morphological signs that allow differentiating them from others generated by conventional design approaches. Nevertheless, the use of shapes or materials of biological origin is enough to emphasize the ecological purpose. Why? It happens because the biological products have a morphological identity recognizable as ecological. That is why it is possible to identify the biological structures from other in the environment regardless their shape. So, if the identification is possible through shape diversity, it means that the ecological quality should contain a particular design process which implements a specific morphological pattern, *i.e.*, an identity.

The ecological design strategies implemented in contemporary architecture are still not able to introduce this identity in their solutions. So this research intends to help in the definition of an ecological pattern that allows reducing the morphological divergence between human structures (Hstr) and biological structures (Bstr). Being the goal a morphologic design problem, its contributions to ecological pattern will be made at a geometric level. So, to achieve this morphologic coherence by geometric essence, the research defines as main goals the following aspects: (1) identify a set of geometric qualities that characterize the morphological pattern of Bstr and (2) develop a generative drawing tool of geometric essence able of transferring the geometric qualities into structures of architectural purpose.

To achieve the proposed goals this research will focus on the following topics: 1) characterization of the mechanism that controls the biological design process (growth); 2) interpretation of biologic geometry in terms of structural organization and geometric vocabulary and 3) identification of generative design tools able to decode and implement the geometric patterns of Bstr (Voronoi diagrams and Shape Grammars).

So, the drawing tool will emerge in the ecologic design field as a design process that proposes the generation of Hstr through a biological perspective. Its intention is providing to architecture the follow contributions: (1) a generative design tool of geometric essence, which allows experiencing a process of spatial modulation through principles of biologic organization; and (2) a design perspective based on formal simplification, where shape and structure share the same geometric configuration (self-supported structures).

BACKGROUND

The development of ecological strategies is common in the design field. Architecture is no exception. It has been fertile in the emergence of several design strategies that aim reducing the environmental impact of human activity. However, while following a common purpose, not all share the same principles. The divergences come from environmental ethics issues (CAPRA, 2003). Two distinct approaches can be pointed out. On the one hand, an ecological ideal based on a less harm strategy (superficial ecology) and on the other hand an ecological ideal based on participative cooperation (deep ecology) (JÚNIOR, 2004).

Although following distinct strategies, both approaches have generated dissatisfaction opinions with the obtained results. In superficial ecology, the slowdown policies of human harmful practices in the environment are questioned. Trying to balance the level doing less harm is not seen as sufficient (LITTMAN, 2003). The abandonment of sustainable policies by others that should maintain the connection between human and biology are proposed. In deep ecology, is the dependence on the use of technologies from superficial ecology to satisfy some of the human needs that is questioned. By considering the environmental crisis, a design crisis, it is suggested that the design process

should abandon the current degenerative technologies. As an alternative, it should encourage a design process that slowly establishes a reconciliation principle with the environment (REED, 2007). Although with good intentions, these ideas still reveal a utopian perspective. However, it is relevant to emphasize that they share a common opinion about the knowledge already acquired. Ecological goals require an approximation to Bstr in all of its aspects to be actively integrated. This idea is also shared by Alexander (2001). The author argues that the integration ability of the architectural structures in the environment is related with the use of biological geometrical qualities. The loss or absence of these qualities in architectural design interferes with the integration ability of the shapes in the environment, which in his opinion decreases the architectural quality. So, authors want to show through a geometric approach, that coherence is crucial to the coexistence of different structures on the same equality level. However, Alexander goes deeper. He proposes the idea that ecology should no longer be made through the copy of the ecologic object. It should start to be done through the process that generates it, because it is the process that generates the morphological identity. However, according to his opinion, if Hstr aim to achieve the Bstr level, the transference of the geometrical qualities is not enough.

It is necessary the entire ecological pattern.

ECOLOGICAL PATTERN

Alexander suggests that the reconciliation process between Hstr to Bstr should follow an ecological pattern (Alexander, 2001). However, the author does not clarify or parameterize it. This hypothesis is presented by Craig Loehle. Loehle argues that ecological pattern results from the interaction of at least six different levels of complexity (space, time, structure, behavior, process and geometry) (LOEHLE, 2004). So, the author establishes a set of research fields that architectural design strategies should follow in order to pursuit an ecological goal. However, this proposal is not a direct formula. Each of these complexity levels will require a huge effort from several research teams and a long experimental process. So, focusing this research on the morphological divergence between Bstr and Hstr, its contribution to the ecological pattern will be at the geometric complexity level.

ECOLOGICAL STRUCTURES IDENTITY. THE MORPHOLOGICAL DIVERGENCE

The absence of biological identity in the structures morphology is not a new subject in the ecologic design field. Several authors argue that ecological design should reveal its own identity and stop of being disguised with another morphological identity that does not suit its purposes. These strategies use different ideas and design processes, so they should start to reveal their own identity. The biomimetic research line came precisely to fill this morphological problem. It is its strategy to demonstrate the potential of biological shapes / processes in optimizing the goals of human activity in several fields by following biological knowledge. So, it is a strategy that never dissociates the shape

purpose from function and uses a design principle based on shape similarity in order to optimize a specific goal. However, for Alexander the copy by similarity is not enough to solve the morphological divergence between Hstr e Bstr. According to his opinion, it is the generation process that carries the geometric qualities of the morphological identity and not the shape contour design by itself. So, the author argues that it will only be possible to implement the biological identity in Hstr by identifying the geometric qualities that characterize it and without separating them from the process that generate them (ALEXANDER, 2003).

Given the relevance raised by Alexander and the goal of this research to implement morphological qualities of Bstr in architectural structures, it seems relevant to start by analyzing which design processes of ecologic order are being implemented to avoid shape copy and how they respond to the biological identity problem.

DESIGN PROCESSES WITH BIOLOGICAL STRUCTURES

Research lines that highlight the implementation of design strategies based on morphological processes of Bstr have been emerged recently. In this field strategies as digital morphogenetic (HENSEL, 2004) and living architectures (TATARELLA, 2014) stands out.

The digital morphogenetic concept introduced in architecture is a metaphorical interpretation of its origin (biological morphogenetic). It shares the idea of a process of gradual development, but without adopting growth mechanisms and morphological adaptation of Bstr. Its generative mechanism uses algorithms (rules and patterns), which are introduced into a computational process, in order to generate shapes that provide maximum material optimization under functional, material and environmental restrictions. This strategy is also characterized by an inverted design logic. It opposes to the conventional design process of the pre-idealized shape, proposing a design process based on a concept of form finding. In this concept the designers do not have any direct participation on the design process. They only control the parameters/restrictions that the shape should follow. So, the ideal morphology is proposed by the computational process. In this field, the work of Neri Oxman (2010), Achim Menges (2012) and R & Sie (CORBELLINI, 2010) is highlighted.

In a field where the use of digital tools loses influence in relation to metabolic resources of Bstr, the research line of living architectures stands out. The work developed by this strategy can be approached through two different perspectives. On the one hand, design strategies that materialize their morphology using Bstr (MITCHELL, 2008; SANFTE STRUKTUREN, 2016). On the other hand, design strategies that use the metabolic qualities of Bstr to developed materials (LARSSON, 2010; ARMSTRONG, 2011).

Regardless the geometric complexity achieved by these strategies the geometric configuration of their structures shows a pattern closer to Bstr. What can be deduced? That life inputs a sort of biosignature in its structures. If so, it should share a common generative process. But what kind of process is that? What geometry characterizes it?

BIOLOGICAL GEOMETRY

The biological geometry has been studied through at least three different types of approaches, focusing each one a particular quality of Bstr (growth, identity and minimal inventory / maximum diversity). In the growth mechanisms approach the work of Alexander (2001), Thompson (1992) and Ghyka (1977) stands out. Alexander focuses his research on the growth process of Bstr and in the geometric qualities associated to it. In his opinion the identity of something is inseparable from the process that generates it. In turn, Thompson focuses only on the allometry qualities of Bstr growth, i.e. the proportional relationships of shapes during the process of growth and evolution. Ghyka, also works in the proportion field, but analyzing the divergence that exists between the proportion of life and the proportion on art. His intention is to realize where the two coincide. In the identity approach, the work of Maggie Macnab (2011) is highlight. The author interprets the biological identity as a set of geometrical qualities that should be combined simultaneously. Finally, in the inventory / diversity approach the work of Blackwood (2012), Pearce (1978) and Mandelbrot (1977) stands out. Their research only focuses on particular geometrical qualities of Bstr. Blackwood deepening the symmetry, Pearce the morphological character and Mandelbrot the self-similarity.

Despite their purpose, all the approaches reveal similar qualities between them. However, only the qualities identified by Alexander have the particularity of embody all the others (Figure 1).

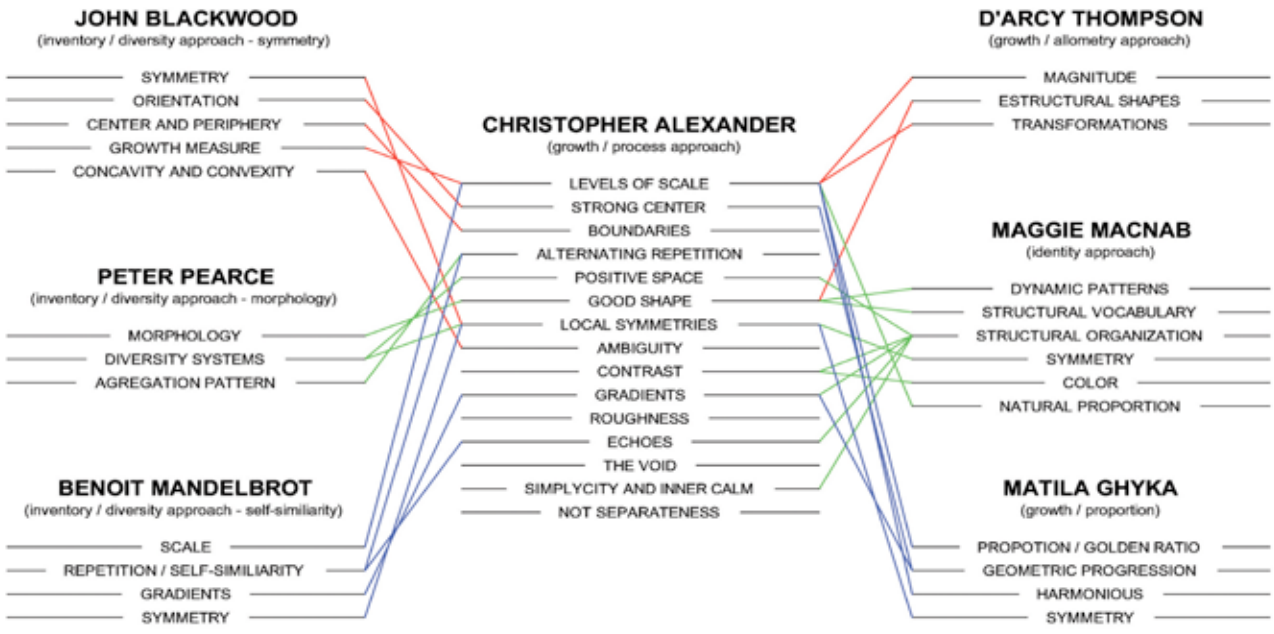

Figure 1 - Author's geometric characteristics.
Source: The author.

GEOMETRICAL PATTERN OF BIOLOGICAL STRUCTURES

The growth approach has proven to be the most comprehensive in the biological shape characterization. So, it seems relevant to understand how this process is characterized.

The growth process may be characterized as a quality which always begins with something, that expands and never ceases to be a part of the environment that contains it. So, it is a process that includes at least three qualities: origin, expansion and connection. What geometric qualities can be associated to each one? The origin is the source of all information that will control to structural configuration. It will define the morphological character of the structure and its structural cohesion. So, the geometric characteristics associated to origin include the definition of a geometric vocabulary and proportion ratios. These qualities will be addressed on the subject of allometry (Figure 2). In turn, the expansion focuses on the reproduction process from origin and in the cohesive way how the reproduction spreads in space. It requires two geometric characteristics, repetition and growth center and they will be approached on the subject of structural expansion (Figure 2). Finally, the connection focuses on how Bstr work the splice in the environment. So, the geometric characteristic associated to connection is union and is approached under the theme of spatial integration (Figure 2).

These qualities cannot be applied separately or randomly. Their presence through a growth perspective should follow a structural organization that should reveal a geometric configuration with the following requirements: structural fluidity, elements dependency and evolutive balance (Figure 2).

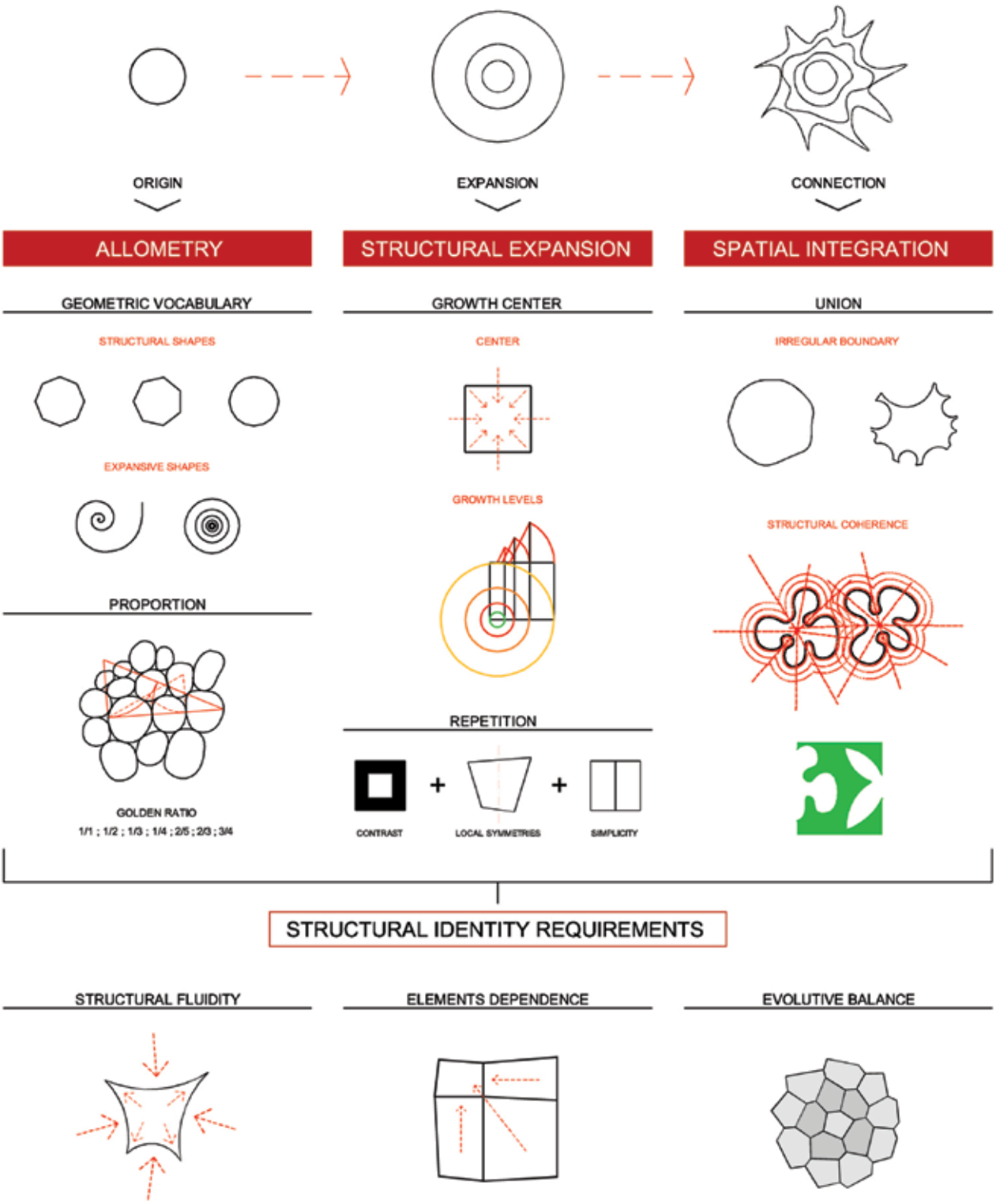

Figure 2 - The geometrical pattern of biological structures.
Source: The author.

GEOMETRIC QUALITIES

ALLOMETRY

Growth results from a process of elements addition generated by a reproductive process of formal replication. However, the addition is not random. It follows a cognitive order of proportional distribution that allows shape transformation without jeopardizing the structural cohesion of the whole. So, the generation of Bstr requires a specific geometric vocabulary and a proportional control of the reproductive and expansion process.

GEOMETRIC VOCABULARY

Biological morphology results from the combination of two distinct shapes: structural shapes and expansive shapes. Elemental shapes generate the structural body. They are composed by shapes of triangular derivation (polygons) being the hexagonal shape the main reference (PEARCE, 1978; THOMPSON, 1992). Nevertheless, other polygonal or even curved surfaces can have emerged depending on the deformation caused by the universal forces. However, their distribution is not random. They are arranged through an expansive shape characterized by wave and spiral patterns. What have these shapes in common? A balanced organization based on a structural center. According to Arnheim (1982) a balanced shape is a dynamic structure which is directed to a state of pause, i.e., a center. The elemental shapes achieve it through the force field that their closed shapes generate to a particular point in its interior (geometric center). In turn, the expansive shapes achieve it by using a design of progressive gradation that forward the look to a specific point of the shape (dynamic center) (Figure 3).

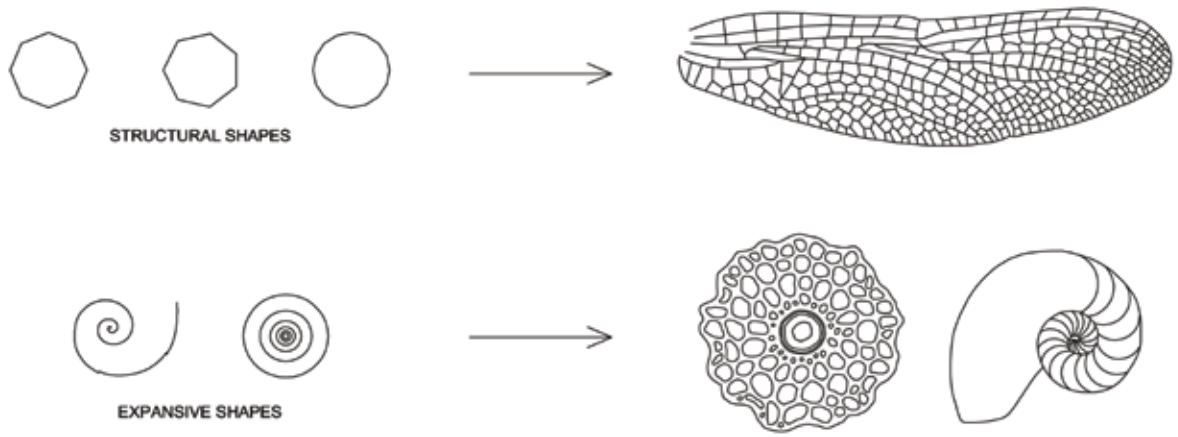

Figure 3 - Geometrical vocabulary of Bstr _ structural and expansive shapes.
Source: The author.

PROPORTION

Biological life manifests in space with harmonious structures. Their morphology is arranged in such a manner that seems to be unbreakable. This sensation is directly related with the proportional variations that exist between structural elements. This shows that the structural cohesion establishes proportional values between elements connected in continuity that should not be exceeded, otherwise the shape cohesion can be broken. Which values are these? Vitruvius establishes a number of harmonious proportional relations taken from the dimensions of the human body (1/2, 1/3, 1/4, 2/3, 3/4) (POLLIO, 1960). In turn, Alexander establishes a reduced set of proportions (1/2, 1/3, 1/4) (Alexander, 2001) referring to them as being the most common in Bstr. However, the geometric division method of golden ratio reveals a broader set of proportional relationships (1/1, 1/2, 1/3, 1/4, 2/5, 2/3, 3/4) (DOCZI, 2005). All these hypotheses lead to a very similar uniformity of values. Therefore, the golden ratio encompasses all the proposals (Figure 4).

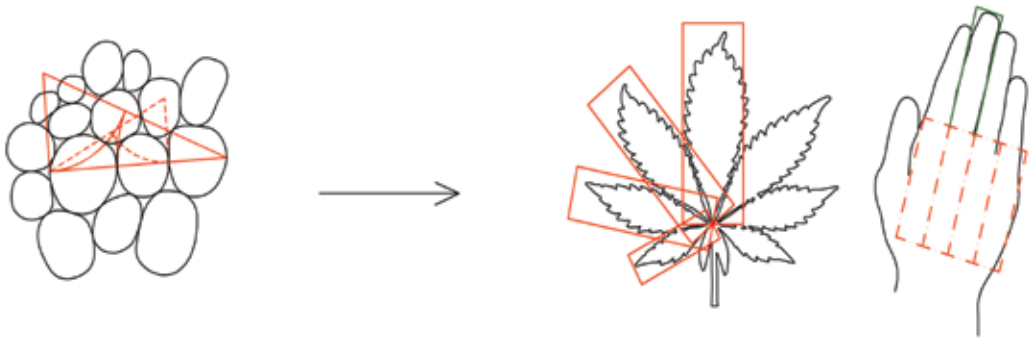

Figure 4 - Harmonious orders of magnitude between adjacent elements in Bstr.
Source: The author.

STRUCTURAL GROWTH

The growth process of Bstr requires expansion. They expand by using a reproductive process of replication, which means their evolutive structure is achieved by elements repetition and not by mass increase. This expansion ability allows the structure transformation without affect its cohesion. It happens because all elements are arranged in order to follow a common purpose, i.e., the entire structure is directed to a point of pause _ a center. So, structural growth requires addition of new elements that should be controlled by a generator center.

GENERATOR CENTER

The dynamism that characterizes the growth transformations requires a mutable generator center. It should maintain the structural reference (origin), but allowing an evolutive expansion of the structure. So, the generator center requires at least two qualities, a center and growth levels.

- Center – Bstr have an area to which their morphological composition converges without any resistance. The composition is all structured in its favor, giving it a prominent role. This area is referred by center (Figure 5). However, for something stands out in a shape, it is necessary that everything that involves it be forwarded for that purpose. This effect is obtained by a gradual variation of something in space, i.e., with the use of gradients. They emerge by two different ways, by elements increase and by oscillation effect. In the first, the elements should be displaced following a progressive arrangement through proportional variations without disturbing the structure fluidity from one point to another. In the second, the elements can be arrangement through an increase/ decrease pattern. However, the pattern repetition should increase its magnitude order progressively (Figure 6).

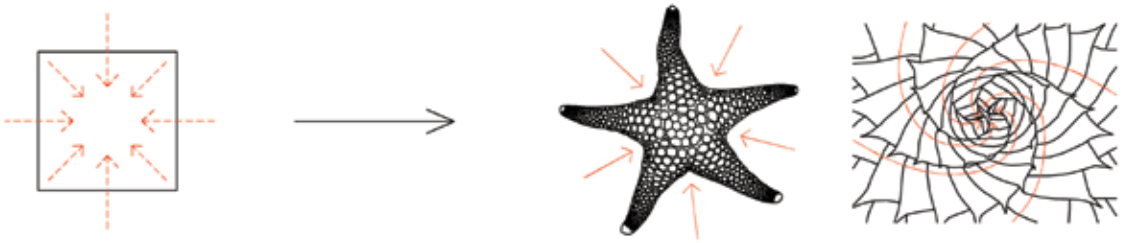

Figure 5 - Generator center in Bstr.
Source: The author.

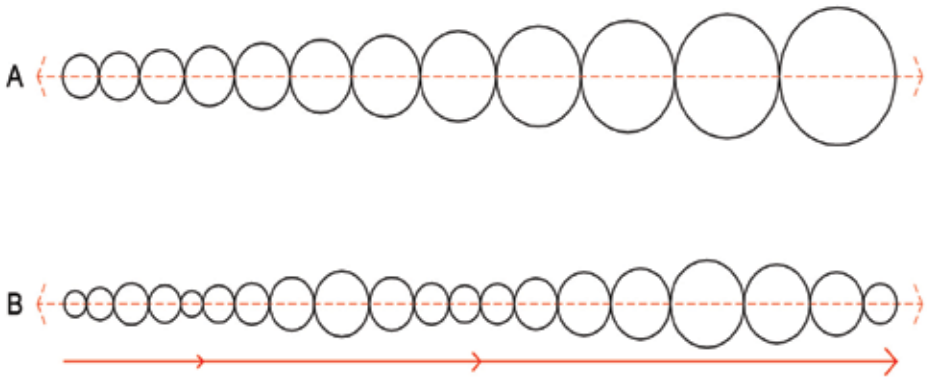

Figure 6 - Gradients. (A) Gradients by elements increase. (B) Gradients by gradual oscillation.
Source: The author.

- Growth levels – The center of Bstr does not exist isolated in the environment. It always emerges surrounded by a familiar mass. This zone protects and affirms the structural uniqueness of it. This structural mass is assumed as a transition zone. On the one hand, it creates a clear separation between center and environment. On the other hand, helps to establish a connection between them. These transition zones are denominated by expansion levels. So, center and expansion levels are inseparable. Their dependence is

so intense that it can be translated with orders of magnitude. The magnitude of the expansion level is always proportionally related with the magnitude of the center (2/3 of the diameter of the center). The relation between both is mutable. Each expansion level has as reference the order of magnitude of the total mass that precedes it (the center) (Figure 7). So, it is a process of proportional variations based on recursion.

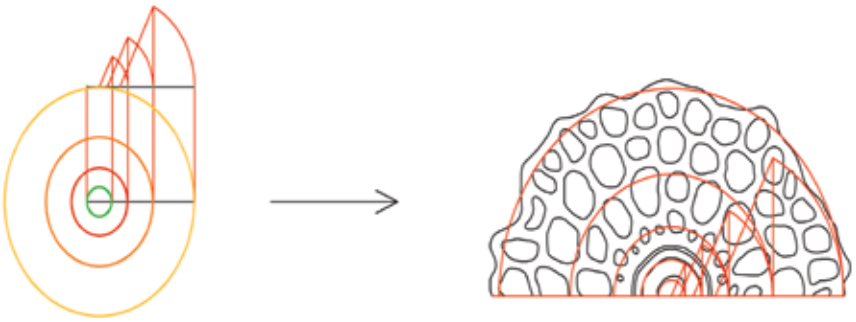

Figure 7 - Structural expansion through growth levels.
Source: The author.

REPETITION

Bstr result from elements repetition. Their structure always gives the idea that something has already been seen before. However, it is not a simple repetition of the same elements. It has a particularity. It reveals spatial exclusivity. It means that the elements have their own space and rules, i.e., they do not result from other elements, neither are parts of others. They are unique.

The emergence of this quality in Bstr requires the presence of the following geometric characteristics: 1) contrast, to determine accurately the boundaries of each structural element; 2) local symmetries, to provide irregularity in the linear continuity of the structural meshes and 3) simplicity, Bstr composition should only contain the necessary elements to their structural cohesion. (Figure 8).

How can these geometrical qualities be characterized?

- Contrast – Bstr are generated from the interaction of oppositions. They are crucial to identify and understand the shape composition. Two types of contrast can be pointed out, by colour (Black-white, dark-light, green-red, yellow-blue) and by structural variation (empty-full, convex-concave, dynamic-calm).
- Local symmetries – Bstr are symmetric. However, the symmetry is not perfect. It is based on irregular similarity. The irregularity has an important role in structural cohesion. It frees the shapes and increases their aggregation ability. Though, to achieve a fluid pattern the internal angles to the shapes should not be repeated. A simple repetition is enough to generate structural stiffness by the appearance of parallelism.

- Simplicity – The complex biological morphology results from a simple aggregation process. This process follows two simple geometrical requirements: 1) shapes intersection should be avoided and 2) shapes boundaries should be overlap. So, the simplicity concept is not related with the idea of regularity. The idea is to turn the shape perfectly legible regardless its complex geometry.

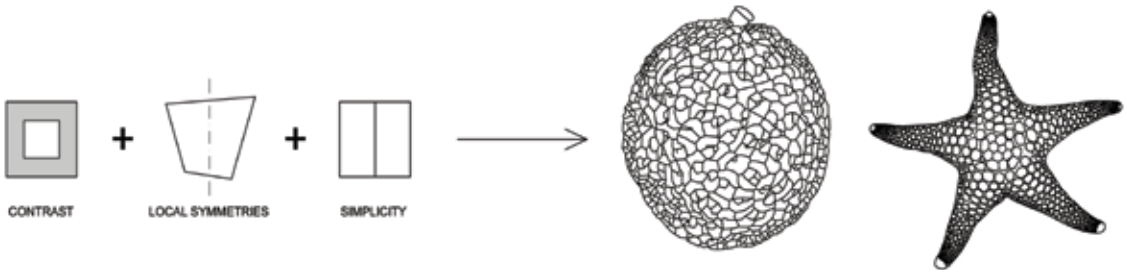

Figure 8 - Spatial exclusivity requirements.
Source: The author.

SPATIAL INTEGRATION

The spontaneous integration ability of Bstr with the environment is a quality that accompanies them from the initial shape. Since their origin, these structures appear to be part of it. This ability requires at least two geometrical qualities _ irregular boundaries and structural coherence.

IRREGULAR BOUNDARIES

The connection between shapes tends to be stronger the greater the diversity of links between them. This is the principle used by Bstr. However, their strategy uses something more than junctions, it uses “friction”. Friction increases the connection level between shapes by imposing cuts in the geometric regularity. The more irregularities the boundaries reveal more abrasive and sharper it becomes. The immediate result is the creation of stronger connections that are harder to split (Figure 9).

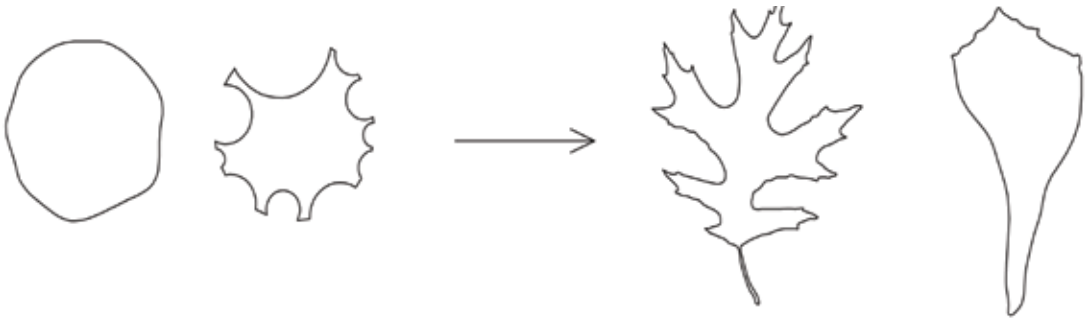

Figure 9 - Irregularity by diversity increase the friction between shapes and the surrounding.
Source: The author.

STRUCTURAL COHERENCE

Bstr have the particularity of emerging, connecting and being indistinguishable in the surrounding. However, their uniqueness and distinctness not generates opposition or affirmation. Even their connection is not made by physical continuity, but by separation. To achieve this set of qualities the structures should be morphologically coherent. It means that they need to share common morphological solutions. Bstr boundaries are characterized by concave and convex surfaces. By using the same pattern, they achieve a coexistence balance regardless their shapes. So, the connection between them is so unbreakable, because when different structures show the same qualities, the space between them will be an expansion of it. This fact gives rise to a third identity (the void) with similar qualities. It is in this process of sharing qualities between physical and nonphysical shapes that lays the connection by separation (Figure 10).

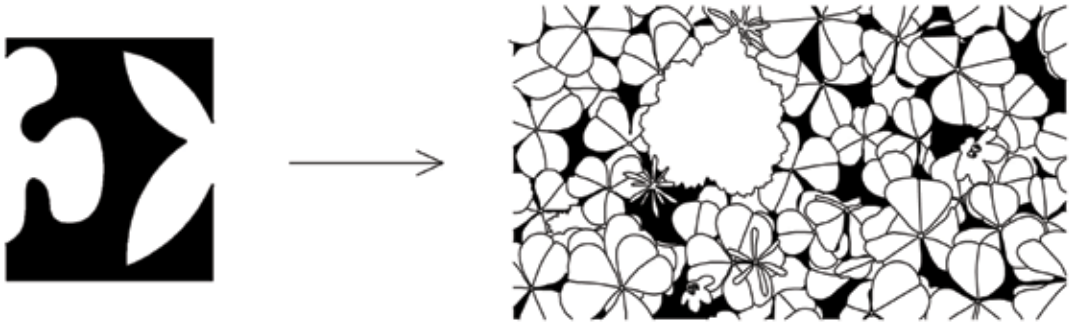

Figure 10 - Morphological coherence between shapes and the void.
Source: The author.

STRUCTURAL IDENTITY REQUIREMENTS

The morphological identity of biological structures does not result from a process of simple addition. The geometrical characteristics described previously cannot be added in the design process one by one. They are all related to each other and this relation is so intense that their simultaneous presence generates other geometrical characteristics of the whole. It means that the geometric pattern of Bstr reveals recursive levels of geometrical complexity. It is in the configuration that results from their interaction where identity emerges.

So, when organized through a growth process the geometrical qualities reveal at least three geometrical qualities that characterize the morphological identity of Bstr _ structural fluidity, elements dependency and evolutive balance. How are these qualities characterized?

STRUCTURAL FLUIDITY

Bstr are dissipative structures. They receive, transform and return stuff from the environment (energy). If it happens this characteristic cannot be only a metabolic quality. It should

be implemented in its morphology. If so, how can it be described in geometrical terms? By using two different methods. On the one hand, Bstr generate external tension in the environment by using concave and convex surfaces. They are responsible for the emergence of attraction and repulsion forces (ARNHEIM, 1982). On the other hand, they generate internal structural fluidity using a gradient organization based on a generator center in order to pull and conduct the forces to its interior (Figure 11). However, these forces should be eliminated inside the shape. The purpose of this annulment is to fix an origin, i.e., to define a clear position of the shape in the environment. To balance the exchange of forces, the structures expand in the opposite direction. This means that while they let themselves to invade, they also emanate invasive weaves in the environment. So, it is in this game of forces exchange that underlies the fluidity (Figure 12). Thus, biological shapes cannot be interpreted as physical barriers, but as a mass of force transfer.

Figure 11 - Curved surfaces generate tension by opposition.
Source: The author.

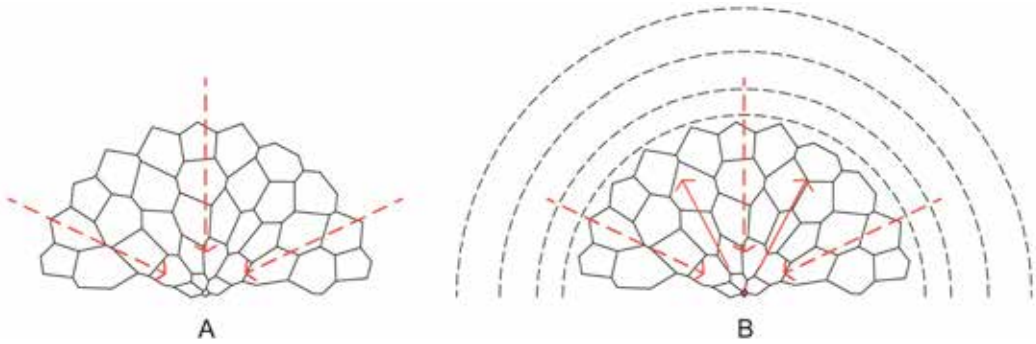

Figure 12 - Forces exchange – (A) attraction; (B) repulsion.
Source: The author.

ELEMENTS DEPENDENCY

According to Capra (1982) all the elements of the Bstr are related and play an important role in the whole. They all exist for a structural purpose, which means they reveal a relation by dependence. In geometrical terms, elements dependency is related with structural balance. To generate balance two qualities are required. First, all the elements exist in order to emphasizes a particular point of the structure (Figure 13). Second, the elements cannot be replaced by other from

the composition (ARNHEIM, 1982). To achieve their uniqueness, proportional variations between them are required (Figure 14).

Structures with elements dependency also reveal structural simplicity. It means that the morphological configuration of shapes only contains the elements that they need, i.e., without leftover elements. Each lost element results in a new configuration.

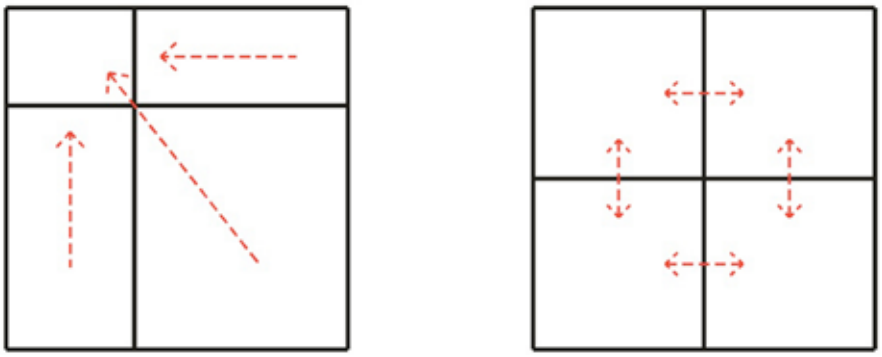

Figure 13 - Shapes with (left) and without (right) structural balance.
Source: The author.

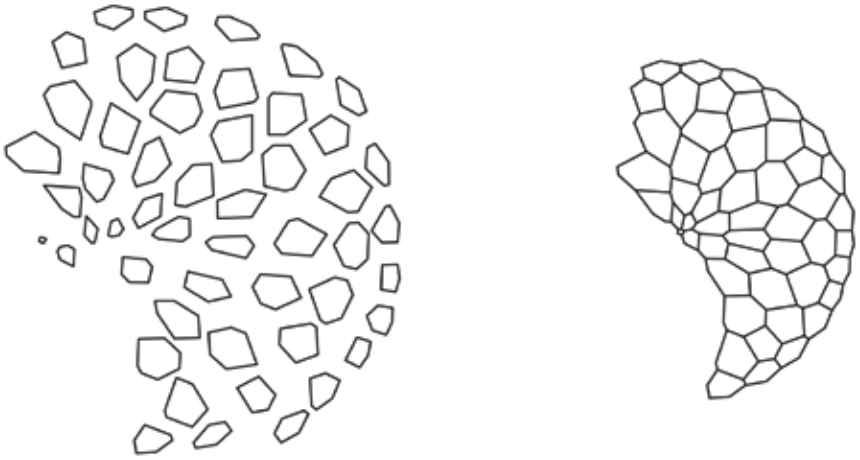

Figure 14 - Geometrical uniqueness of the structural elements.
Source: The author.

EVOLUTIVE BALANCE

Bstr are continuously evolving. Their morphology is continually changing, but without undermining the structural stability of the shapes. So, they reveal structures with evolutive balance. This quality is related with shape transformations. Each transformation that results from elements addition should reinforce even more the structural cohesion of the shape. It means that the transformations have to maintain the structural fluidity (force field) and the geometrical composition of the previous transformations. So, it is a design process that allows shape mutation without losing its morphological identity (Figure 15).

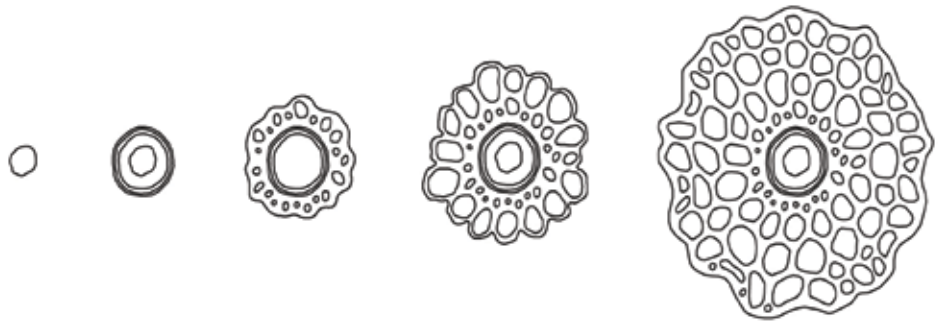

Figure 15 - Shape transformations maintaining the structural cohesion.
Source: The author.

THE BIOLOGICAL PATTERN IN ARCHITECTURAL STRUCTURES

The morphological divergence between Hstr and Bstr is clear. However, the geometrical characteristics identified are not strange in Hstr. They arise individually or in small groups, but never simultaneously in the same structure as it occurs in Bstr (Figure 16). It suggests that the human design process does not provide the means to achieve it, i.e., the morphological divergence comes from a design problem.

Bstr use a design process based on growth mechanisms. So, it seems relevant that to transfer such qualities for Hstr, it will be necessary to include not only the geometric characteristics, but also the process that makes them emerge.

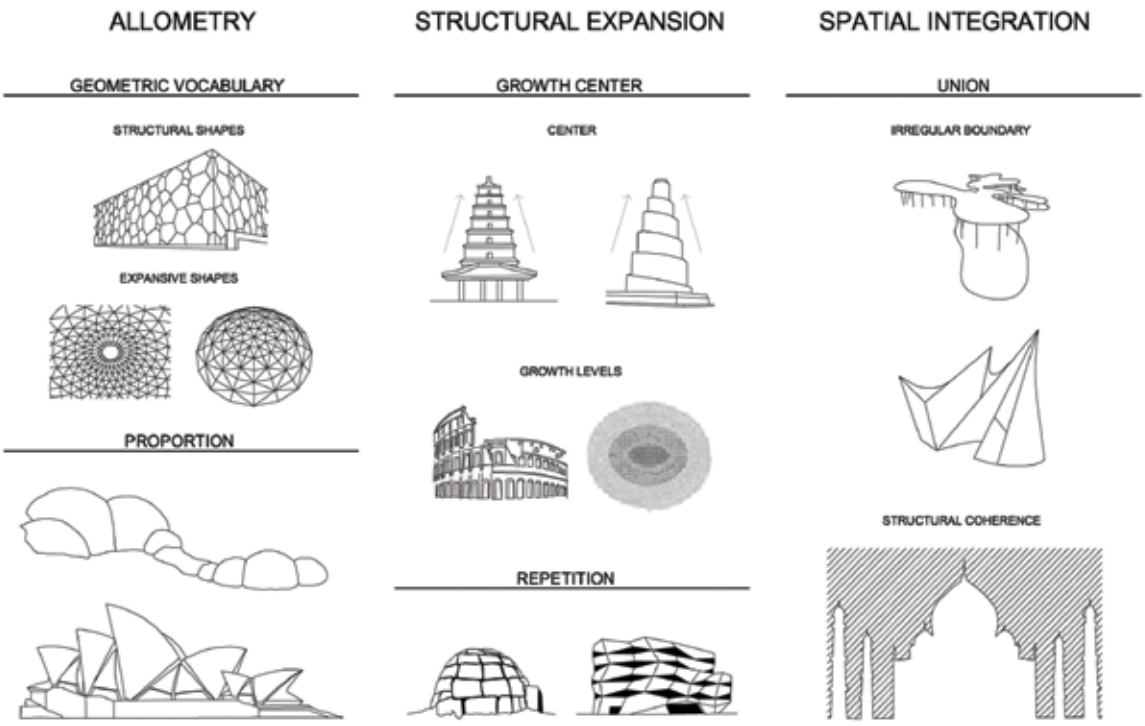

Figure 16 - The geometrical pattern of Bstr in architectural structures.
Source: The author.

DESIGN PROCESS

This research aims to develop a design process able to transfer this pattern to human structures. For that purpose, drawing tools are required.

The mechanisms of biological growth are generative. They generate shape diversity through a process of rules with a short inventory. So to implement these qualities a generative design process is requires. For that purpose, two drawing tools were identified _ voronoi diagrams (AURENHAMMER *et al.*, 2013) and shape grammars (STINY, 1980; 2008). A voronoi diagram is a design tool used in the design field by its ability in generates patterns similar to the biological ones. The tool is characterized by a process of spatial division referenced in a set of points located randomly in space. It can achieve a large diversity of patterns with the same morphological identity (Figure 17).

Growth requires an expansion process based on a centroidal configuration. The voronoi diagrams have the flexibility to achieve it, but its generator points should be controlled for that purpose. So, another drawing tool is required to order the points location _ shape grammars. Shape grammars are a shape decoder tool using rules described through a geometrical and algebraic language. It controls all the proportion aspects and the structural relations of the geometry.

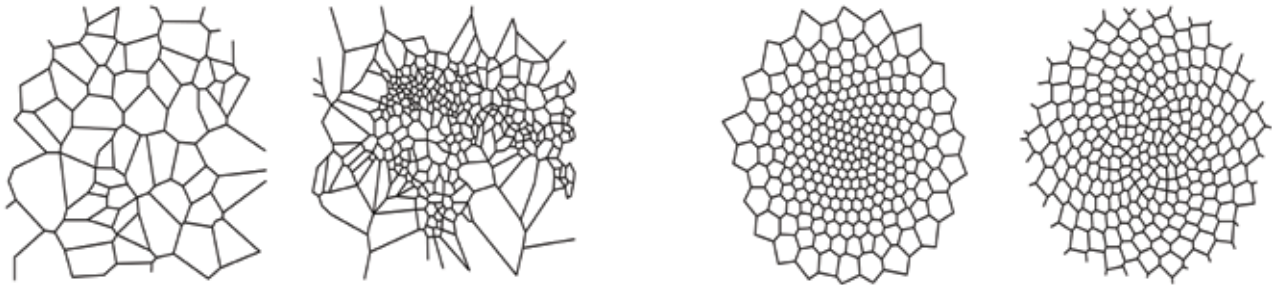

Figure 17 - Voronoi diagrams tessellations. Random arrangement (left). Centroidal arrangement (right).
Source: The author.

DECODING PROCESS

The generation of structures by shape diversity that reveals the same geometrical identity requires the definition of a geometrical inventory. The inventory should reveal the aforementioned qualities of the Bstr decoded by rules described through the geometric and algebraic language of shape grammars. The decoding process focuses on the following geometric requirements: generator center, centroidal structure, force field pattern, shapes of triangular derivation, referential points, curved surfaces and symmetry.

The generator center requires rules that will define the origin of the shape in space (Figure 18-A). In turn, the centroidal structure requires rules to define the expansion configuration of the shapes (wave or spiral) (Figure 18-B). The force field pattern based its rules in the definition of the gradient pattern which will allow the force transfers between shape and surrounding (Figure 18-C).

The shapes of triangular derivation will require rules that decode the generative process of the voronoi diagrams in order to define the boundaries of the structural shapes (fig.18-D). In turn, the referential points requirement will define rules for controlling the arrangement of the structural shapes in space (Figure 18-E). The curved boundaries require rules that will define the contour configuration of the shape. The use of concave and convex surfaces is essential to attract external forces into shape (Figure 18-F). Finally, the symmetry requires rules that will allow implementing structural balance through a reflective pattern of repetition (Figure 18-G).

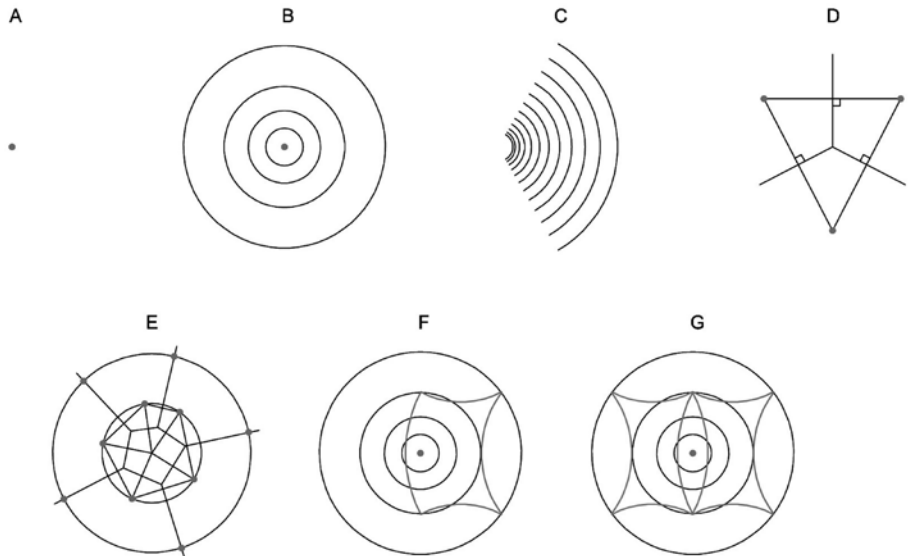

Figure 18 - Geometrical inventory. Generator center (A); centroidal structure (B); force field pattern (C); shapes of triangular derivation (D); referential points (E); curved surfaces (F); symmetry (G).

Source: The author.

GRAMMAR RULES

The implementation of these qualities in Hstr requires a generative design process divided in four distinct phases, which one with its own rules. In the first phase, the proportion rules define the structural base of the shape. In the following phase the morphological rules generate the shape contour. In the third phase, the materialization rules define the structural "body" of the shape. Finally, in the fourth phase, the spatial rules transfer the geometric composition to a curved surface in space.

PROPORTION RULES

The shape generation starts with the definition of the generator center and the expansion pattern that will be controlled by it. The structural shapes can be organized following two expansion patterns _ spiral and wave. Due to the geometric uniqueness of each one, it is not possible to approach them through a common grammatical description. For that reason, the grammar developed only considers the wave expansion.

Bstr proliferate in space through expansion levels that emerge from the same center. These have such an important role in the geometric composition that all the structural elements are organized through their rules. So, it seems relevant that the first phase of the design process be aimed at the development of structural bases where all the subsequent phases will be referenced. Thus, the proportion rules will control the proportional relations of the shapes and the proportional variations between the structural elements. For that purpose, the generation process will have to take into account the following requirements: the expansion levels should be generated from a common center and de magnitude values in their generation should follow the center / expansion level relation.

The expansion levels are not always part of the border rings that control all the structural shapes. The spatial void between two expansion levels can be filled with many structural shapes that have no contact with them. This fact implies the existence of secondary rings, which organize the structural shapes inside the void. So, the proportion rules define structural bases with levels and sublevels of expansion. However, the distribution of the sublevels should not be random. They should follow a gradient organization that develops a force field in favor of the center. The force field could be achieved from two different ways, by elements increase and by oscillation effect.

So, the proportion rules are responsible for the hidden geometry that controls and organizes the structural pattern of the shapes (Figure 19).

MORPHOLOGICAL RULES

In the second phase, the morphological rules aim the implementation of the union geometrical qualities in the design process. Their purpose is to generate irregular shapes contour over the structural base able to reveal the multi diverse connectivity of the union principles. The generation of the shapes requires at least four steps. In the first step, a mesh of points is introduced over the expansion levels rings. The points will be the contour guide reference of the shapes boundaries. However, their disposition in the structural base should follow several patterns. The shape does not have to fill the entire structural base. Bstr developed through a wave pattern do not have to be rounded. They can reveal other morphological configurations. To establish these limitations, the design process defines several expansion angles. These are related with the proportion values of the golden ratio (Figure 20).

In the second step, the shape definition begins. Straight lines will join several points inside the expansion angle. They will define a temporary contour for the shape. In order to achieve a temporary closed shape the contour will be symmetrically replicated. Then, the straight lines will be replaced by concave or convex surfaces. This process defines the shape boundaries. Finally, the fourth step will remove all the references of the expansion angle from the structural base (Figure 21).

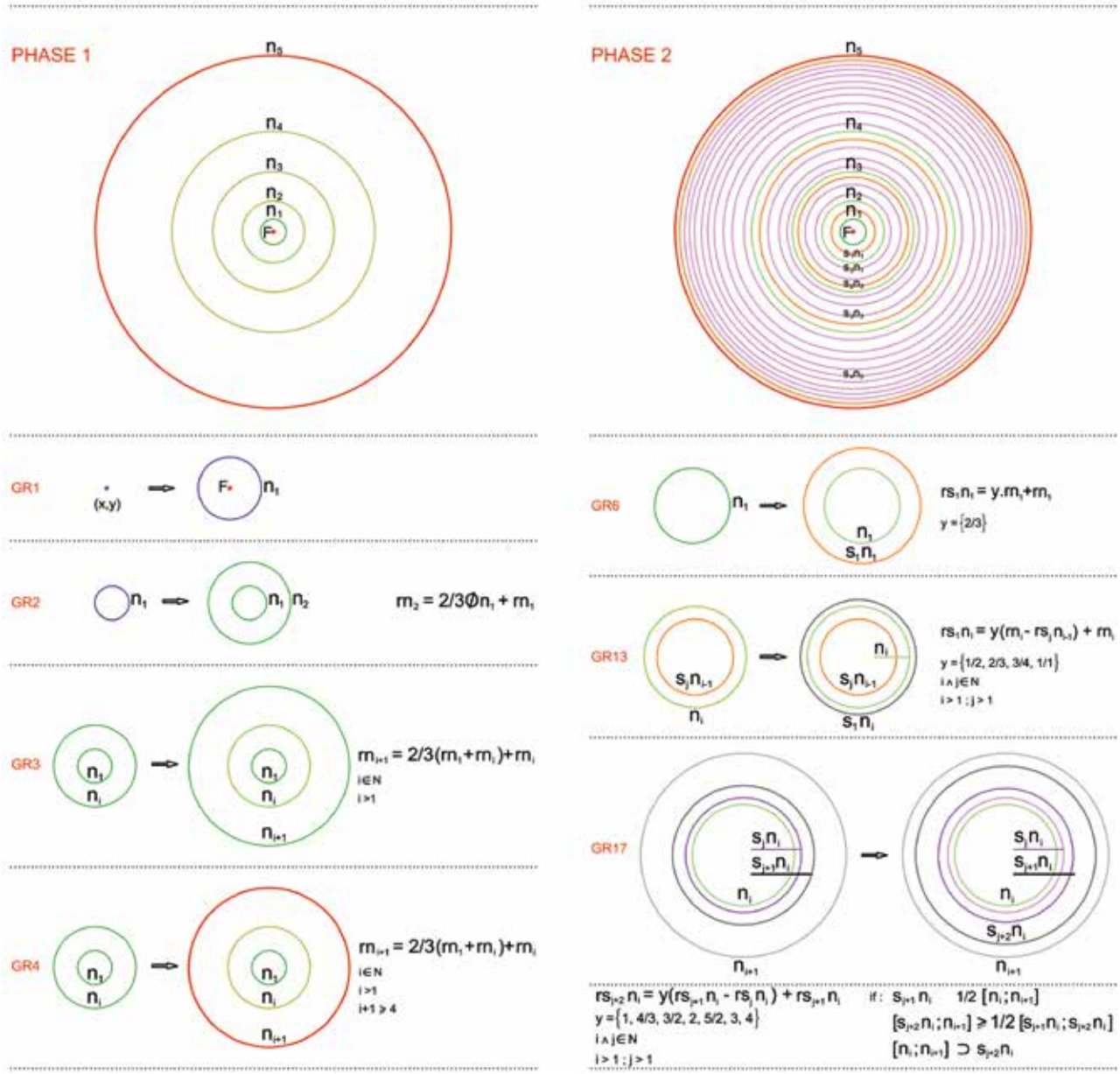

Figure 19 - Proportion rules. Generation phases and grammar rules examples.
Source: The author.

MATERIALIZATION RULES

This rules matches with the shape materialization phase. A physical structure where stays portrayed all the geometric decisions established in the earlier phases is generated. These rules will implement the structural shapes in the design process (shapes of triangular derivation). The shapes generation follows the concept of the non-regular space division from Voronoi diagram. However, the generation process denotes a particularity. The reference points necessary for the shapes generation are positioned over the rings of the expansion levels and sublevels defined by the proportion rules. To simplify the generation process, the grammar only contemplates the use of polygonal shapes.

The generation process of the structural shapes should fill the interior of the main shape defined by the morphological rules. All the structural shapes generated outside the shape boundaries or those which more than a half of its internal area is also outside the boundaries should be removed. After this selection the boundaries of the referential shape can be removed, leaving the geometric composition defined only by its structural shapes (Figure 22).

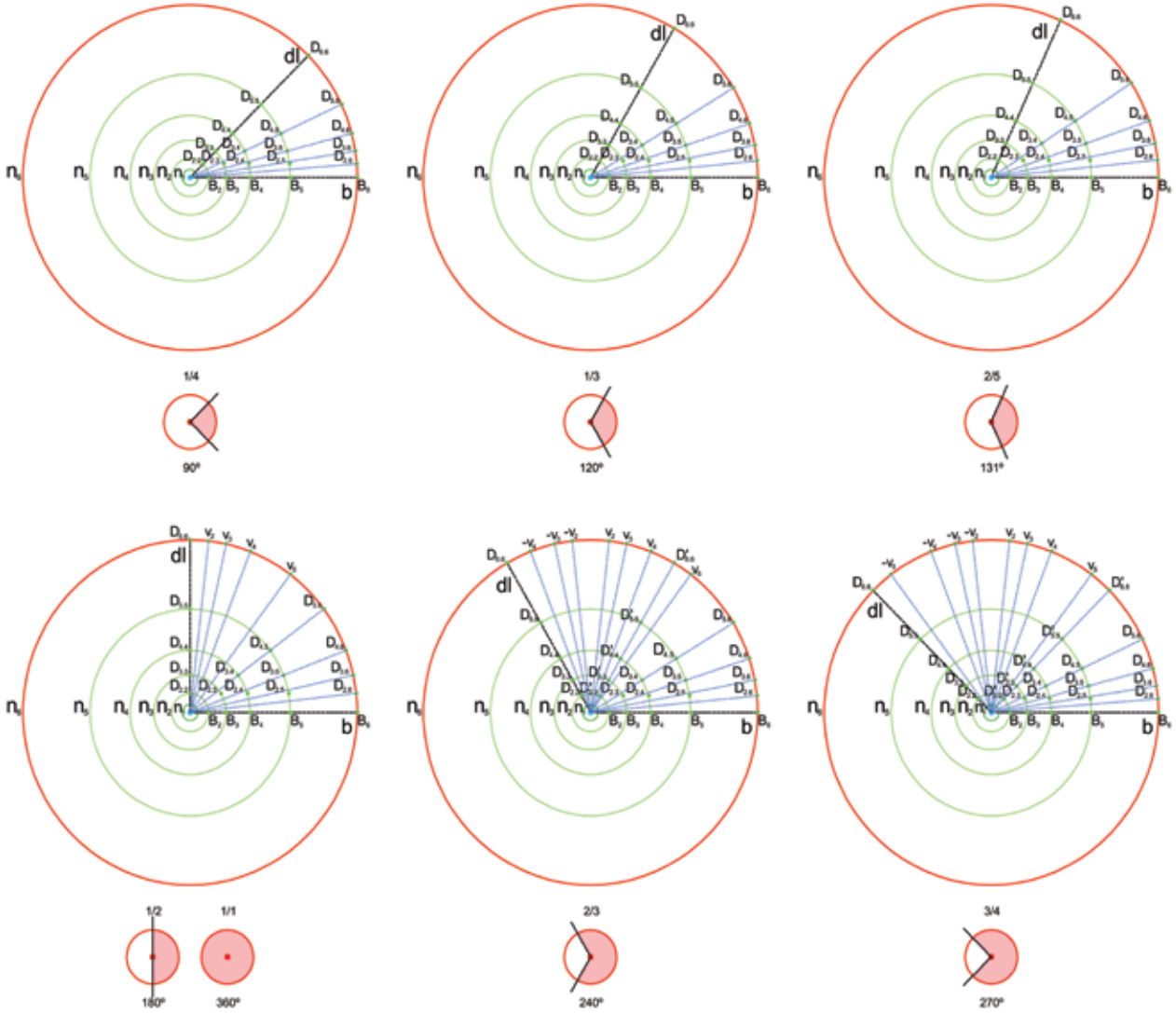

Figure 20 - Expansion angles.
Source: The author.

SPATIAL RULES

The spatial rules aim to transfer the geometric composition generated by the tool to a curved surface. The selection of these surfaces cannot be random. They need to reflect in space the geometric qualities that characterize the structural base. So, both should share the following

qualities: expansive shape in wave, a growth center, expansive ability and concave /convex surfaces. Taking into account these requirements two geometric surfaces were identified _ the torus and the sphere. The concavity of these surfaces allows enclose internal space. This particularity gives a structural purpose of “shelter”, which enables the human occupation.

The transference of the mesh for the curved surface will be made through the intersection points of the structural shapes. Each of these points should be attached to the generator center through a straight line. In each of these lines the arc of the chosen surface should be placed and the transference of the point done. The points on the curved surface should then be connected following the same pattern of the two-dimensional mesh (Figure 23).

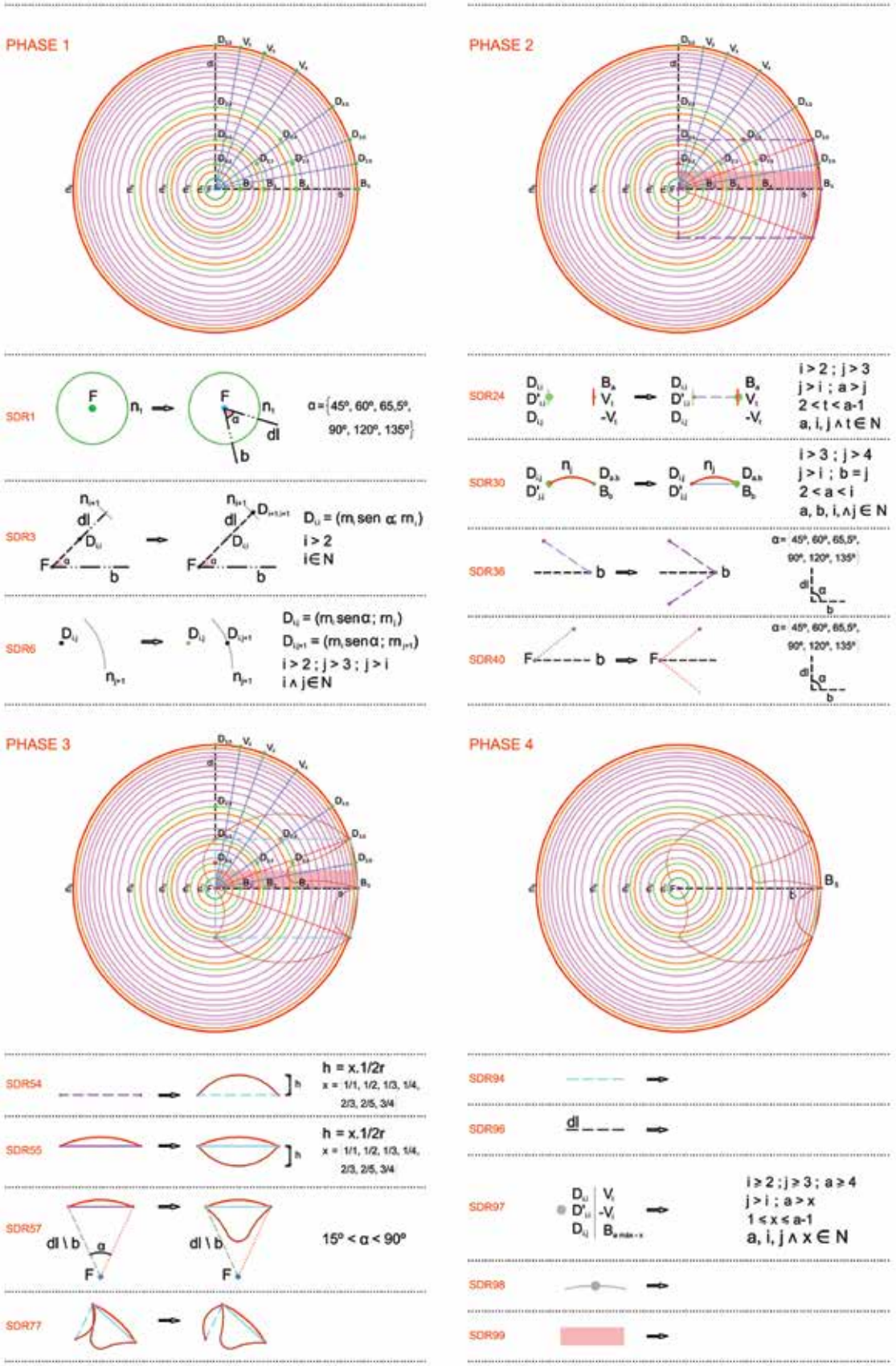

Figure 21 - Morphological rules. Generation phases and grammar rules examples.

Source: The author.

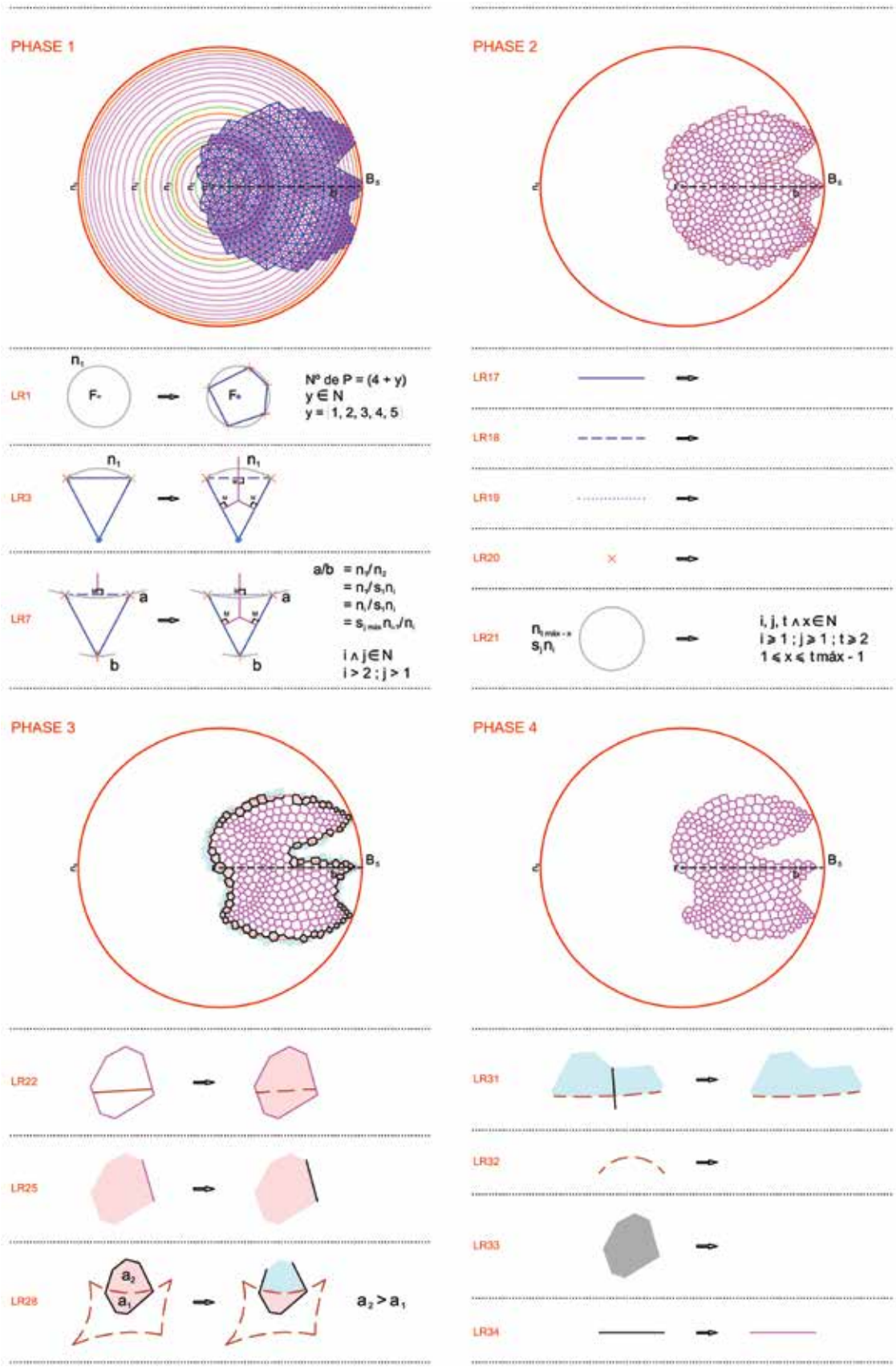

Figure 22 - Materialization rules. Generation phases and grammar rules examples.

Source: The author.

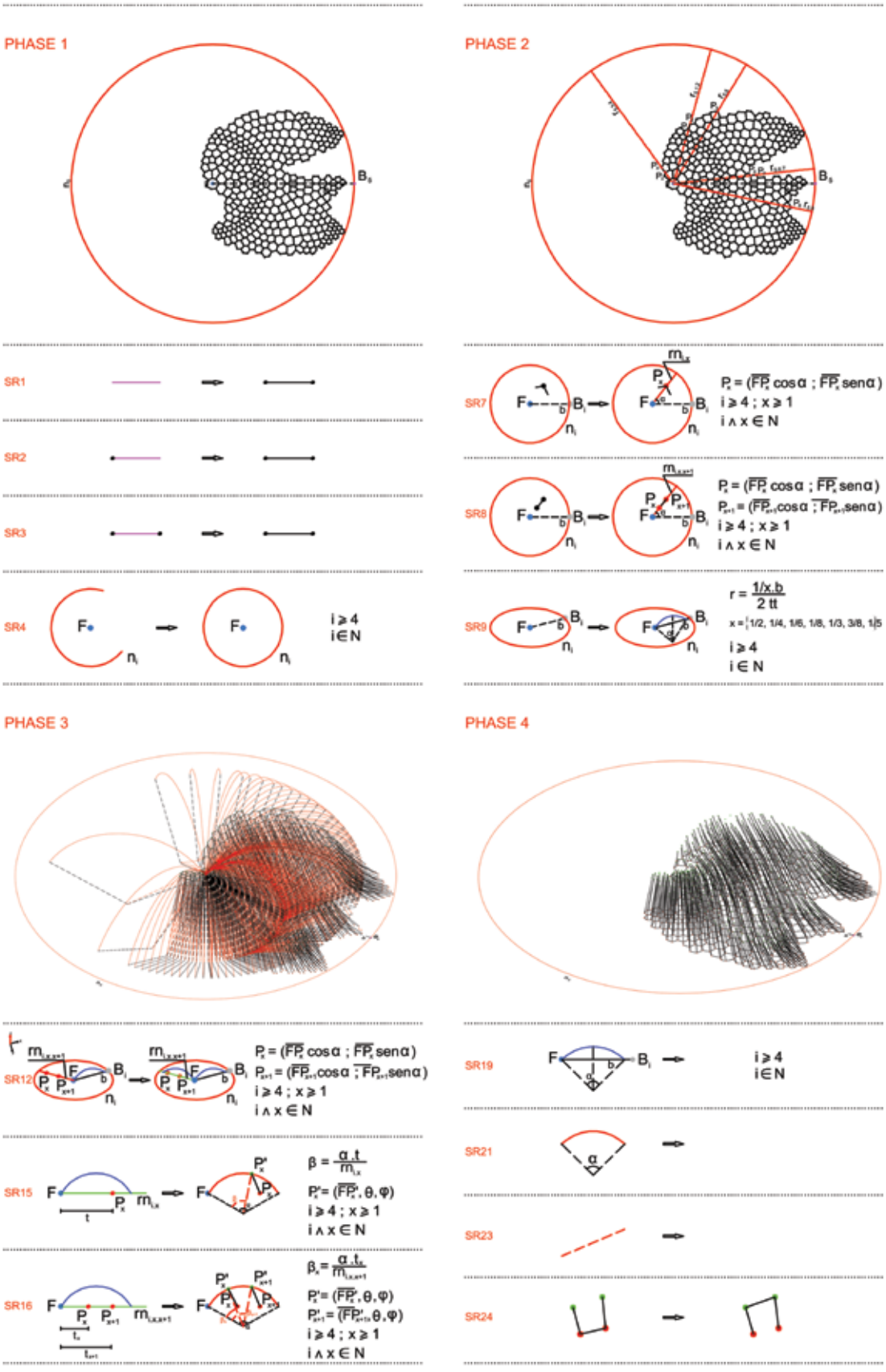

Figure 23 - Spatial rules. Generation phases and grammar rules examples.
Source: The author.

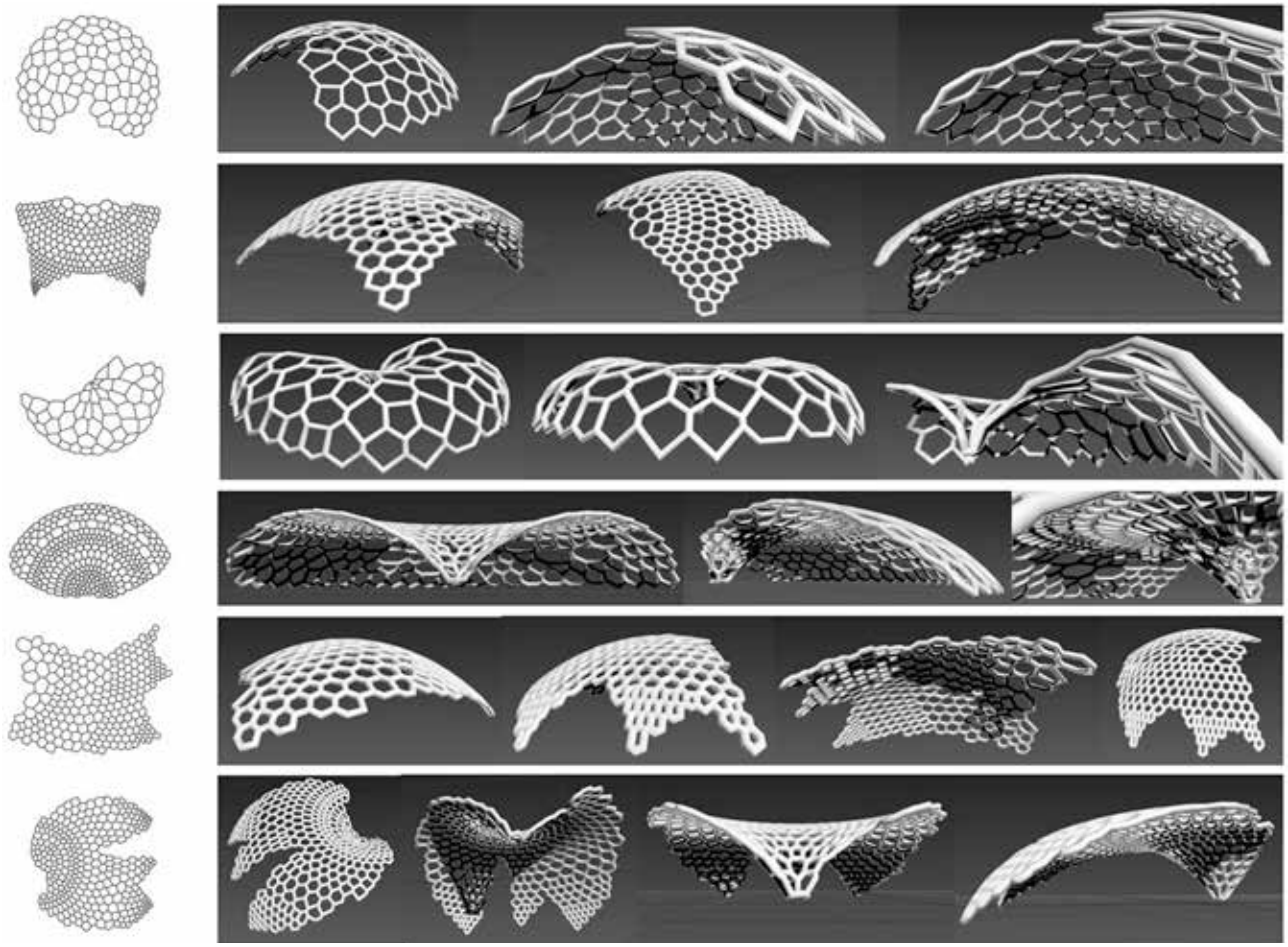

Figure 24 - Examples of models generated by the drawing tool. Shape diversity with the same morphological identity.
Source: The author.

VALIDATION

To validate the purpose of the tool developed it is necessary to check out if the design process reached the proposed goals.

GEOMETRICAL PATTERN

The design tool is able to transfer the geometric pattern proposed successfully. The models reveal the allometry qualities. The structural shapes have a geometric vocabulary with the same morphological character (polygons) and their disposition in space follow an expansive organization in wave. The proportional variations between adjacent elements also reveal harmonious magnitude values.

The qualities of the structural expansion were also achieved. The models reveal a growth center. They are referenced and forwarded to a specific point in their composition. Their growth uses

expansion levels referenced in the center. As regards to repetition, has been proven in the allometry that the models use elements from the same family. It is now proven that these elements hold spatial exclusivity. This means that structural shapes do not result or are a part of other shapes. They have their own rules, being perfectly legible and delimited by a full / empty contrast. The models also reveal a structural organization based on local symmetries and structural simplicity (structural shapes boundaries overlapped). The presence of the repetition qualities generates roughness effect, which gives them dynamism and vibration.

As regards the spatial integration characteristics, the models also reveal the union qualities. The connection between them and the surrounding is made through irregular boundaries that do not repeat the same configuration and the morphologic pattern follows a coherent configuration based on concave and convex surfaces (fig.25).

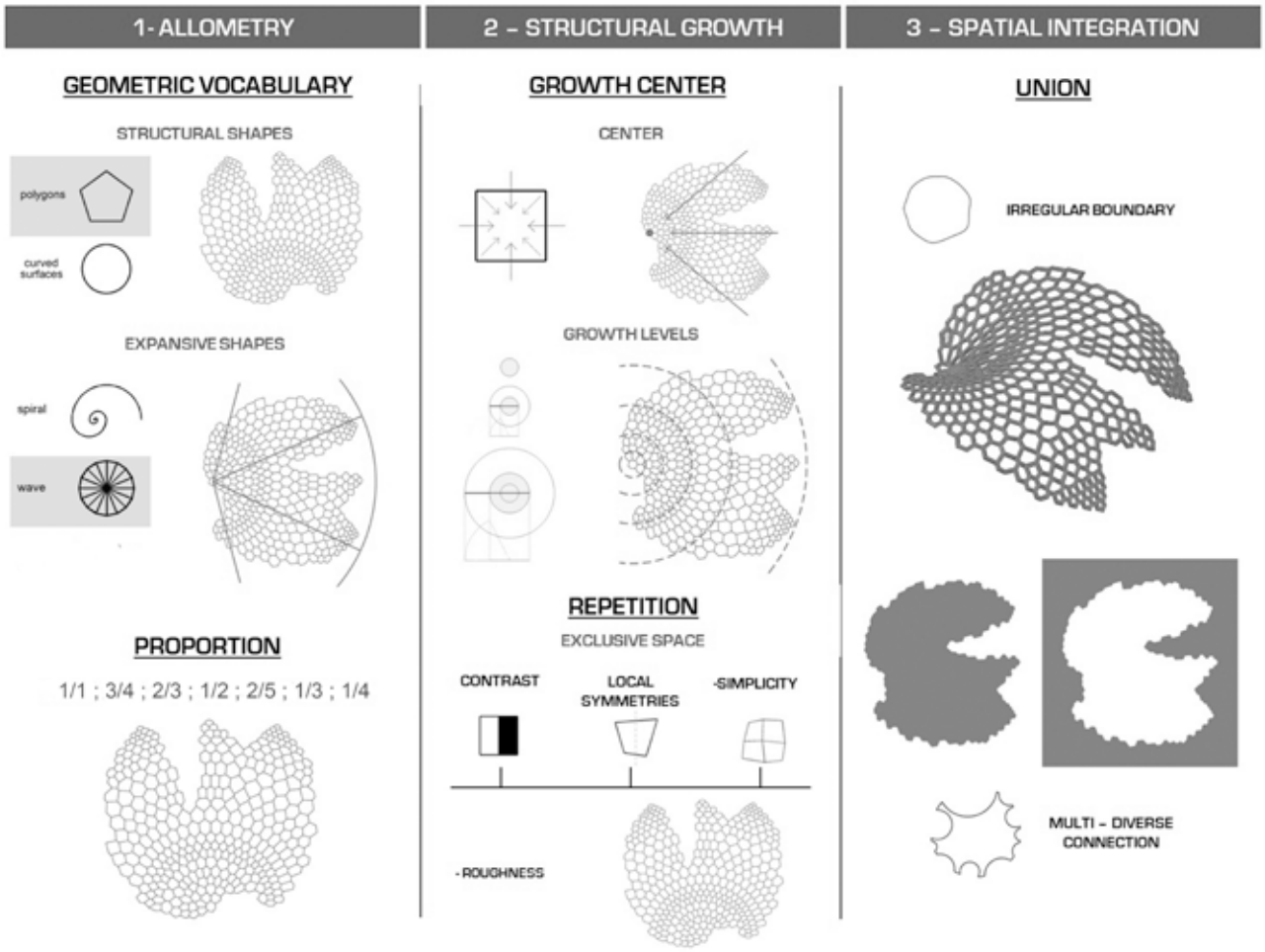

Figure 25 - Validation schema.
Source: The author.

STRUCTURAL IDENTITY REQUIREMENTS

The presence of these geometrical characteristics simultaneously in the models gave rise to other geometric qualities that characterize the morphological identity of the Bstr. The models reveal structural fluidity. They allow forces exchange between shape and surrounding without revealing any geometrical disturbance in the shape configuration that prevents it (fig.26-A). The evolutive balance was also achieved by the models morphology. The models evolve by elements addition without disturbing the structural coherence of the whole and maintaining the previous elements in each transformation (fig.26-B). Finally, the models also reveal elements dependence. All the elements are generated with a common purpose, i.e., put in evidence the generator center. The geometric irregularity of the elements implements in them a unique identity, making its position irreplaceable by another in the composition (fig.26-C).

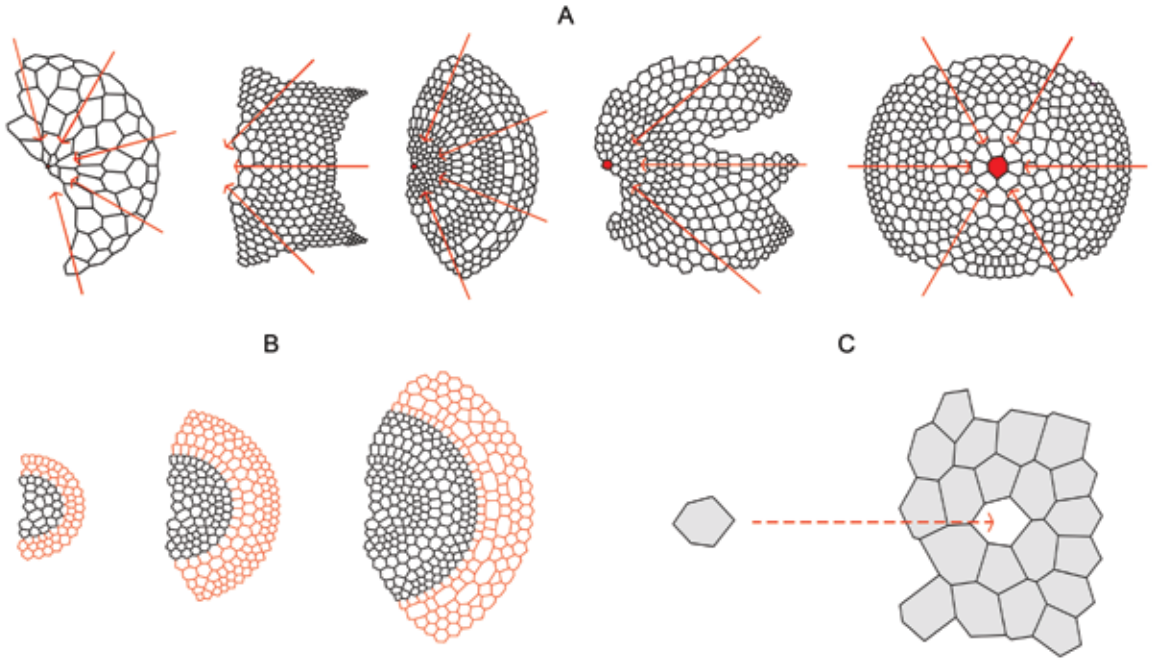

Figure 26 - Structural identity requirements. (A) Structural fluidity; (B) Evolutive balance; (C) Elements dependence.
Source: The author.

CONCLUSION

This research has shown by geometric means the following aspects:

1. the morphological divergence between Bstr and Hstr comes from a design problem;
2. the shape generation by morphological coherence requires a design process that does not dissociate geometric characteristics from the process that generates it (growth);

3. following a biological design process allows designers the freedom to continue developing structures by morphological differentiation with the same identity and without copying the existing ones.

The implementation of the growth variable in the human design process, influences the geometric composition in two distinct levels. On the one hand, at the structural organization level with the introduction of organizational requirements (growth center, expansive orientation, expansion levels and force fields). On the other hand, at the geometric level with the introduction of a specific geometric vocabulary and proportional relations. The combination of both reveals to be crucial to achieve other geometrical qualities of the biological identity (evolutive equilibrium, structural fluidity, structural simplicity and elements dependence).

To implement these qualities in Hstr, shape grammars revealed as an important design tool. Its main contributions in models generation were the following:

1. tool manipulation – a geometric pattern described by rules can be used easily by anyone who has interest in developing structures with these biological qualities;
2. detach the geometric pattern from referential shapes – decode the pattern into rules allows to deviate the generation process from formal copy;
3. shape diversity – the decoding of the geometric pattern in rules allows its emergence in several formal configurations.

Therefore, the shape grammar allowed the development of a generative design tool in the architectural field with the following qualities:

1. allows spatial organization through a biological perspective;
2. the experimentation of a design process based on formal simplicity by multifuncionality (the structural and morphological shape are the same);
3. the possibility of shape generation by geometric coherence and not by formal copy.

Summing up, this research shows that ecologic design should take into account the essence of its morphological origin and not only its direct achievements. This factor will inevitably generate changes in human design. However, understand its process allows designers to achieve one the main goals of the ecological design, i.e., design in coherence with Bstr, but with morphological differentiation. So, the design process through a biological perspective is really different from the human current design. However, this research shows that it does not have to be equal to what Bstr do. Only need to exist coherence between them.

Currently, a direct implementation of this knowledge in architecture cannot be considered, because the design tool does not have yet a fabrication process associated to it. However, it can be applied as a geometric referential of architectural solutions, more precisely, in the study of self-supported solutions and for enhancing material and structural optimization in architectural design. Even so, given the positive results obtained, it is future intention to continue improving the design tool in order to encourage the approach to the evolutionary identity of Bst.

CHAPTER 02

AUTOMATED GENERATION OF LAYOUTS WITH EVOLUTIONARY ALGORITHMS

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AUTOMATED GENERATION OF LAYOUTS WITH EVOLUTIONARY ALGORITHMS

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ABSTRACT

Computational design begun in the early 1960s and one of the widely discussed methodologies at the time was Space Planning (SP), a field of research that studies the arrangement of a series of topological and/or geometric elements in a given space, in which distance, adjacency and other criteria are main goals. This study is part of a research whose hypothesis consists in the affirmation that the new tools for architectural design support (CAAD - computer aided architectural design) are helping in the dissemination and approximation of architects to a series of computational design methodologies, and that they could help spreading SP methods. The present study consists in a literature review, with the purpose of identifying processes, experiments and designs that used evolutionary algorithms as a method to solve space planning problems. Although SP methods with evolutionary approach have been studied for more than 20 years, this is still a field with many non-explored possibilities of research. The authors believe that space planning techniques may effectively become useful for architects in their daily life, provided that they are aware of it and know how to implement it with the available resources.

INTRODUCTION

Over the last decades, the use of computational tools in the process and production of design and architecture have been significantly increasing. Parametric design, generative tools and digital production are methodologies that have been recurrently discussed in architecture and urban design offices, from undergraduate to graduate courses of universities and international institutes as well as in corporations specialized in connecting companies and architects.

The post-World War II computation advances have reached all knowledge fields. Among the new computational methods developed in the 1950s were those that tried to grasp and simulate

nature's generative capacity, whereas others sought to understand and simulate human beings' cognitive characteristics (RUSSELL; NORVIG; INTELLIGENCE, 1995).

This development culminated in a new field of research, named Artificial Intelligence, a term created by John McCarthy in 1956, at a workshop in Boston. Currently, the definition of Artificial Intelligence varies between two dimensions (RUSSEL; NORVIG; INTELLIGENCE, 1995). The first one focuses on human beings, as an empiric science, with hypotheses and experiments. The second one turns to rationality, combining mathematics and engineering (RUSSELL; NORVIG; INTELLIGENCE, 1995), the latter being closest to the processes and methods developed over the years in computational design.

However, computational design is not a new field of research, as it has been discussed since the 1960s, when the first computer aided-design software (CAD) was in the beginning of its development (Rocha, 2004). One of the computational design methodologies widely discussed in parallel with CAD tools development was Space Planning (GRASON, 1971; MILLER, 1970; EASTMAN, 1971; EASTMAN, 1973).

Space Planning (SP) is a field of research that studies the arrangement process of a series of topological and/or geometric elements in a given space, in which distance, adjacency and other arrangement functions are main goals (EASTMAN, 1971; EASTMAN, 1973). In general, SP problems are defined by two concepts: (1) topological and (2) geometric restrictions. At first, topological restrictions define a spatial relations hierarchy, such as adjacencies, non-adjacencies, proximities and depths between spatial elements (HOMAYOUNI, 2007). In turn, geometric restrictions are defined by surfaces, dimensions and spatial orientation, among other methods.

The 1970s were particularly productive regarding SP research (GRASON, 1971; MILLER, 1970; LIGGETT; MITCHELL, 1981). In that period, some SP researchers used graph theory, a mathematical theory that describes topological relations through vertices and edges. All this discussion happened before the popularization of CAD tools among architects and designers.

In 1975, Mitchell published a crucial essay on the foundations of computational design, titled "The theoretical foundation of computer-aided architectural design" (MITCHELL, 1975). In this study, the author conceptualized design as a specific type of problem solution process (ROCHA, 2004). In 1964, the "Architecture and the Computer" conference held in Boston involved architects, computer scientists, urbanists and economists to discuss new possibilities of computer use in their respective fields of research (ROCHA, 2004). Important names attended the conference, such as Marvin Minsky, a cognitive scientist, co-founder of MIT's artificial institute, and pioneer in this research field. Well-known architects were also involved, such as Christopher Alexander, pioneer in the studies of the Design Methods, and Walter Gropius, who, thirty years earlier, had been essential to the construction of the modern movement in architecture (ROCHA, 2004).

In the early 1990s, many studies in computational design connecting design methods with artificial intelligence were published. They sought to discuss generative mechanisms, which worked

as a mediator between the architect and the design, in a collaborative decision-making process, amplifying the potential of the calculation of architectural variables and suggesting new possibilities, unimaginable without the use of computers increasing, thus, the human capacity for information processing (TERZIDIS, 2006).

Later, Rivka Oxman defined the use of these mechanisms as generative models (OXMAN, 2006). In "Theory and design in the first digital age", she defines five models of the so-called Digital Design, a term created in the early 1990s: CAD Models, Digital Formations Models, Motion-based Formation Models, Generative Models, and Performance Models. She also defines sub classes for some of them and calls the integration between two or more models as Integrated Models. In all of them, the computer is an essential part of the process of conceiving the design and producing the building by digital manufacturing methods. Without being limited by Oxman's categories, the present study focuses on how Generative Design Models (and in particular its sub class Evolutionary Design Models) can be explored for space planning problems solutions, seeking a better functional and qualitative exploration of spaces.

OBJECTIVES

This study is part of a research whose hypothesis is the affirmation that the new architecture design support tools (CAAD), besides helping in the dissemination and approximation of architects to a series of computational design methodologies – which were previously restricted to academic circles –, could also help in the dissemination of SP methods, both in academic and professional circles. Moreover, this whole process could be enhanced by the creation of specific space planning tools or algorithms.

This study consists in a literature review with the purpose of identifying processes, experiments and designs that have used evolutionary algorithms as a method to solve SP problems. This type of studies is found mainly in publications of events, because it is still a very speculative subject, with very few real world applications. A survey in online databases available between 1994 and 2014 was carried out, encompassing authors from the fields of computer sciences, such as John Holland, Melanie Mitchell, Michalewicz, and Fogel (HOLLAND, 1975; MITCHELL, 1998; MICHALEWICZ, 2013; FOGEL, 2006), and architecture, such as Peter Bentley, John Frazer, Paul Coates, and Kostas Terzidis (BENTLEY, 1999; FRAZER, 1995; COATES, 2010; TERZIDIS, 2006).

METHODOLOGY

The literature review presented in this study included 31 articles, including applications and revisions of SP problems with an evolutionary approach. The databases used for the selection of papers were CUMINCAD, IEEXplore, ACM Digital Library, Research Gate, ScienceDirect and CiteSeerX.

The method used for article selection was as follows:

1. Their identification on the online databases (CUMINCAD, IEEXplore, ACM Digital Library, Research Gate, ScienceDirect e CiteSeerX) using specific keywords: “facility layout problem,” “space planning” and “space layout planning.”
2. Combination of the expressions: “genetic algorithm,” “evolutionary” and “genetic programming” with the keywords of the previous step to refine the search.
3. Analysis of the bibliography of the resultant articles to identify new potential articles.
4. Some publications were discarded for being considered out of the architectonic scope.
5. Critical review of the selected articles.
6. Classification and comparison of each publication by: evolutionary method, space planning method, type of algorithmic representation used by the evolutionary method, and the type of space planning problem solved. In the proposed parameter, we selected only articles in English because of their widespread dissemination and international acknowledgment as scientific dissemination standard.

LITERATURE REVIEWS (1992-2014)

We identified three literature reviews connecting SP problems with evolutionary algorithms in the last 15 years. The first review (LIGGETT, 2000) is not specifically on evolutionary methods, but establishes a classification of SP problems, mentioning, for the first time, the evolutionary approach. Homayouni (2007) presents some of the main studies and methods for SP solution with evolutionary approach. Finally, the third literature review, conducted by Dutta and Sarthak (2011), was the most complete one, categorizing and comparing 16 articles related to the theme.

However, none of these reviews has used online databases to cover the publications from the very beginning of the researches in this field; thus, a study through a dynamic and up-to-date database is necessary.

SLICE TREE STRUCTURE (STS) WITH EVOLUTIONARY APPROACH

The first study to connect evolutionary algorithms with space planning (TAM, 1992) has identified the potential that this class of algorithms should have for the solution of this kind of problem. Tam’s research indicates two main problems found in the heuristic procedures used until then (TAM, 1992):

1. The search space is developed through a single point in the solution space.
2. Geometric restrictions are difficult to implement.

Both the Simulating Annealing (SA) method as other search methods do not assimilate the interactions performed in the solution space. From the problems found in other methods, Tam (1992) has identified that the Genetic Algorithm (GA) method uses a more effective procedure in SP problems solution; besides, he has developed a symbolic and hierarchical language for the representation of architectonic layouts designs.

Layouts were represented by a structure called Slice Tree Structure (STS). This method was developed by Otten (1982) and establishes layout sections through a top-down recursive process of slicing a rectangle.

Each structure node of the slicing tree system represents a different way of sectioning the rectangles by a letter. As the tree structure of the system follows a hierarchy in the representation of the layout, the internal exchange of nodes represents a sequence of different layouts.

Through the GA, every individual of Tam's layouts population was represented through a chromosome defined by a Polish expression. The objective function was directed to solve the flows of material between facilities by the Quadratic Assignment Problem (QAP) method. To validate the method, Tam has compared the results obtained in his research with other search methods, such as the SA method. Genetic algorithms after 150 generations and with 10 different pieces of incoming data in the initial population showed better results in both the best solutions produced and in the average of solutions produced for 12, 15, 20 and 30 facilities.

Tam's work, a pioneer regarding the theme, was developed in the same year in which Koza (1992) developed the concept of genetic programming, which would be essential for the method of varying the number of configurations of a layout in a same population. Although Tam's work has not explored the variation of chromosomes in a same population, it may be considered the beginning of the development of the STS technique in SP problems, which later would be used through a genetic programming algorithm.

Kado (1995) also explored the potential of the structure of the STS method with evolutionary algorithms. Kado compares previous works produced with the GA, Simulated Annealing, Hill Climbing e quasi-Newton methods. Methods were compared between different GA configurations and other heuristic search methods.

The work of Garces-Perez, Schoenefeld and Wainwright (1996) has explored the STS system with genetic programming and compared it with the previous works, obtaining some advances in the production of layouts with 20 and 30 facilities. Layouts were produced by a bottom-up slicing process that had already been described by Kado (1995).

In his Master's Degree dissertation, Doulgerakis (2007) has developed, through a series of experiments, an algorithm of genetic programming that solved SP problems by the STS method. The system was implanted in Processing, which consists in an adaptation of Java language made by MIT's researches, being very popular among artists and designers who use programming in their works.

Doulgerakis' objective function was linked to preferences of location, connectivity between spaces and quantity of activity per spaces. The optimization was performed through a multiple criteria function developed as follows: optimization by weighted sum and ranked method.

Flack and Ross (2011) have also explored in their Master's Degree dissertation the use of genetic programming and the STS system, comparing distinct methods of selection of individuals.

ONE-TO-ONE ASSIGNMENT WITH EVOLUTIONARY APPROACH

The one-to-one assignment method is the allocation of a set of discrete activities to a set of discrete locations (LIGGETT, 2000). There are two main methods for this approach: the equal areas and unequal areas. In the equal areas system, a plan is subdivided in equal parts so that each part represents a site, whereas in the unequal areas method a plan is subdivided into small units, and the site is created from the sum of the units, according to the requested areas. Jo and Gero (1995) have developed a grammar of generation of forms in which formal composition rules were introduced into the individuals' genotype. Jo and Gero (1995) defined by the chromosomes composition system as:

$gi = \{locus, allele\}$
$Gi = \sum gi$
$P = m(G)$
$p(t) = \{G1, G2, G3 ..., Gn\}$

Where:

gi	a gene.
Gi	a genotype string.
m	mapping or interpretation operator.
P	a phenotype.
p(t)	population of the t-th generation.

The grammar operated with the Left-Hand Side (LHS) – Right-Hand Side (RHS) system, where LHS represented the design element to be transformed and RHS represented the element after a transformation operation (JO; GERO, 1995): LHS then RSH or LHS –> RSH

$\{Sr = Ex, (En, \alpha)\}$
$\{\square, (\blacktriangle, \rightarrow)\}$

Where:

α is a transformation action.

En a new design element.

Ex the existent design element.

Sr operation result.

The grammar also operated with a system of markers in which, for instance: in case of the existence of an element (Ex) with the marker (•), transform it, introducing the element (En) with the action α,

Where:

* marker.

The system was constructed with procedures composed by connection and topological transformations actions, which were represented through a 00,01,10,11 binary systems, that is, there were four rules of connections and four rules of topological transformations (Jo; Gero, 1995):

(Sr{m,(Ln,ac,at)})

(Sg{Ln,(Ln,ac,at})

Where:

m a marker.

Ln a label of a new space element,

ac connectional transformation action,

at topological transformation action

Where:

r1 separation relationship,

r2 door or accessibility relationship,

r3 window or transparency relationship,

r4 wall or isolation relationship.

The rooms were also represented by a binary system, as follows: room (00), dining room (01), kitchen (10) and bedroom (11); thus, the complete genotype could be represented as {...,(00, 10, 10)}, (01, 10, 10)}, (10, 01, 01)}, (11, 11, 00)}...}, or 001010011010100101111100. The general scheme of codification of the system and its decoding in a solution was illustrated through a flowchart developed by Jo and Gero (1995):

From the system developed to represent the individuals of a population, Jo and Gero have developed a program called Evolutionary Design using Genetic Evolution (EDGE), created on a UNIX platform using C language.

The evolutionary algorithm had the following steps: an initial population was randomly generated and evaluated according to its aptitude; then, one or more individuals were selected and placed into a mating pool to go through genetic operations of recombination and mutation. The individuals transformed were reevaluated and the new population was composed of old and new individuals; this process happened through interactions over several generations, up to the population converged or a certain number of generations was reached. The EDGE software was applied to a SP planning problem developed by Liggett and Mitchell (1981). The system was based on a heuristic method of programming (improvement method) with geometric and topological restrictions.

The problem consisted in a four-store service building, composed of 21 offices, five of which were previously allocated. Liggett's problem involved the optimization of the transportation cost between pairs of sites, as well as the travel time from going to one site to another. The evaluation method used was the typical equation of QAP:

$$(\sum aij + \sum \sum qi1i2cj1j2)$$

Where:

aij	Fixed cost of assigning element i to location j
cj1j2	distance measured from location j1 to location j2
i	spatial unit to be located
j	possible location
qi1i2	interactions between spatial i1 units and spatial i2 units

The individuals genotype was calculated by multiplying the number of genes, the number of the gene's components and the number of bits in a byte. In Liggett's problem, the length of the chromosome that composed the solution was 95 bits, and 19 were design's genes. Each gene had 1 component and each component had 5 bits. Then, each gene was separated from the genotype and decoded, to comply with the design rules that mapped the solution, producing a phenotype.

After 500 generations, the behavior produced by the solutions of the EDGE system of Jo and Gero (1995) showed an improvement of 8.2% over the original solution produced by Liggett and Mitchell (1981).

Jagielski and Gero (1997) have also explored the Liggett and Mitchell (1981) problem through generic programming, but this approach has adopted a different way of representation of the individuals' chromosomes, through a chain of characters, in which each character represented a spatial unit to be allocated to a pre-defined matrix.

The objective function was based on the QAP model and aimed to optimize the transportation and location costs from one site to another, defined by the following equation:

$$Cost\ (A) = fip(i) + \sum \sum qij\ cip(i)p(j)$$

Results have proved that the use of genetic programming further reduced the cost regarding the original problem of Liggett e Mitchell (1981), in which the lowest cost obtained was 2405.0, besides reducing the cost regarding the experiment performed by Jagielski and Gero (1997), in which the lowest cost obtained was 2254.5.

Li and Love (1998) have created, in Visual Basic Language, a software based on a GA for the solution of One-to-One Assignment problems, called GenePlan. The individual's chromosomes were represented by whole numbers, and the evaluation method used was the QAP.

Kochhar, Foster and Heragu (1998) have developed a GA algorithm called HOPE, in which the search model for solution was also based on QAP method. Tavakkoli-Moghaddain and Shayan (1998) have used the same methods (GA+QAP) for the solution One-to-One Assignment problems.

Garza and Maher have used the GA-QAP model for solution of One-to-One Assignment problems in an unusual way. They have created the algorithm by a case-based reasoning model (CBR), a method that uses a database of pre-defined solutions. This CBR algorithm went through an evolutionary process by a sub routine, developed through a GA.

The algorithm's emphasis was in creating new solutions, based on knowledge from previous solutions, because the restrictions of the objective function were intended to optimize subject questions, linked to the Chinese Feng-shui culture.

Rodrigues, Gaspar and Gomes (2013a) have developed an algorithm of evolutionary strategies combined with the of Stochastic Hill Climbing (SHC) method. The algorithm was called Evolutionary Program for the Space Allocation Problem (ESAP), and its first step was to generate a random population through the evolutionary strategy method; then, the individuals were evaluated through the SHC process and ranked according to the objective function, which evaluated the following criteria: connectivity and adjacency, spatial overlap, openings overlap, openings orientation, floor dimensions, compactness and overflow. The multi-criteria were evaluated through a sum of weights in which each objective could be evaluated according to its importance (weighted sum). The next step of the algorithm was to analyze the elite group of individuals from the last 5 searches, and in case of being greater than the negative of the average of the evaluations based on the last sum of weights obtained, the second stage would finish and the algorithm would return to the first ES's step; otherwise, the SHC's algorithm kept on applying a series of operators for each individual. When the condition of SHC's termination was met, the second stage would finish and the first stage was resumed. The EE's mutation operators then generated a series of geometric transformations in the individuals, which underwent evaluation again and then were ranked. Those with below-average aptitude values were selected for the next generation, while the remainder was discarded and the

reposition of the population was redone, through new randomly generated individuals. When the condition of EE's termination was met, the best individuals were shown.

Rodrigues, Gaspar and Gomes (2013b) have performed a series of experiments in one- or multiple-story buildings. The algorithm was effective when allocating more than 132 elements, among spaces, doors, windows, elevators and stairs. The ESAP was a significant advance in SP methods with evolutionary approach, for the quantity of elements allocated, the multi-criteria optimization that evaluated a series of queries and the quality of results obtained.

INTERACTIVE APPROACH OF THE OBJECTIVE FUNCTION

Based on formal grammar, Rosenman and Gero (1999) have explored layout creation through simple rules and an evolutionary process with Genetic Programming implemented in C++. The individuals' chromosome was defined by orientation vectors:

North, South, East and West. The polygon was then created from the sum of the vectors obtained by the operation.

The process of selection of individuals happened interactively with the users, and the solutions were evaluated by generations and hierarchical levels: spaces, zones, and buildings.

Elezkurtaj and Franck (2000) have developed an algorithm that combined evolutionary strategies with genetic algorithms. This algorithm's objective function was specified to solve issues of spatial proportions and their relations with neighbors, through the QAP method, combined with the graph theory; however, it was the final user that determined and selected the options that best fit his/her needs. Thus, the objective function worked in a hybrid way between user interactions and topological and geometric restrictions given by the algorithm.

Harmanani, Zouein and Hajar (2004) have developed a genetic algorithm through the SP solution method called blocking, in which the polygons represent fixed-dimension spaces, that should be combined with other spaces in a certain area (Liggett, 2000). The evaluation method of the objective function was QAP. The algorithm operated through a parallel computing system, in which populations evolved through parallel processing.

The program was developed in C++ in a cluster of parallel machines on Linux operating system. The results obtained were compared with the experiments that have used the sequential genetic algorithm and other experiments that have used the parallel algorithm.

Banerjee, Quiroz and Louis (2008) have proposed a genetic algorithm for the solution of SP problems in which besides having an interactive objective function, this interaction was performed by several users in a collaborative way.

STS and genetic programming was the method used for layout construction – although the authors have identified the algorithm as genetic. The selection of the individuals was made through a peer-to-peer model.

The collaborative process was compared with the interactive method, in which there was no collaboration, and the authors evaluated that there was an improvement in the solutions in the five queries that have evaluated the practical aspect of the layouts and their originality.

Fernando (2014) has developed an interactive genetic algorithm for the initial stages of the conception of the architectonic layout. The user drew free forms, by controlling points, and the computer identified these drawings through the polygonal closing in a grid. The objective function was related to the adjacency issues and dimensions of grid cells. The hand-drawn free forms evolved according to the criteria established by the GA.

GENETIC ENGINEERING IN THE IMPROVEMENT OF SOLUTIONS

Genetic Engineering (GE) applied to evolutionary algorithms was a method developed by Gero and Kazakov (1997a), which extended the classical method of genetic algorithms through a model based on genetic engineering applied to natural organisms. The GE system was developed to identify genes, sequences or structures of genes associated to the performance when facing an objective function.

The GE method identified characteristics of the problem and automatically reproduced chromosomes called “evolved genes,” which were patterns of solutions introduced into the randomly generated population. This process happened prior to the recombination and mutation stages. Through this method, the population convergence occurred faster and more efficiently, because it identified good recurrent solutions, preserving and reinserting them into randomly generated population.

Gero and Kazakov (1997a) have tested the EG method in a SP problem composed of 19 spaces, with a 30-m2 activity area on average. The results have demonstrated that, out of the 19 spaces, good allocation solutions tended to repeat, and the spaces from 0 to 12 formed an evolved gene, which consisted of a cluster of spaces without empty areas.

Gero and Kazakov (1997b), in another research, have performed an experiment with the Liggett e Mitchell (1981) problem using the EG method. They have compared the results obtained with the experiment performed previously by Jo and Gero (1995), and the results showed that the use of evolved genes has collaborated with the solution convergence more efficiently.

Homayouni (2007), in his Master’s Degree dissertation, has explored the concepts of genetic engineering applied to GA, developed by Gero and Kazakov (1997a), and implemented an algorithm in MATLAB using a GA toolkit, expanding it with GE methods. Houmayouni’s algorithm worked with input data from questions made to the user. The first stage of questions was as follows:

1. How many rooms does your building have?
2. Do you want to minimize the area of the building as much as possible?
3. Do you want to minimize the perimeter of the building?
4. Which is the best length/width ratio for the building?

After selecting the data, the user confirmed and answered other questions related to the first room of the building:

1. Which is the name of this room?
2. Which is the best area for the room?
3. Do you prefer compact forms?
4. Which is the best proportion for the room?

After the user submits the data, the room generation occurred, the process initiated the interactions of algorithms and the whole process was presented through an interface, which showed the record of the best solutions and the individuals of the current population.

After defining all choices at space level, the user determined the relations of adjacency of rooms through an interface that presented an adjacency matrix.

After the definition of the adjacency relations, the algorithm operated on the scale of the building, evolving the best layouts solutions.

GRAPH THEORY AND THE EVOLUTIONARY METHOD

Wong and Chan (2009) have developed an evolutionary algorithm called EvoArch, which aimed to find, through graphs, the best topological situations between spaces. The algorithm consisted of the following steps:

1. Initialization of a random population of graphs and coding of these graphs through an adjacencies matrix.
2. Evaluation of the graphs.
3. Selection of two graphs to be reproduced through the roulette method.
4. Application of the operators of recombination and mutation to the chosen graphs.
5. Replacement of the worst individuals of the given population for new descendants.
6. Repetition of step 2 to 5 up to the conclusion function (which establishes the end of the algorithm search for solutions) was found.

The graphs recombination process occurred in the adjacencies matrix, through a cut point.

The objective function was based on an evaluation process called Adjacency Preference Scale (APS), in which one ranked, through a matrix, the relations of preference between spaces; then, the objective was to organize these relations to maximize the number obtained from the sum of this ranking.

Thakur, Kumari and Das (2010) have created a genetic algorithm for the solution of SP problems through graphs and adjacencies matrices. The 4×4 matrix had a limit of 16 spaces and the

objective function solved topological and geometric restrictions, in addition to a subroutine that analyzed the best escape routes through a Dijkstra's algorithm.

HALF PLAN AND K-D TREES WITH EVOLUTIONARY APPROACH

Damski and Gero (1997) have developed a system for solution of SP problems with evolutionary approach through a method called half plan. This system subdivided a plan into sub plans by identifications of borders, generating spaces through Boolean Logic Operators.

The stages of creation of the evolutionary system based on half-planes were defined by Damski and Gero (1997):

A set H of half-planes is generated;

A population of arrangements of half-planes is generated, where every member Hi is a subset of H;

For each Hi, generate a set of layouts L;

Each layout in L is evaluated against the set of constrains;

The layouts are evolved according to the results of the fitness function;

Each arrangement of Hi is evolved according to the evaluation of the population of layouts in that topology;

Arrangements are evolved in H.

RESULTS

In this section, we will compare the data from the selected papers through charts. As shown in Figure 27, the period from 1995 to 2000 was the most productive regarding scientific papers publication. At least two papers per year were published regarding the theme.

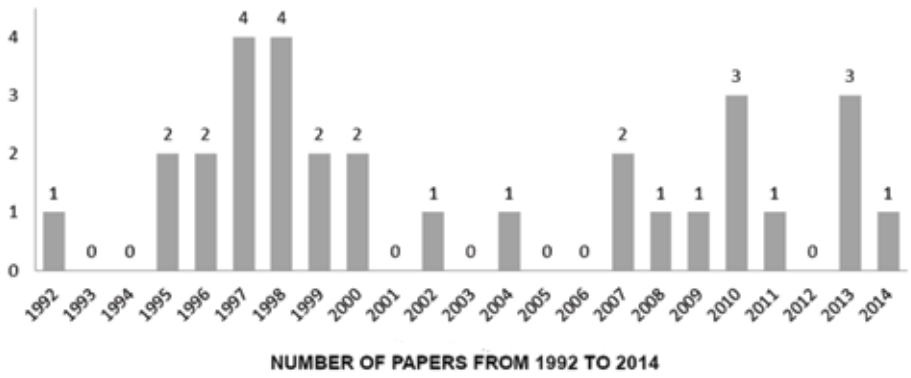

Figure 27 - Number of papers published per year.
Source: Authors.

Several evolutionary methods were identified in the papers analyzed, showing the diversity of problems related to the theme. We identified six evolutionary methods and two methods complementary to the evolutionary ones: (1) genetic algorithms (GA), (2) genetic programming (GP), (3) evolutionary strategies, (4) genetic engineering (GE), (5) interactive evolutionary algorithm (IEA), and (6) parallel genetic algorithm (PGA). The two complementary methods were: (1) Stochastic Hill Climbing (SHC) and (2) case-based reasoning (CBR). Figure 28 shows the number of articles published according to the evolutionary method.

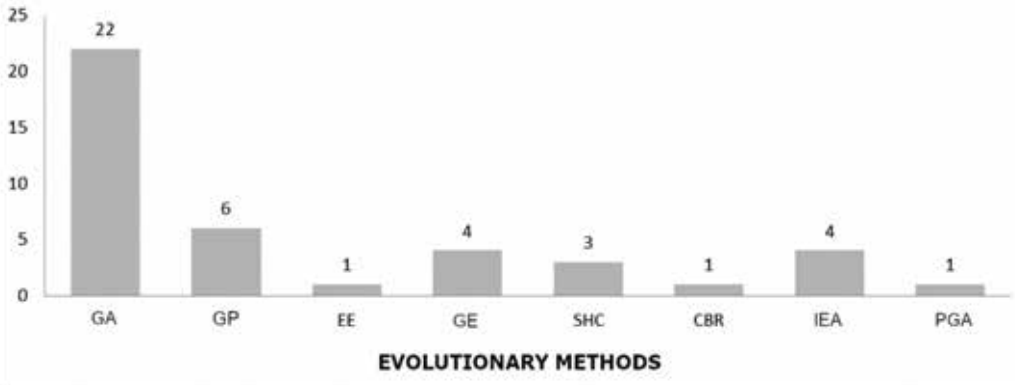

Figure 28 - Evolutionary and complementary methods identified in the papers selected.
Source: Authors.

Among the methods of generation of the layout form, blocking and one-to-one assignment were the most used, followed by the slice tree structure method (Figure 29).

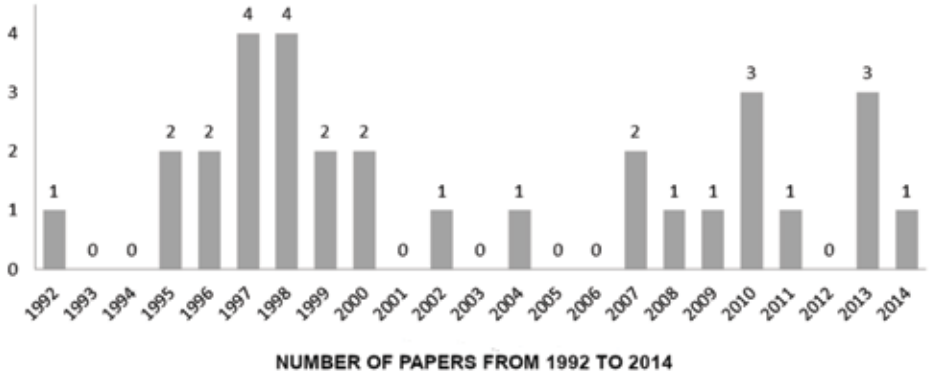

Figure 29 - Methods of layout creation identified in the papers selected.
Source: Authors.

Among the methods used to represent the individuals' chromosomes, whole numbers were the most used (Figure 30).

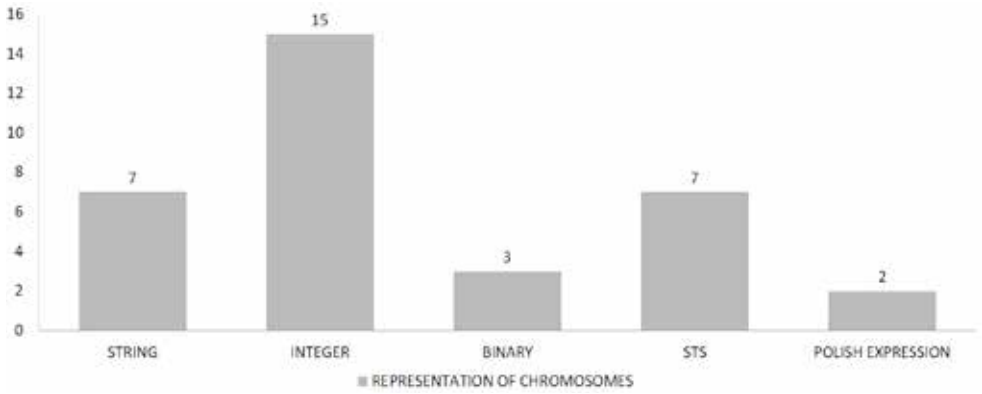

Figure 30 - Methods of representation of the chromosomes identified in the papers selected.
Source: Authors.

The most used evaluation method of evolutionary algorithms was QAP. It is possible to notice that the equation formulated by the Q AP method simplifies the translation of the evolutionary algorithm into the objective function.

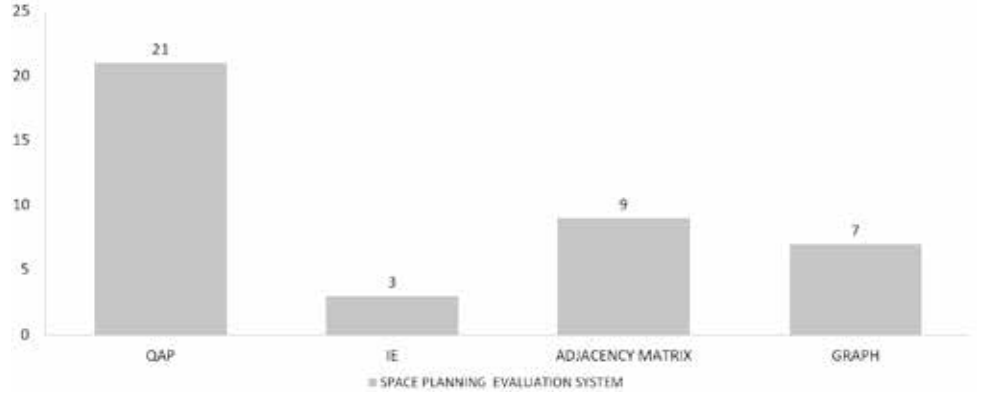

Figure 31 - Evaluation methods used in the papers selected.
Source: Authors.

Gero and Kazakov (1997a) have argued that the computational time is extremely high for large-scale designs concerning SP problems. Advances in computational power over the last years apparently has not significantly affected the development of this kind of problem. The largest number of allocated spaces found in our survey was 132 (RODRIGUES; GASPAR; GOMES, 2013a. RODRIGUES; GASPAR; GOMES, 2013b). Figure 32 shows the number of spaces computed in the papers analyzed.

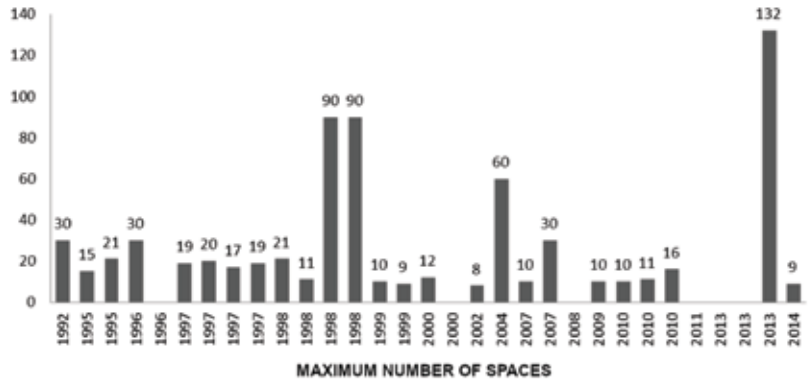

Figure 32 - Maximum number of spaces computed in the papers analyzed, per year.
Source: Authors.

Comparing the maximum number of elements per population and the maximum number of generations (algorithm interactions) in this period, we observed that 7,000 extra interactions per maximum population were needed in 1998 in comparison to 2013, and the number of elements computed in the 1998 was 2850 times smaller than in 2013.

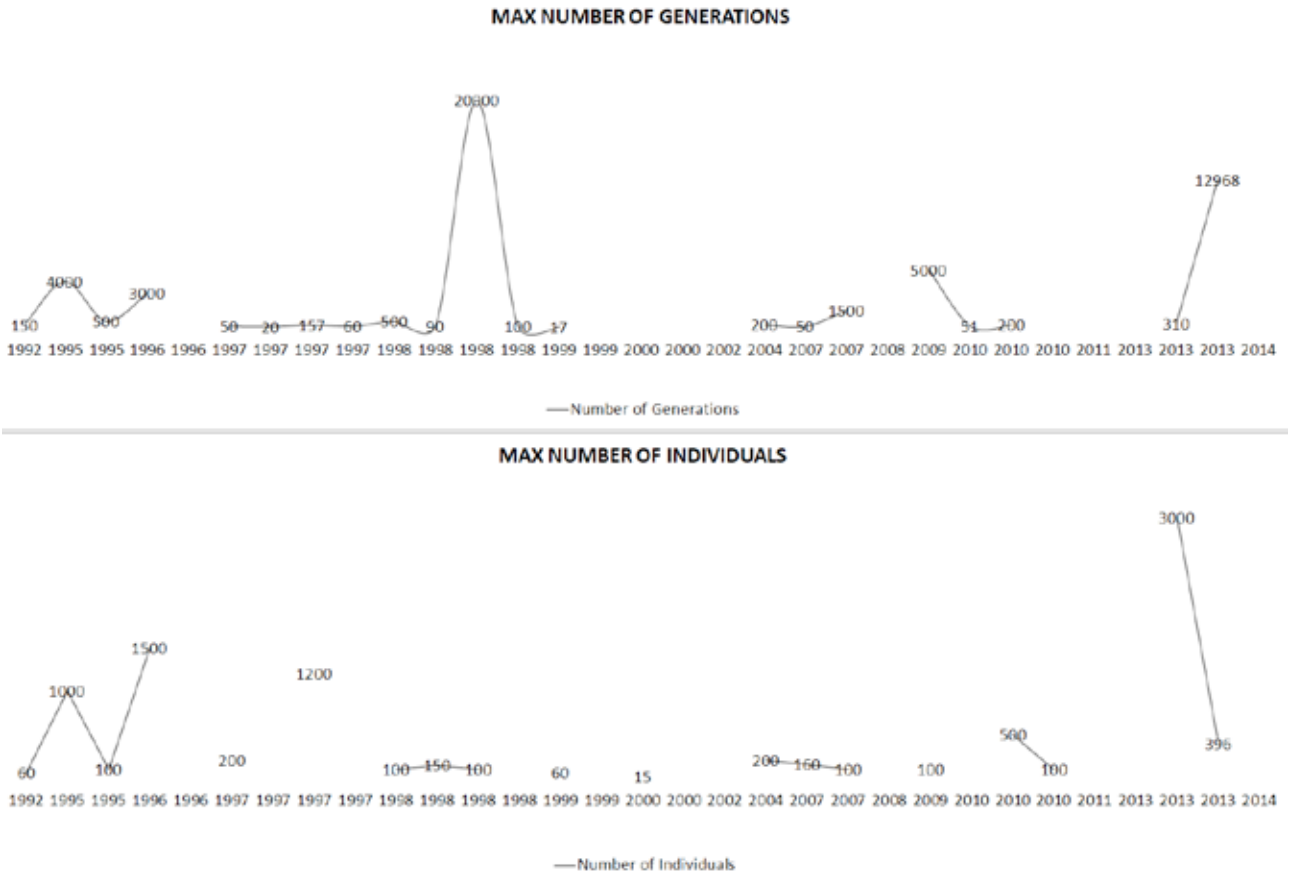

Figure 33 - Maximum number of generations in the papers analyzed per year and maximum number of population per year, respectively.
Source: Authors.

The studies have shown the preference for the use of genetic algorithms or for hybrid methods for the solution of SP problems throughout the period studied. Figure 34 indicates the main types evolutionary methods used during the period.

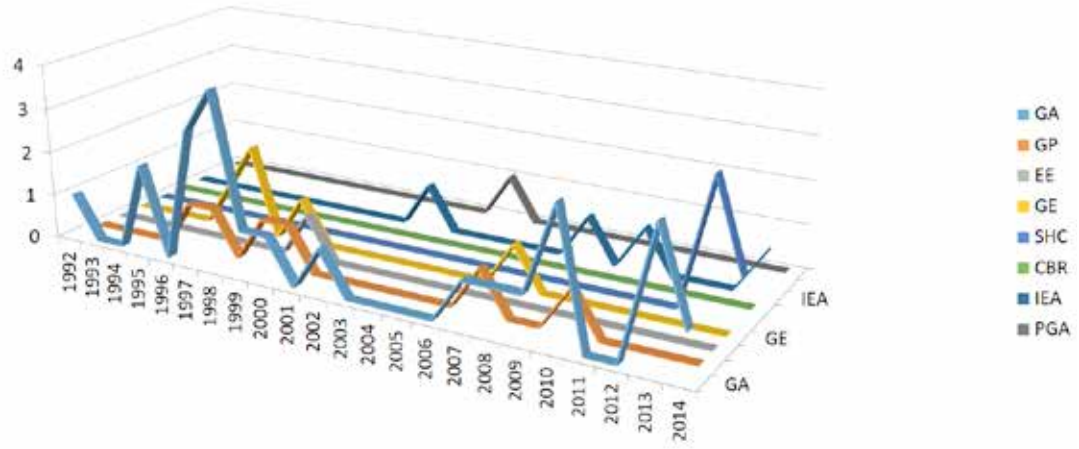

Figure 34 - Main types evolutionary methods used during the period.
Source: Authors.

DEMANDS FOR FUTURE STUDIES

After checking the prospects and demands for future studies reported in the articles analyzed, we have identified the following demands: (1) the refinement of recombination methods (KOCHHAR; FOSTER; HERAGU, 1998), (2) more applications that use an interactive objective function (HOMAYOUNI, 2007), (3) more genetic engineering methods that improve the recombination operators, (4) more applications related to layout three-dimensional problems through a single objective function (HOMAYOUNI, 2007; DOULGERAKIS, 2007; FLACK; ROSS, 2011), and (5) more applications related to non-orthogonal planes (KNECHT; KOENIG, 2010). All these demands indicate the need for future studies and have not been fully explored to date.

DISCUSSION

SP methods with an evolutionary approach have been studied for more than 20 years, but still comprise a field with many non-explored possibilities of research. Advances in computational power over the last years have apparently not significantly affected the development of the field. Thus, it is necessary to develop new algorithms that optimize computers processing, increasing the number of spaces computed.

SP methods have been explored since the early development of computational design. Nonetheless, new methods should be created and old methods must be improved, so that this research field keeps on developing. Although new computational environments have contributed

to the popularization of the computational design field (MARTINO, 2015), few algorithms aimed at solving SP problems have been developed.

The main issue and the justification of this research are related to the potential of evolutionary algorithms studies to optimize layout problems. The literature review in this field of study shows that there has been great interest in this subject, until a computational limit was reached regarding method application. Besides, these applications always required great knowledge of programming and of artificial intelligence techniques, which was usually beyond architects' skills.

Currently, we live in a postindustrial context, with a paradigm shift from a standardized mass production logic to one of mass customization production. The evolutionary approach, on the one hand, allows generating combinatorial variations with similar characteristics, and, on the other, to select those that best meet the requirements needed.

In the 1950s, psychologist Joy Paul Guilford made the distinction between divergent and convergent thinking (GUILFORD, 1967), the divergent thinking being the ability to find the maximum number of possible answers to a specific problem, and the convergent thinking the ability to find the best answer to a certain problem. The evolutionary approach directed to design is developed precisely within this theoretical framework, in a cyclic process between divergence and convergence, because at the same time that it generates a family of possible solutions to each generation, it searches for the best answer among the populations through the objective function (fitness function).

The application of evolutionary systems in architecture may be one way of meeting this new paradigm of the current society's desire for exclusivity and production, because through evolutionary algorithms it is possible to produce, by a generative process, a set of architectural compositions that meet singular desires and needs, in addition to the new environmental agenda in which performance in architecture becomes an indispensable item towards the sustainability paradigm.

In their daily routine, architecture and urban design offices often encounter problems related to how functionally and qualitatively arrange spaces, whether in the composition of internal layouts or in the arrangement of buildings in the urban space.

Nowadays, with the great availability of applications that simplify the creation of algorithms within CAD environments– not to mention plugins that provide evolutionary algorithms resources in this same type of software –, the use of SP techniques may effectively become more useful for architects in their daily work, as long as they know this technique and how to implement it with the available resources.

The continuation of this research shall seek to verify, through the development of applications and workshops, if these new computational graphic tools could help to popularize SP methods, and if SP methods could be effectively used in the daily life of architectural offices, as complementary methods to the process of arrangement and spatial composition.

CHAPTER 03

GENERATIVE DESIGN IN TEXTUAL AND VISUAL PROGRAMMING LANGUAGES

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GENERATIVE DESIGN IN TEXTUAL AND VISUAL PROGRAMMING LANGUAGES

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ABSTRACT

The use of generative design is a current challenge to designers, architects, and urbanists, as most graduation curriculums for these professionals do not include algorithmic thinking. However, the use of algorithms is frequently the best option for the conception of complex parametric projects as it is necessary to assemble many different shapes to achieve one total formal composition. This chapter aims to present a case of study of programming for generative design by developing a practical application using textual and visual programming languages (using Python and Grasshopper). Programs in both paradigms, purposely generating the same result, are detailed and discussed. Readers will learn how the same logic can be applied to different programming languages, developing the ability to use different techniques according to their necessities. We also expect them to learn that an adequate use of computational thinking (CT) is as important as the use of programming languages.

INTRODUCTION

This paper discusses the parametric modeling technique through an experimental methodology based on acquisitions and transfer of knowledge.

Parametric modeling, also known as relational modeling or variational design, is a technique based on the use of parametric algorithms to design virtual models (FIORITO, 2016. MONEDERO, 2000). By changing the values of the algorithm's parameters it is possible to generate numerous different designs (STAVRIC; MARINA, 2011). This is useful when the model needs to be changed frequently during the design process (MYUNG; HAN, 2001), e.g., for the creation of free forms intended to be fabricated with the help of digital manufacturing machines (CELANI; VAZ, 2012).

Algorithmic design is frequently the best option for the conception of complex parametric projects. Despite its recognized importance, algorithmic design is currently a challenge to designers, architects, and urbanists, as it is a subject whose teaching is not yet widespread in the curricula of those professionals. Moreover, in order to use algorithmic design, it is necessary to be able to implement algorithms in a given programming language.

Unfortunately, programming is difficult for the professional that was not trained to deal with this scientific area. Research points to the generalized use of computational thinking (CT) (LEE *et al.*, 2011; PAPERT, 1980; WING, 2008) and this paper applies it to the task of scripting the same parametric example in two different programming languages: Textual (TPL) and visual (VPL).

In this paper we describe an experiment based on the implementation of two practical examples of parametric modeling. The first one deals with the acquisition of knowledge, and the second deals with the transfer of knowledge, where information acquired in a one situation is applied to a different one. Acquisition of knowledge happens when new concepts and methods are added and new skills are assimilated and related with other constructs (DIBELLA, A. J.; NEVIS, 1999). Knowledge is the adequacy of the subject to the object (GAVIRA, 2003). Transfer of knowledge is the final point of learning process, and is the central objective of education (FOGARTY, 1995. PRAWAT, 1989).

"There is also the implicit assumption that intellectual skills gained during a course of study can be transferred to other situations which may occur at a place far removed and a time somewhat distant from the original learning situation". (LAUDER; REYNOLDS; ANGUS, 1999, p. 480).

It is expected that using the both languages in these experiments, we can compare the languages and research the hypothesis that it is possible to design the same model, using the same logic, in these two paradigms.

For the TPL experiment, Python + Khepri was chosen. Python is a programming language designed to be a high-level language that facilitates the learning process, especially for beginners (ROSSUM, 1999. VILLARES; MOREIRA, 2017). Python is the most used freeware language nowadays, according to the IEEE Spectrum ranking (DIAKOPOULO, NICK; CASS, 2017). Its syntax is simple, intuitive and clean, and most Python implementations come with a read-eval-print-loop (REPL) that allows the user to interactively experiment with the language, making the language user-friendly and easy to learn. Finally, many CAD and 3D modeling software packages embed Python as a scripting language (VILLARES; MOREIRA, 2017). Khepri is a pedagogical architectural modeling layer that abstracts different Computer-Aided Design tools, such as AutoCAD and Rhino 3D and, thus, facilitates the use of Python for design purposes.

For the VPL experiment, Grasshopper + Anemone was chosen. Grasshopper is an algorithmic modeling tool based on a visual programming language. This allows users that do not have programming knowledge to develop programs by graphically combining different components into a workflow. It works as a Rhinoceros plugin and is wildly adopted in offices that work with parametric design (BUENO, 2016). The parametric capabilities of Grasshopper enable the generation and

modification of the design simply by changing parameters, avoiding the need to re-write substantial amounts of code (OXMAN, 2017). Anemone (ZWIERZYCKI, n.d.) is a freeware Grasshopper plug-in which enables the user to create loops with two components inside the workflow.

COMPUTATIONAL THINKING

The term Computational Thinking (CT) was first used by Seymour Papert, who was developing a pedagogical approach to teach children this particular way of thinking (PAPERT, 1980). CT is a form of analytical thinking that, in a general way, can be applied to solve any (solvable) problem. If computational thinking can be used by anyone in any situation, it must also be applicable to solve the same computational problem through different programming languages. The use of computational thinking is divided in tree key aspects: Abstraction, Automation, and Analysis (WING, 2008). See figure 35 below.

Abstraction is the process of generalizing from specific instances, removing unnecessary details, to help formulate the problem to be solved (LEE *et al*., 2011. WING, 2008). To this end, we need to recognize the patterns and parameters of the problem so that we can decompose it, breaking down the repetitive actions needed to solve the complex problem into some manageable smaller ones.

The automation of the abstraction entails revealing the step-by-step instructions on how to do something (WING, 2008). In this paper case, this entails instructing a computer by coding the needed algorithm that takes the input and produces the desired output.

Analysis is the moment to evaluate if the final result corresponds to the expectations regarding the generated data, models, and others (LEE *et al*., 2011. WING, 2008). If the results were negative it is also time to evaluate if the initial abstractions were correct, if important factors were left out, if there were situations not taken into account, etc. (LEE *et al.*, 2011).

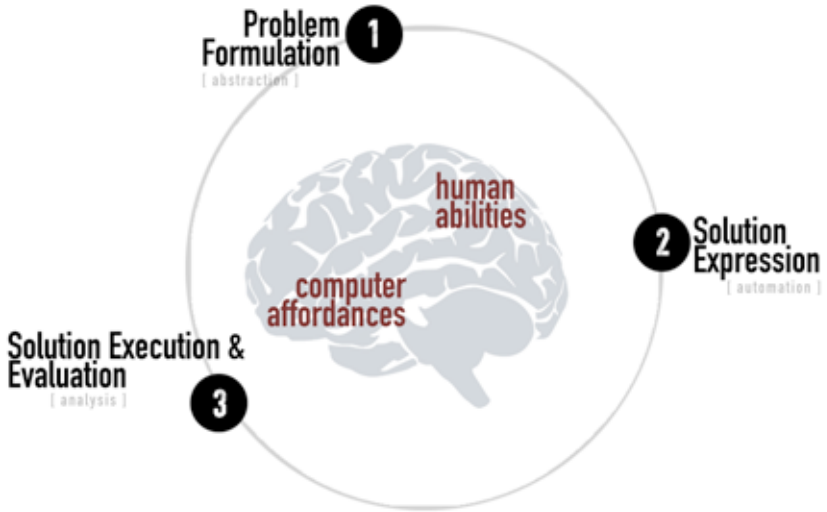


Figure 35 - Procedures of Computational Thinking.
Source: Authors.

These aspects will be explained through two practical examples, one for knowledge acquisition strategy, and another for knowledge transfer.

KNOWLEDGE ACQUISITION

During an inquiry made in 2017 in classes of programming for architects in Portugal, we discovered that the subject that the students considered harder to understand was “functions”, particularly, recursive functions (PONTES, THIAGO BESSA; MIRANDA, GUILHERMINA LOBATO; SANTOS, 2016). That is the main reason we decided to pick up a recursive example to do this experiment. The second reason, is that most problems can be solved by recursion. A third reason was that recursion is a concept that, with some creativity, can fit in all scales, including Design, Architecture, and Urbanism.

Figure 36 - Ring (jelwery design).
Souce:https://edmarshalljewelers.com/image/cache/catalog/R15498-1000x1000.JPG

Figure 37 - Step cake (cake design).
Souce:https://img.elo7.com.br/product/original/F2C02A/bolo-quadrado-clean-bolo-casamento.jpg

Figure 38 - Stairs inside Nordic pavilion at the 2016 Venice Biennale (architecture scale).

Souce: http://images.adsttc.com/media/images/5748/ed85/e58e/ceea/7900/0034/slideshow/copyright_laurian_ghinitoiu_nordic_(2_of_49).jpg?1464397186

Figure 39 - Retaining urban wall (Urbanism scale).

Souce: https://i.pinimg.com/736x/e0/2e/2c/e02e2c853cb07ecea2b94130a4c6eae7--retaining-walls-garden-ideas.jpg

ABSTRACTION

Abstracting the figures 36,37,38, and 40, it is possible to see a step pyramid shape in all of them. A few sketches were used to identify what is relevant and to remove the unnecessary parts. Using this first computational thinking process, we defined our main task: to design a parametric step pyramid shape model.

The next task is to design another sketch that represents the model. After that it is possible to decompose the problem, understand what are the repetitive parts and the parameters that we need to manage (Figure 40).

During the firsts sketches, we figured out that each pyramid step is a regular pyramidal frustum. Decomposing this problem, it was clear that the first thing we had to do to decompose the problem was to design one step of the pyramid, placing a smaller pyramid on top of this first step. Repeating this logic until achieve a pyramid of zero steps we can generate the entire pyramid.

To design the first step, we adopted the logic of designing one polygon for the bottom base, another for the top base and connect both, filling the holes. After that, we named with different letters all the variables that we could numerically change and tried to understand their relations. These variables will become the inputs of the program.

The identified variables for the first step were (Figure 41):

P = center point of the base

b = bottom base radius

t = top base radius

h = height of step

s = side numbers of polygons

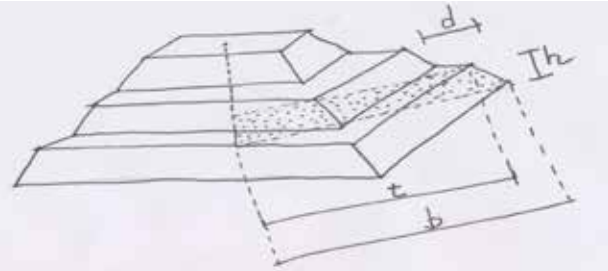


Figure 40 - Drawing of a regular pyramid frustum.

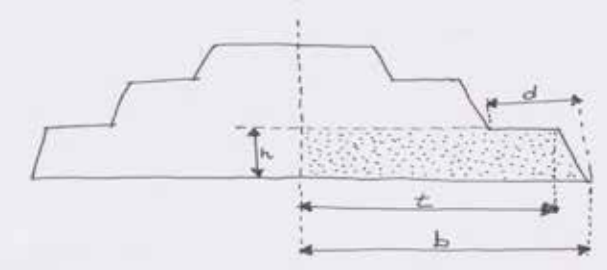


Figure 41 - Drawing of a regular pyramid frustum.

After coding the first pyramid step, it is necessary to place on top of it – with vertical height distance h - a smaller pyramid with one less step than before (n-1) and repeat this logic until turns up a pyramid with zero steps (n=0). This new first step of the smaller pyramid entails subtracting from the polygon radius (top and base) the difference (d) between the pyramid steps. In that way, we need two more parameters to generate the hole pyramid.

d = horizontal distances between steps

n = number of steps

AUTOMATION

The same logic developed in the abstraction phase was applied in a VPL and in a TPL to design a step pyramid in the Rhinoceros 3D environment. The VPL adopted is Grasshopper and the TPL adopted is Python that also runs in Rhinoceros 3D through the Python editor (Rhinoceros/

Tools/PythonScript). If the reader wants to repeat this experiment, it is necessary to download some software packages first. They are: Rhinoceros software, Grasshopper, Anemone, and the Khepri package (https://github.com/tbpontes/Kephri)

We start the TPL coding process by importing all Khepri functions, using the statement line "from khepri.rhino import *". Usually, we also begin by invoking the function "delete_all_shapes". This function erases whatever data was previously available in the CAD tool, so that we start modeling from scratch. It that is not what is intended, we just remove this line of script. See figure 42.

```
1  from khepri.rhino import *
2  delete_all_shapes()
```

Figure 42 - Zero point to TPL script.
Source: Authors.

DEFINING PARAMETERS/VARIABLES

Next, we define the step parameters in both languages. In the VPL, the parameters were set by a number slider, while in the TPL they correspond to the parameters of a new function "step" (Figures 43 and 44).

In Python, the variables were expressed by letters in first line of the function. Later, the user can associate any number to each parameter.

```
3
4  def step(s, p, b, h, t):
```

Figure 43 - Parameters of the step in TPL.
Source: Authors.

In Grasshopper, the variables are presented by predefined number slides which the user can change just by moving the slider bar.

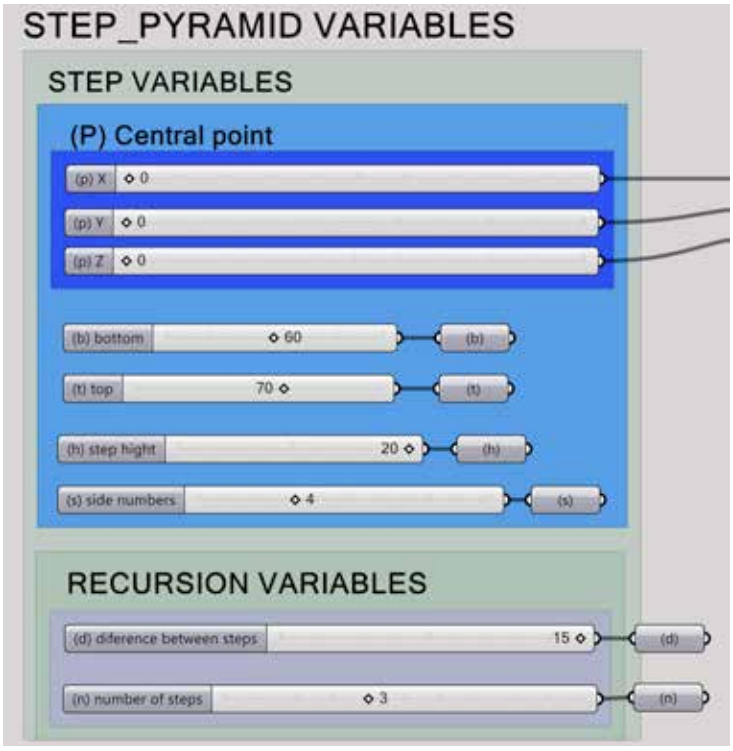


Figure 44 - Parameters of the step in VPL.
Source: Authors.

DESIGNING THE FIRST STEP

Second, the pyramid trunk was designed by two regular polygons in both languages (Figures 45 and 46). The bottom polygon is generated from the point p. To design the top polygon is necessaire move the initial point p for the height (h) in the Z-axis direction and use the top radius (t). The function/tool polygon/surface_regular_polygon also receives the number of sides.

In Grasshopper, the polygon radius (b and t) is the distance between the central point and the polygon vertices, in other words, is the radius of an imaginary circle that touches all the polygon vertices. In Khepri, the radius of polygon function can be the same of Grasshopper if the last function parameter is “True”, if it is “False” the polygon radius refers to an imaginary circle that touches all the midpoints of the polygon edges.

```
3
4  def step(s, p, b, h, t):
5      loft([
6          surface_regular_polygon(s, p, b, pi/4),
7          surface_regular_polygon(s, p+vz(h), t, pi/4)
8      ])
9
```

Figure 45 - Design of first step in TPL.
Source: Authors.

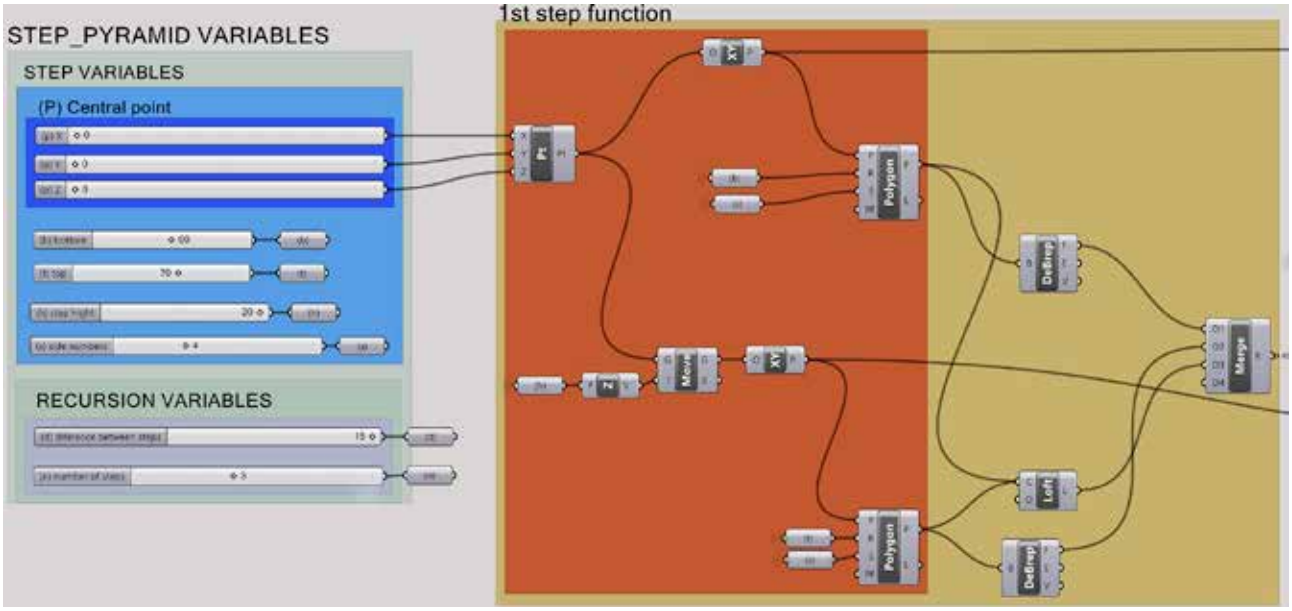


Figure 46 - Design of first step in VPL.
Source: Authors.

THE RECURSIVE FUNCTION

Third, as the next steps can be generated by a repetitive action, a recursive function was adopted. Recursion is a fundamental control structure where a function calls itself. (Martins, 2015)

Grasshopper data are set from the left to the right, consequently, is not possible create recursion in grasshopper by itself (TEDESCHI; WIRZ; ANDREANI, 2014). To insert recursion in Grasshopper, we have to download a Python Script component and insert a fragment of textual language in the workflow. However, given that it was not our intention to mix languages in this study, it was decided to substitute the recursion with a loop instruction, as long as they can be analogous and achieve same results in particular cases as these ones. The loop repeats the execution of a number of statements a given number of times (MARTINS, 2015).

To do loops in Grasshopper there are some free add-ons for Grasshopper that provide special components to create a loop, *e.g.*, Hoopsnake or Anemone. After experimenting some of them we concluded that Anemone is actually the easiest to understand and use.

Anemone presents two components that must be connected: loop start and loop ends (Figure 48). It works by replacing an input parameter of the “loop starts” with an output of the “loop ends” a certain number of times chosen by the user.

In figures 47 and 48 there is a recursive function in TPL and a loop in VPL designing the remaining steps of the pyramid. In figure 47 there is the definition of function “step-pyramid” and its variables: if the number of steps given is equal to zero, we do not do anything, otherwise, we create a step and call these functions the number of steps given, changing the variables:

“p” for “ p+ vz(h),
“b” for “b-d”,
“t” for “t-d”,
“n” for “n-1”

```
def step_pyramid(p, b, t, h, s, d, n):
    if n == 0:
        pass
    else:
        step(s, p, b, h, t)
        step_pyramid(p + vz(h), b - d, t - d, h, s, d, n - 1)

```

Figure 47 - Recursion in TPL.
Source: Authors.

The same relation between the variables happens in a VPL and are presented in the workflow of figure 48. These operations are inside of loop start and loop end of the Anemone components. After the loop ends, the generated polygons are lofted to generate the steps.

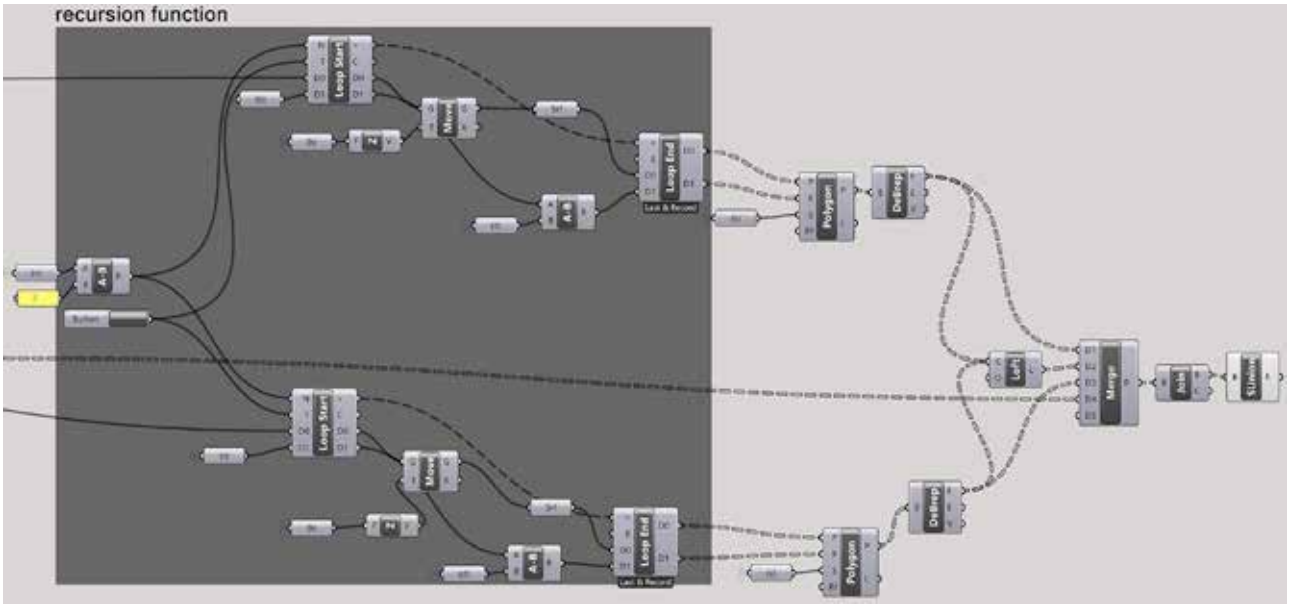


Figure 48 - Loop in VPL.
Source: Authors.

FINAL SCRIPTS

VPL FINAL SCRIPT

The grasshopper logic works as a sequence of commands that flows through the components boxes from left to right. To facilitate understanding, it is possible to make evident that a specific collection of components is working together to generate one specific final result, by creating colored groups and scribbling informational comments.

Reading this script (Figure 49) from the left, we see a large gray square with all the model variables (parameters). The next large yellow square, refers to the design of the first step. The orange one refers to the top and bottom polygons and outside this square, the components unite and loft the parts of this step.

The gray square presents the repetitive actions to generate the other steps.

Just after the last square, there are the components to unite and loft the hole step pyramid model.

Organizing the scrip with colors and texts it is easy to understand the intentions of each group of actions. In most cases, other users just need to change the variables/parameters and they are easy to find in that way, for example. However, as the script is becoming complex it is hard to read all the components intentions and their connections.

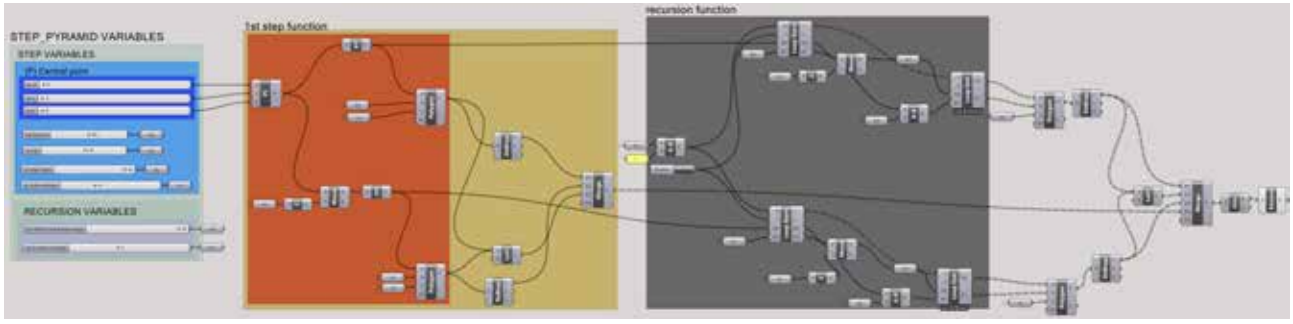


Figure 49 - VPL final script.
Source: Authors.

TEXTUAL FINAL SCRIPT

For a beginner in a Textual Programming Language, it is possible be hard to understand each script line, but with practice it becomes easier.

The last step to design the pyramid is call the function step_pyramid(p, b, t, h, s, d, n), but this time inserting absolute values in parameters.

For example:

P = centre point of the base = is a Cartesian coordinate, defined in origin = xyz(0, 0, 0)
b = bottom base radius = absolute value = 120
t = top base radius = absolute value = 115
h = height of step = absolute value = 20
d = horizontal distances between steps = absolute value = 15
n = number of steps = absolute value = 6
s = side numbers of polygons = absolute value = 4

```
17  step_pyramid(xyz(0,0,0), 120, 115, 20, 4, 15, 6)
18
```

Figure 50 - Calling the function in TPL.
Source: Authors.

```
1  from khepri.rhino import *
2  delete_all_shapes()
3
4  def step(s, p, b, h, t):
5      loft([
6          surface_regular_polygon(s, p, b, pi/4),
7          surface_regular_polygon(s, p+vz(h), t, pi/4)
8      ])
9
10 def step_pyramid(p, b, t, h, s, d, n):
11     if n == 0:
12         pass
13     else:
14         step(s, p, b, h, t)
15         step_pyramid(p + vz(h), b - d, t - d, h, s, d, n - 1)
16
17 step_pyramid(xyz(0,0,0), 120, 115, 20, 4, 15, 6)
```

Figure 51 - Final script in TPL.
Source: Authors.

ANALYSIS

By the end of this experiment it was possible to achieve in both languages the same model shape using the same variables numbers (Figure 52).

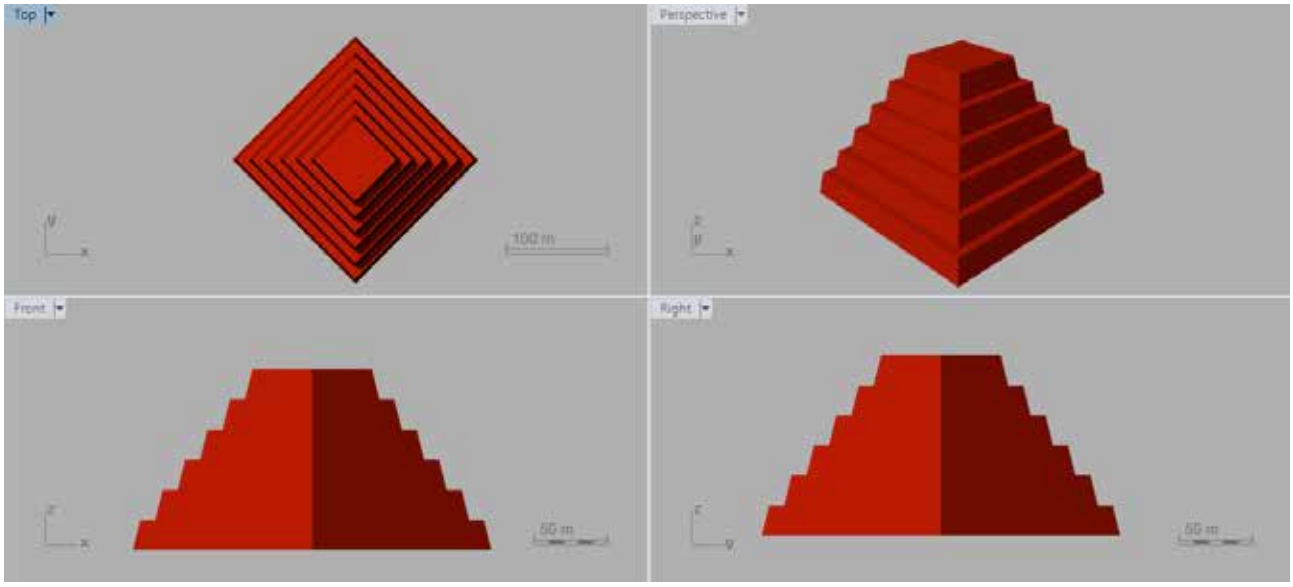
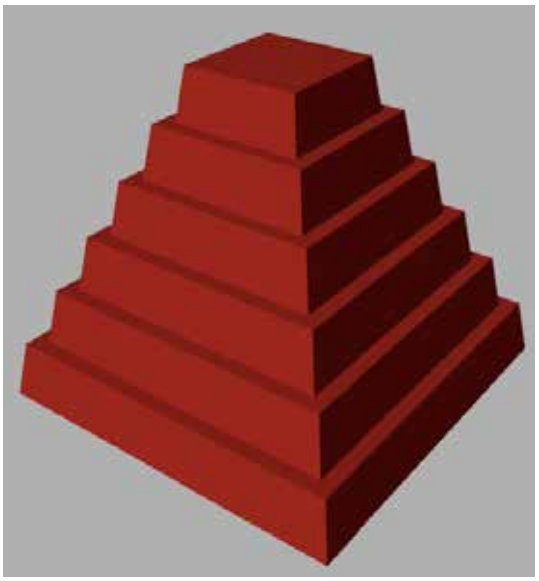
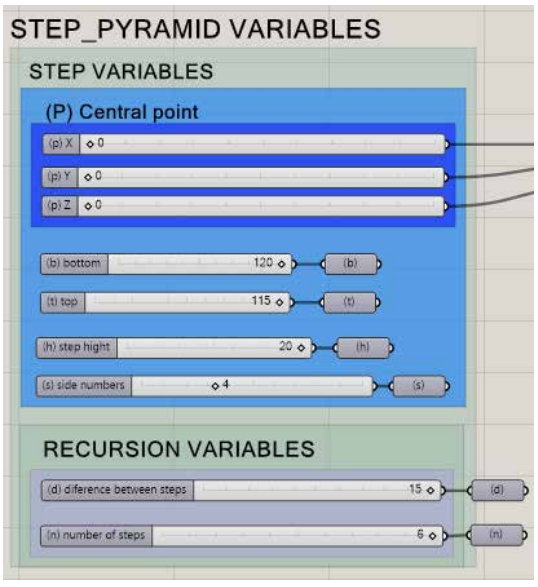


Figure 52 - Final model shape.
Source: Authors.

After the script was done, it was tested applications of different numbers to generate various pyramids (Fig. 53). For TPL was a question of change the call of function and run, for VPL just change the sliders and “bake” the final component.






```
17  step_pyramid(xyz(0,0,0), 120, 115, 20, 4, 15, 6)
18
```

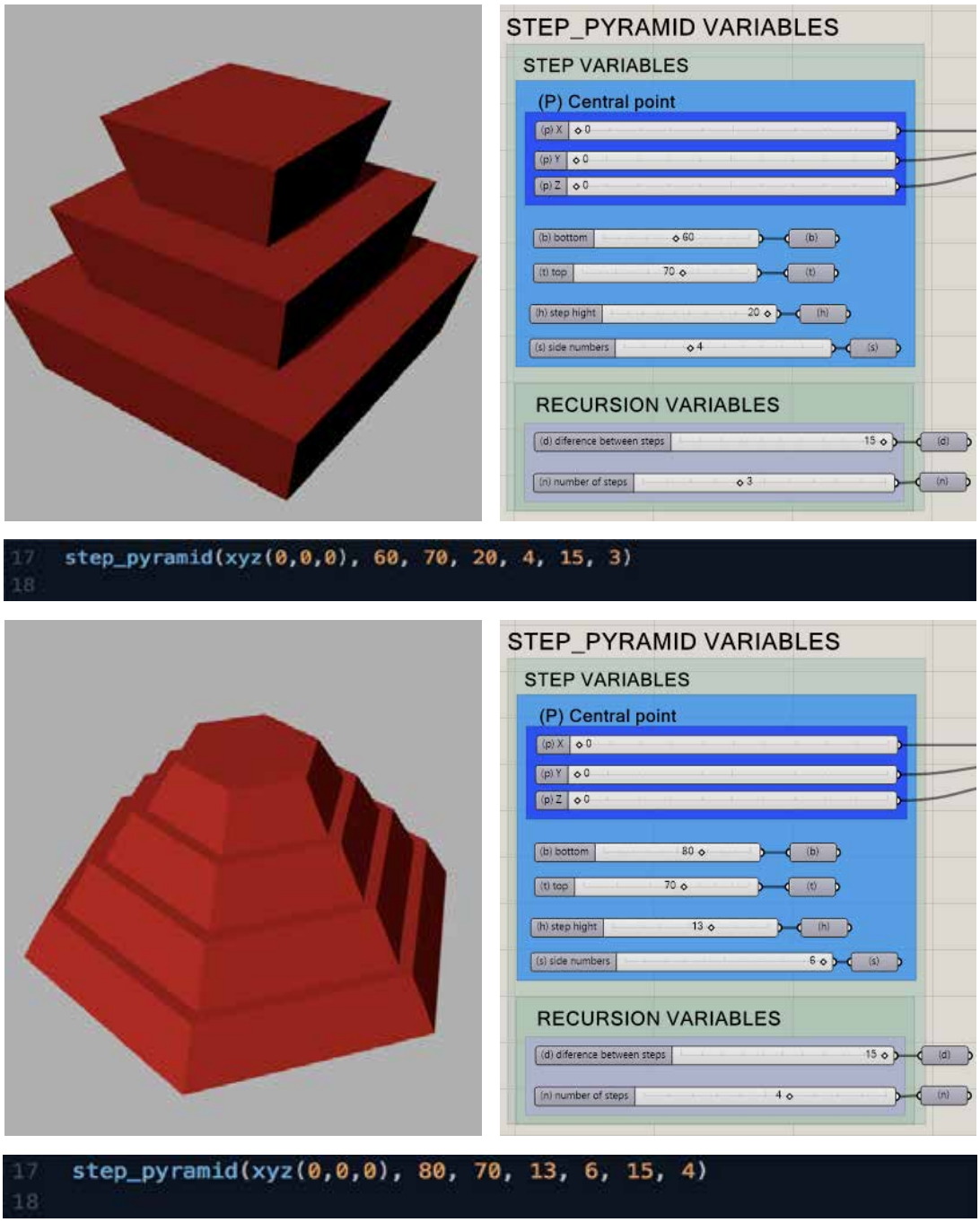


Figure 53 - Variationally shape from changing numeric variables.
Source: Authors.

KNOWLEDGE TRANSFER: EXAMPLE TWO

Knowledge transfer consists in retain the new information by the application of other example that needs the same skills.

As strategy of knowledge transfer, it is presented another problem situation that can use recursion to solve. The objective is design a volumetric model of a monotonous city with the same both languages. After that it can be inserted some randomness in the buildings height.

Figure 54 - Example of monotonous city.
Source: http://www.vitruvius.com.br/media/images/magazines/grid_9/cf00_1-sw.jpg

ABSTRACTION

The monotonous city case is divided by blocks and buildings. For each block we assume that there is one single building. The length building is determined by the block dimensions.

The abstraction of the problem, led us to understand that we need to design first a block, second a street, third a city and fourth the buildings. We designed a sketch and pointed the variables of the problem (Figure 55):

P = initial point
l = block length
s = street length

h = height of the building

N = number of streets

M = buildings greed

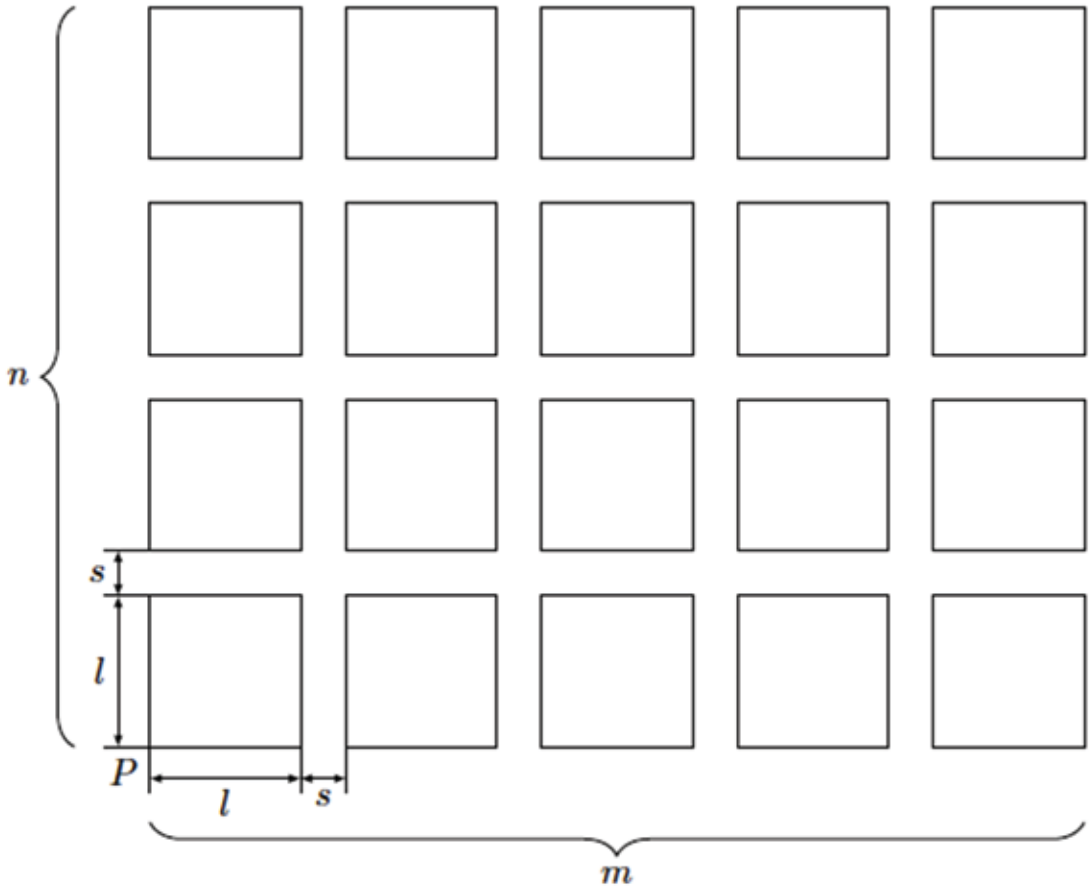


Figure 55 - Sketch of abstraction process.
Source: Authors.

AUTOMATION

DEFINING PARAMETERS / VARIABLES

First, the step parameters were set in both languages. In VPL the parameters were set by "number slider", in TPL by the creation of a new function "step" (Figures 56 and 57).

In Python script, the variables were expressed by letters in first line of step function, later the user can associate any number to each parameter.

```
11  def grid_buildings(p, n_streets, m_buildings, l, h, s):
```

Figure 56 - Parameters of the city in TPL.

In grasshopper, the variables are presented by number slides predefined, the user can change the variables just moving the slider bar.

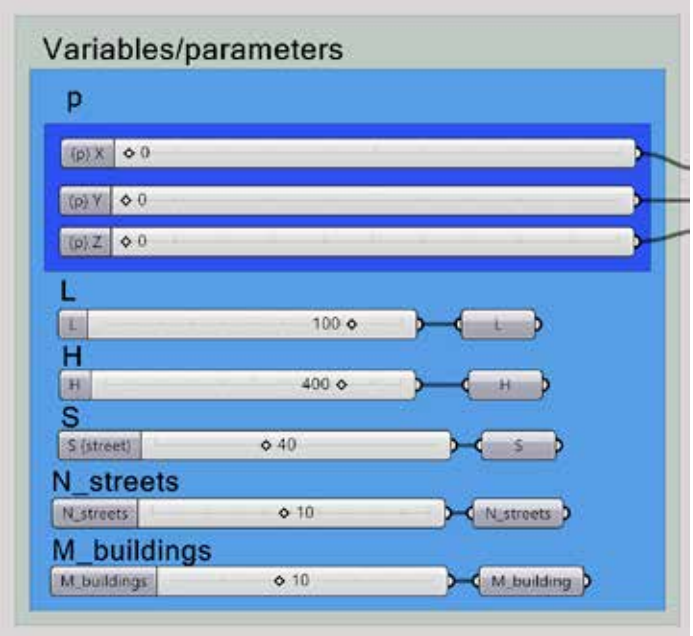


Figure 57 - Parameters of the city in VPL.
Source: Authors.

DEFINING A STREET

It is time to define a line of blocks which we call as street. Later on this street will receive the buildings. As said before, recursion makes solving problems easier by breaking them into smaller sub problems. In that way, we defined the function “street_building” with the parameters “p”, “m_buildings”, “l”, “h”, “s”, if the “m_building” is equals to zero, pass. For any number else, repeat the “street_building” function that calls itself changing the parameters “p” and “m_building” for each repetition (fig. 24).

```
def street_buildings(p, m_buildings, l, h, s):
    if m_buildings == 0:
        pass
    else:
        building(p, l, h)
        street_buildings(p + vx(l + s), m_buildings - 1, l, h, s)

```

Figure 58 - Street function in TPL.
Source: Authors.

The same relation between the variables happens in VPL and are presented in workflow of figure 59. The same operation “vx(l+s)” is inside of loop start and loop end of anemone components.

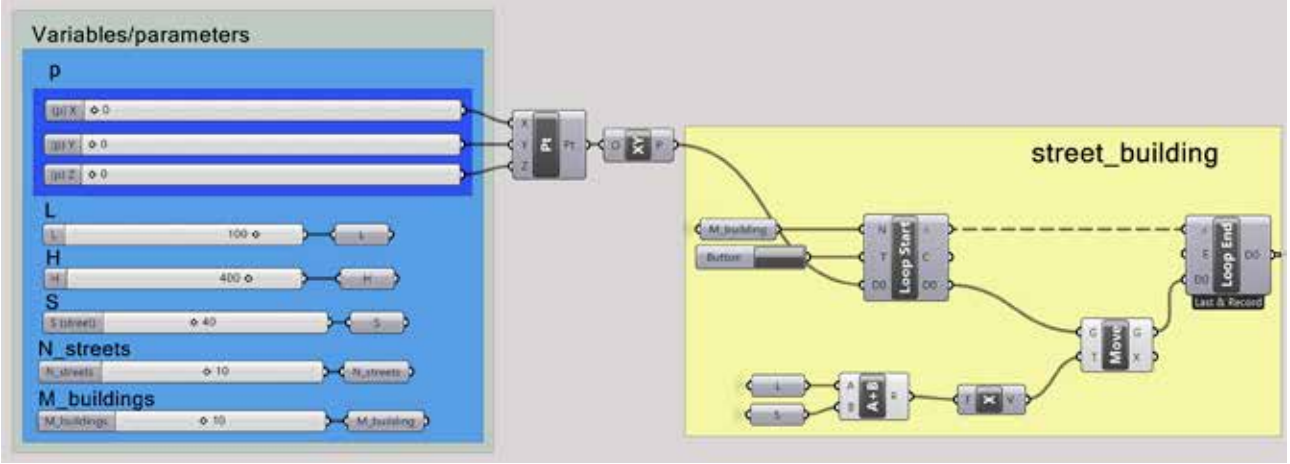


Figure 59 - Street function in VPL.
Source: Authors.

DEFINING A CITY

Once the street is designed, the logic is applying other recursive function to generate the city grid. In TPL was defined the function “grid_building” with the parameters “p”, “n_streets”, “l”, “h”, “s”, if the “n_streets” is equals to zero, pass. For any number else, design the “street_building” plus repeat the “grid_building” function that calls itself changing the parameters “p” and “n_streets” for each repetition (fig. 60)

```
11  def grid_buildings(p, n_streets, m_buildings, l, h, s):
12      if n_streets == 0:
13          pass
14      else:
15          street_buildings(p, m_buildings, l, h, s)
16          grid_buildings(p + vy(l + s), n_streets - 1, m_buildings - 1, l, h, s)
17
```

Figure 60 - City function in TPL.
Source: Authors.

Again, the same relation between the variables happens in VPL and are presented in workflow of figure 61. The same operation “vy(l+s)” is inside of loop start and loop end of anemone components.

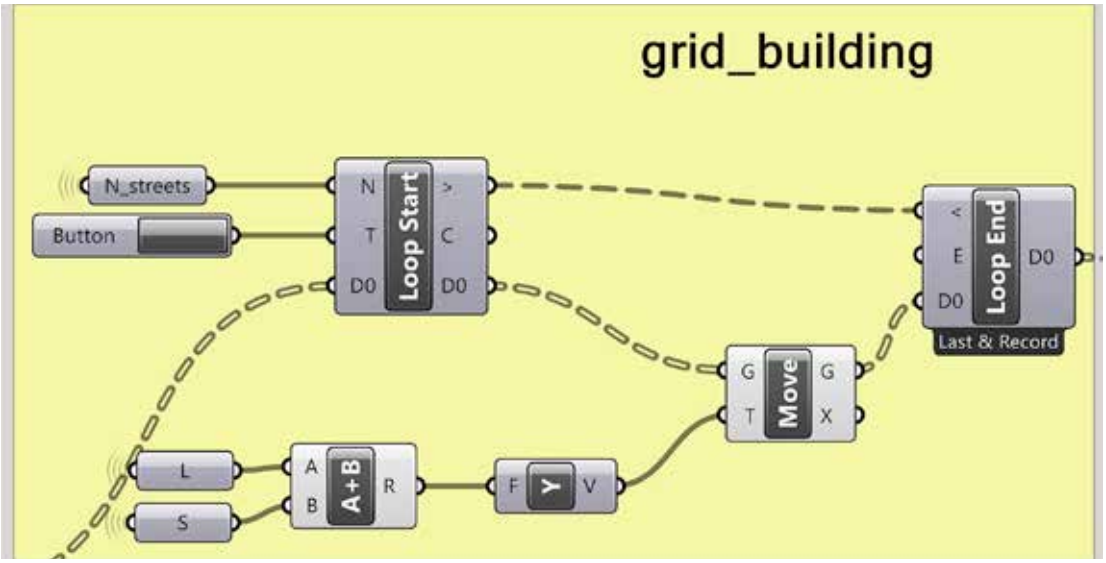


Figure 61 - City function in VPL.
Source: Authors.

DEFINING THE VOLUMETRIC BUILDING

Now, as the city grid is done, it is designed the building to fill the city spaces. For this example, is represented by a volumetric box with the parameters “p” for central point, “l” for laterals length and “h” for height.

For TPL it was written a “building” function designed by a box (Fig. 62)

```
18  def building(p, l, h):
19      box(p, l, l, h)
```

Figure 62 - Building function in TPL.

For VPL it was designed a box baser on a rectangle (Fig. 63)

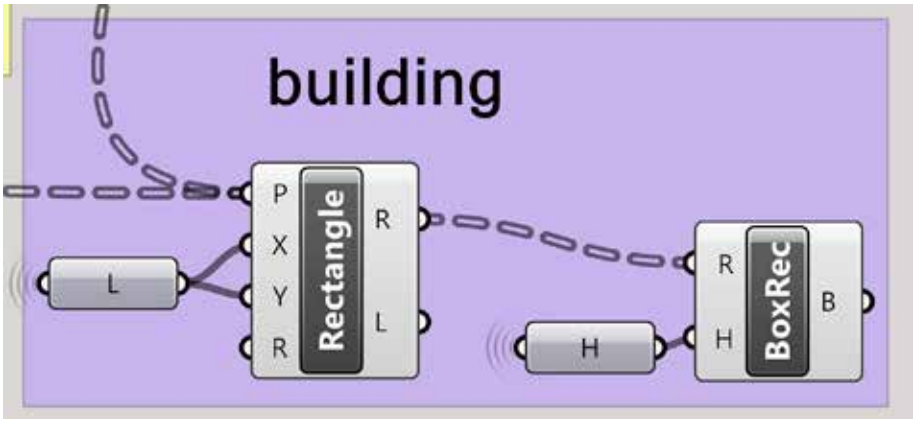


Figure 63 - Building function in VPL.
Source: Authors.

THE FINAL SCRIPTS

As an example of knowledge transference, these examples present two recursive functions or loops. The last step to design the monotonous city in Rhinoceros is call the function “grid_ buildings” with absolute values in TPL, and bake the last component in VPL (Figs. 64 and 65).

```
from khepri.rhino import *
delete_all_shapes()

def street_buildings(p, m_buildings, l, h, s):
    if m_buildings == 0:
        pass
    else:
        building(p, l, h)
        street_buildings(p + vx(l + s), m_buildings - 1, l, h, s)

def grid_buildings(p, n_streets, m_buildings, l, h, s):
    if n_streets == 0:
        pass
    else:
        street_buildings(p, m_buildings, l, h, s)
        grid_buildings(p + vy(l + s), n_streets - 1, m_buildings - 1, l, h, s)

def building(p, l, h):
    box(p, l, l, h)

grid_buildings(xyz(0, 0, 0), 10, 10, 100, 400, 40)
```

Figure 64 - TPL final script.
Source: Authors.

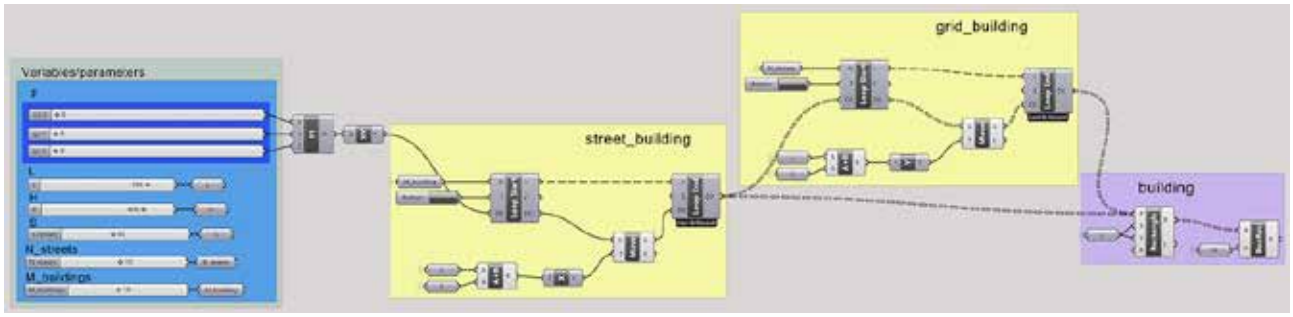


Figure 65 - VPL final script.
Source: Authors.

ANALYSES

Both of languages designed the monotonous city, again applying the same logic using the computational thinking.

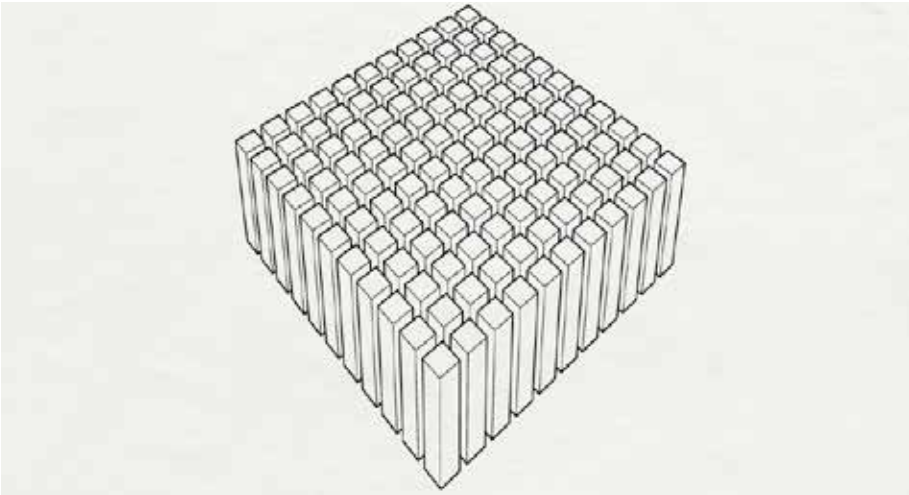


Figure 66 - Monotonous city by VPL or TPL.
Source: Authors.

RANDOMNESS

To design a volumetric city more realistic, the height for the buildings must variate. To do this by programming it is necessaire just do a simple adaptation in both languages in building function. It is possible generate some random values using predefined functions that exists in many languages. In Khepri+python it is used the “random_range” command, and in grasshopper it is used the Random component.

```
def building(p, l, h):
    box(p,
        l,
        l,
        random_range(0.1, 1.0)*h)

```

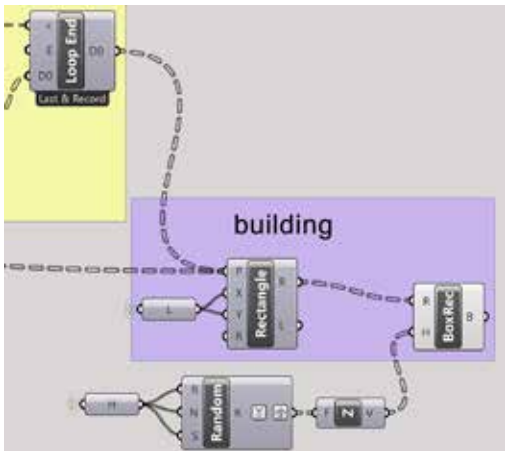


Figure 67 - Random buildings using TPL or VPL.
Source: Authors.

FINAL SCRIPT

In figures 68 and 69, there are the final city scripts with randomness of buildings variation, presented in VPL and TPL respectively. Other variations could be also applied such as buildings

shape, space between streets, sectorizations of buildings per activity (commercial, residential, etc.), to approximate the city skyline furthermore from reality.

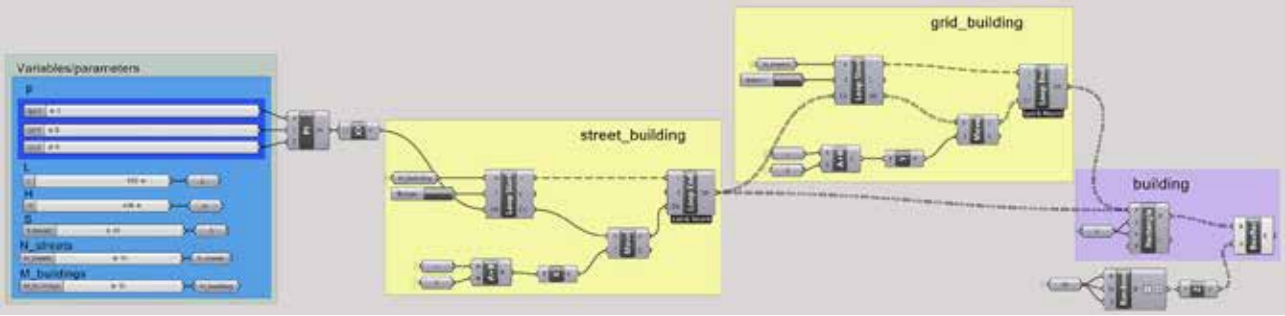


Figure 68 - Final city script in VPL.
Source: Authors.

```
from khepri.rhino import *
delete_all_shapes()

def street_buildings(p, m_buildings, l, h, s):
    if m_buildings == 0:
        pass
    else:
        building(p, l, h)
        street_buildings(p + vx(l + s), m_buildings - 1, l, h, s)

def grid_buildings(p, n_streets, m_buildings, l, h, s):
    if n_streets == 0:
        pass
    else:
        street_buildings(p, m_buildings, l, h, s)
        grid_buildings(p + vy(l + s), n_streets - 1, m_buildings - 1, l, h, s)

def building(p, l, h):
    box(p,
        l,
        l,
        random_range(0.1, 1.0)*h)

grid_buildings(xyz(0, 0, 0), 10, 10, 100, 400, 40)
```

Figure 69 - Final city script in TPL.
Source: Authors.

The virtual models generated of the city, from VPL or TPL, will be always different from each other (Fig. 70). Every time the function is called again in phytonscript, or you refresh the grasshopper. This is a characteristic of the random function, and that's why it was not possible compare the models to validate the scripts logic this time.

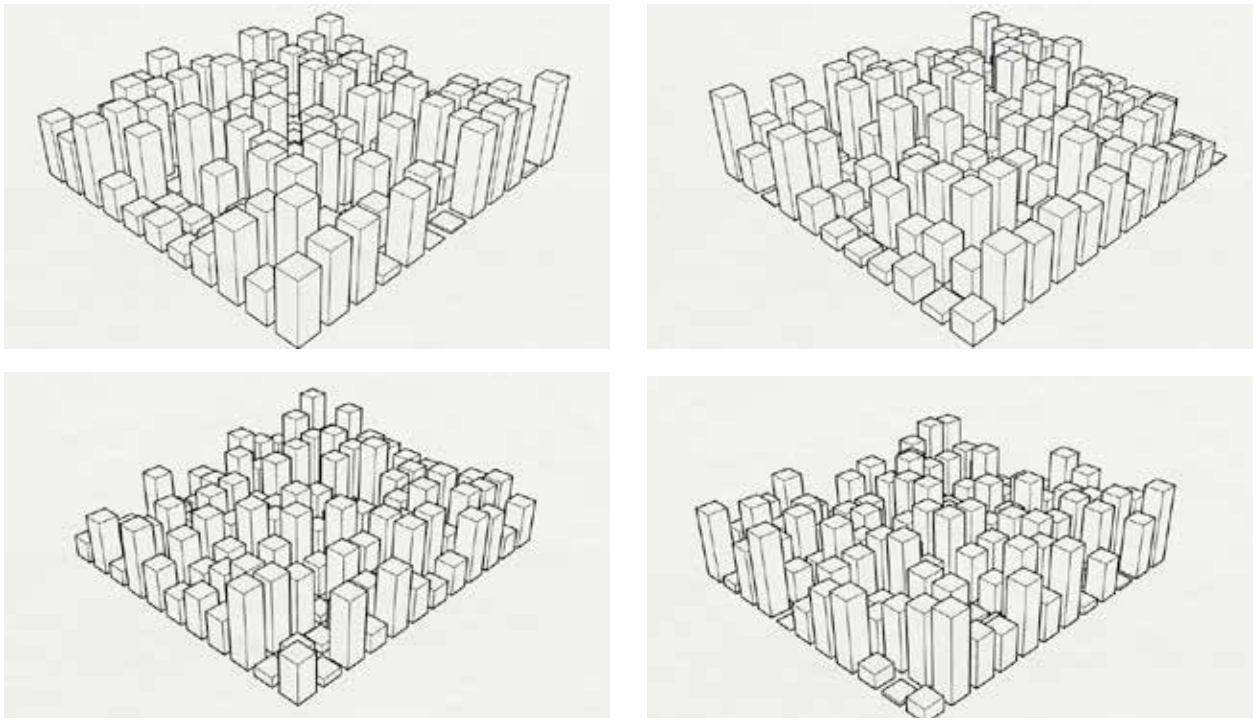


Figure 70 - Variations of city script with random buildings.
Source: Authors.

CONCLUSION / DISCUSSION

We conclude with this experiment that the same logic (computational thinking) can be applied to generate a parametric model in textual and visual language. Even though these results of the parametric models could be achieved adopting different programming strategies, it is fact that they could be solvable by recursion and loop as well, in both textual and visual languages. We could generate the same design in both languages. We expect that learning to program this way would make it easy switch to a new language every time it would be necessary.

With the experiment it was also possible compare visual and textual programming languages and their peculiarities.

According to legibility, we understand that textual programming languages would be a better option than visual language. It seems to be easier to read and understand the script, because clearly, if we submit the script to other people, they can identify easily the connections between inputs, instructions and outputs. As long as the script is becoming complex, those connections becomes harder to identify in visual language.

According to performance, in textual language also seems to be better than visual. In our experiment, the generative models were designed faster, in the same environment, by running the Python Script, then in grasshopper.

On the other hand, it is easier for the programmer, conceive the script in grasshopper. They can see modeling results in real time for each connection made. It allows them to identify possible

hits and misses during the process. As the script is based on the workflow schema, it is also easy to develop the script according to the firsts abstractions of the problem.

Both languages have online Social community and rich free documentation that can help to solve questions and the learning process.

CHAPTER 04

RESPONSIVE SYSTEMS

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RESPONSIVE SYSTEMS

GONÇALO CASTRO HENRIQUES

ABSTRACT

Responsive architecture is often considered as one that merely adapts to change. This reflects the limited and still incipient application in architecture. Due to the current resource crisis, systemic building management is essential. This article argues that there are no established processes for creating and managing responsive architecture. To establish a foundation in this area, it claims that it is necessary to deepen knowledge about systems, computation, mathematics, biology and robotics. Despite being a vast subject, it proposes a state of the art about systems, investigating how to operate them. A method for generating responsive systems is tested and implemented in a practical case. Two methods of adaptation are proposed and tested: static and dynamic adaptation. These methods reinforce the point that responsive architecture can use not only active mechanisms, but also passive methods embedded in its form as information. The research concludes that information management is critical to define what is designated in software engineering as architecture of the system. Thus, it suggests that it is necessary to define meta-systems and to define their methods to support the generation, fabrication, construction and operation of responsive systems.

Note: this text is adapted from the original: HENRIQUES, G. C. Responsive Systems: Foundations and Application - The importance of defining meta-systems and their methods. In: COMPLEXITY & SIMPLICITY - PROCEEDINGS OF THE 34TH ECAADE CONFERENCE, Volume 1, Herneoja, Aulikki; Österlund, Toni and Markkanen, Piia (eds.), University of Oulu, Finland, 2016, pp. 511-520.

INTRODUCTION

New technologies can enable better use of resources that are scarce and limited. New technologies in architecture can stimulate a shorter and integrated design process, enabling more efficient production. However, the most visible expression that emerges from these new possibilities is geometric differentiation. These technologies are also used to manage the design process and digital fabrication. But, seldom are technologies seen to manage buildings after construction, a less explored ability. In the post-industrial society, Personal building(s) management is still considered a luxury available only for special buildings and accessible to few.

Buildings use a significant amount of energy, not only during their construction, but also after they are built for their maintenance. Due to global warming precautions must be taken in building

energy efficiency and resources management. One of the precautions is to use shading devices (KIRIMTAT *et al.*, 2015). This article claims that, although shading devices are important, responsive systems should embrace a wider range of concerns'. New technologies and data management are essential to manage resources and to deal with an increase of the amount of information.

Integrated buildings' management is more than a wish; it is a necessity. The development of mathematics has supported the formulation of general laws described in the General Systems Theory (1950-68). Although the system concept has long been considered in architecture, it has benefited from the development of the discipline that studies the control of systems, cybernetics. In cybernetics, it is indifferent whether a system is social, natural or synthetic (DE LANDA, 2011). To define a responsive building, it is necessary to revise the concept of system. Although there are references described in the literature about responsive buildings, an inclusive state of the art is lacking. This state of the art intends to relate the concept of responsive building with the evolution of mathematical principles that support these systems.

This paper argues that to define responsive buildings it is necessary to design and develop inclusive systems. It investigates how to develop a holistic system and how to manage complex processes with a large amount of information. It is expected that the analysis of the state of the art can be useful for the development of support systems for responsive buildings.

THEORETICAL-PRACTICAL METHODOLOGY

This article will first highlight the importance of energy in buildings, according to available studies. Then it will investigate the mathematical origins of the general systems theory and its development. It will then address cybernetics, the discipline that deals with the systems control. The purpose is to investigate the relationship between the system concept and emergence of responsive buildings. Finally, a practical application of these theories will be presented and discussed.

Today's society faces serious environmental challenges. Edward Mazria studied the relationship between architecture, energy and the environment. Mazria (2003) accounted energy use in three basic sectors in the US: the architecture, transport and industry. According to that study, the architectural sector consumes 48% of the energy, while transport and industry consume respectively 27% and 25%. Furthermore, the architectural sector generates 46% of CO2 emissions annually, a figure that is already significant and likely to increase. If this trend spreads to cities in general, then architecture discipline should reflect about this impact. This justifies the growing concern with reducing energy consumption in architecture and construction. For a more sustainable environment, buildings should be more adapted to the environment and use fewer resources. Digital processes and tools can improve buildings' adaptability to the environment.

Developments in biology, computation, architecture and design enable the development of responsive buildings, which unlike traditional static buildings, can adapt dynamically to the

environment. This implies an ecological vision of populations, giving emphasis to the group process and interaction, in a holistic vision. That can avoid the partial view of buildings as segregated objects. New tools are necessary to consider the city, or the building as a group, considering the context and organizing the flow of information. To have responsive systems one must manages the information of data. A new class of envelopes can be developed to adjust and adapt to the environment - according to climatic variations, time of day and geographical location - and develop customize buildings that use less recourses.

RESPONSIVE SYSTEMS - STATE OF THE ART

After industrial revolution, scientific and technical knowledge became specialized. A necessity to regain a holistic vision of knowledge emerged. The concept and the tools to regain this vision are presented in the General Systems Theory. This theory includes multiple branches of knowledge, such as biology, sociology or computation. Following the development of this theory by Von Bertalanffy, many researchers from different fields have contributed to the development of responsive architecture, such as Pask, Alexander, Weinstock, Negroponte, Menges, Sterk, Mitchell and Achten, among others.

Von Bertalanffy developed the General Systems Theory applicable to living systems, social or mechanical (1950-68). This theory mathematically defines adaptation mechanisms as feedback and equifinality. Gordon Pask developed the systems control theory (Cybernetics 1969), completing the Bertalanffy control mechanisms with goal-oriented mechanisms. If the machines were regarded as closed systems, with the development of cybernetics, they could be considered as open systems as long as they were able to learn and adapt to the environment, as other living systems. These definitions allowed a shift from closed, unidirectional systems to open multi-causal systems. This enabled collaborative man-machine environments and foster responsive architecture.

In the text “Systems Generating Systems” (1968), Christopher Alexander reflects on the relevance of the word “system” in architecture. He reflects how to create holistic systems that guarantee forms synchronized with their environment. Alexander argues that a system can only be considered as such if it possesses a generative system to govern the relationship between the parts and the whole, and vice-versa. He emphasizes the importance of generative systems to define holistic systems.

Nicholas Negroponte was a pioneer of responsive architecture since the 70s, foreseeing how digital technologies could improve the documentation systems and design, generative systems and support intelligent spaces with built-in computers. Tristan-d’Estree Sterk argues that today, this theoretical understanding is not sufficient to implement responsive architecture. According to this author “Responsive architecture is often defined as a type of architecture that has the ability to change its shape in response to changing conditions. While this description successfully captures the essence of the subject, it does not provide a detailed understanding necessary to build it”. He

argues that for that it is crucial to associate architectural knowledge, artificial intelligence, robotics and structural engineering. The lack of knowledge by most architects in these areas justifies the ambivalent responsive architecture proposals, as there is a difficulty in overcoming an aesthetic that could be based in more than events.

Sterk also argues that to understand responsive architecture it is necessary to consider different scales. He cites the previous model of responsive architecture presented by Negroponte that he considers interesting conceptually, but claims that computational models of this theory are still scarce. Sterk highlights the advances in the fields of artificial intelligence and robotics, in defining high-level control systems (deliberative) and low-level (self-regulated). To implement responsive architecture, he proposes a hybrid control system (Figure 72) that could combine high-level computation (deliberative) with low-level computation (self-regulated). However, it can be arguments that Pask already proposed a goal-oriented approach considering low-level loops within deliberative high-level loops (Figure 71). This linkage allows associating the deliberative decisions with self-regulation. The low-level responses can be given via sensors, and when a certain value is reached, a higher-level order is executed. In this threaded process, the feedback loop is essential.

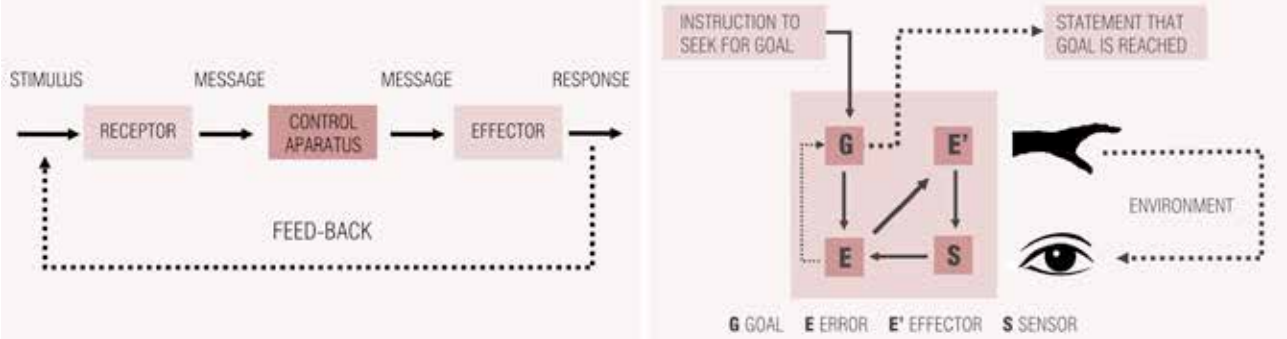

Figure 71 - Simple feedback mechanism and goal-oriented mechanism.
Source: Adapted from Bertalanffy (1969) and Pask (1969).

Sterk aims to combine the deliberative control developed by Yona Friedman (1971) with the self-regulated control proposed by Chuck Eastman (1972). While the deliberative control requires high level computation (*i.e.* use of a coded language, and the user to know how to operate the system), the self-regulated control does not require the use of a coded language and may be controlled by machine code. In self-regulated control, simple reflective procedures are used, and the system state is determined by the interaction among the parts. Mike Weinstock refers to the importance of mathematics in the theory of emergence. Weinstock proposes application of this theory (2004) to architecture to support a new morphogenesis of form.

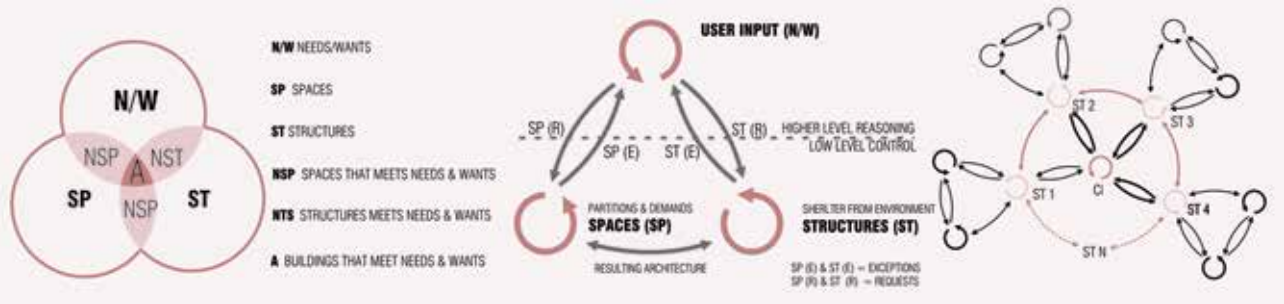

Figure 72 - Hybrid Control Model for a responsive architecture. It combines high-level (deliberative) with low processes (self-regulated). From left to right: 1 Components of a discrete model of Architecture including the wants and needs (n/w), with spaces (sp) and structures (st); 2 High-level user decisions (n/ w), space (SP) structure (ts) and, within each, there are low-level decisions; 3 Responsive architecture applied to network buildings, repeating the above combination, but on a larger scale.

Source: Adapted from Sterk, 2006.

Henry Achten (2014) identifies an amount of terms related to responsive buildings, such as: building automation system, smart home, sentient building, adaptive building, dynamic building, interactive building, kinetic architecture, intelligent building and portable building. Achten provides a definition for each of these terms, concluding there is no possibility of unanimous classification for each of these definitions, because each one is related to a specific technological application. He states that this may be related to the recent application of these technologies, which have not been absorbed into the common language. Achten seeks to characterize the interaction of responsive systems with users. He advocates the use of recent developments in artificial intelligence, with the use of multi-agent networks capable of supporting analysis, design and development of complex systems in all project phases. This latest reference reinforces the architect's need identified by Sterk for more extensive knowledge of different areas to define such systems.

GENERATING RESPONSIVE SYSTEMS

To support a responsive architecture, it is necessary to create systems that manage systems, i.e. metasystems with the characteristics to be introduced into these responsive systems. Pask, in the cybernetics theory, states that architects have to generate systems that generate buildings, rather than just design buildings. Alexander, analyzing systems architecture, agrees - arguing that, to generate systems, it is necessary to design generative systems that enable them. Authors from different fields of knowledge refer to the need to define meta-systems and their generative principles. Sterk draws attention to the point that, to control these meta-systems, it is necessary knowledge different fields. However, despite the model proposed by Sterk, it is not yet clear how this can be implemented.

De Landa states that a system has capabilities that arise from the interaction of the parts that excel the sum of the individual properties. He states that it is necessary to define the procedures and variables of the system so these capabilities can emerge. He also states that the restrictions

applied to the variables increasingly define the systems. He refers to algorithms as the essence of software, comparing mathematics metaphorically to a type of software. He highlights the definition of gravity proposed by Richard Feynman in three stages: 1 - force and acceleration, 2 - force fields, 3 - singularities and solution space (minimum, maximum and variation characteristics). This change is related to the move from quantitative mathematics to qualitative mathematics, from values to parameters. This change is also related to the move from Euclidean geometry and the metric systems to the topological geometry of local spaces. This mathematics allows defining associative behavior among the parts through parameters that can be encoded algorithmically.

To define open systems, computation incorporated findings from natural systems and biology, which are an essential foundation for responsive systems. Open systems have the ability to retrofeed through feedback loop mechanisms and to conform, reconfiguring the relationship among the parts. Living systems possess a hierarchy with different levels of definitions, which allows controlling complex systems as the human body, the skeleton, the muscular tissues and the cells. The relationship among systems is not only hierarchical, but also emergent, from the whole to the parts, and from the parts to the whole.

METHOD FOR A RESPONSIVE ARCHITECTURE

This study intends to contribute to the current state of the art in the field by relating disperse contributions and by presenting a research about how to define, support and generate a responsive system. For this purpose, it will be described the method used to generate a responsive system and to implement it in practice.

META-SYSTEM

To generate a responsive system, a meta-system is proposed to guide the search in the space of solutions. The meta-system is organized in different levels of abstraction. These levels have different mathematical definitions, reducing the search space of the problem. This method was developed with a practical application - the Tetra Script responsive system - that mediates interior and exterior conditions to assure daylight quality and quantity.

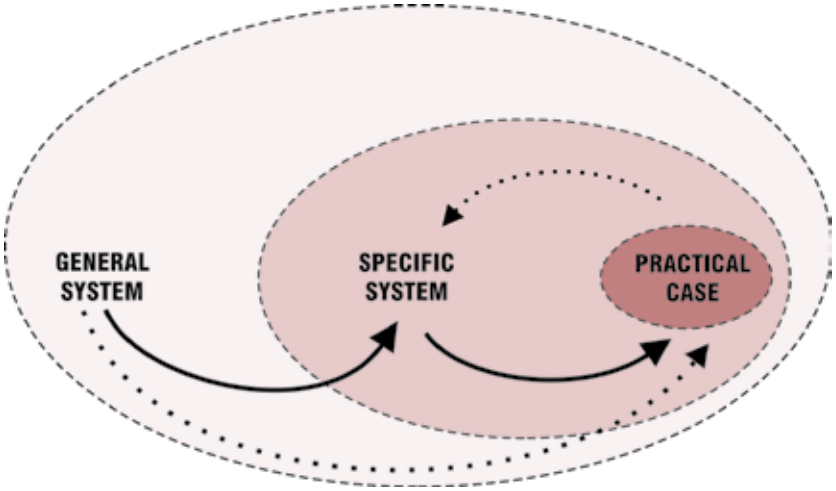

Figure 73 - Proposal to formalize a responsive meta-system, defining the general search space for the particular (deliberative hierarchy), and the particular for the general (distributed hierarchy, emergence).
Source: The author.

The meta-system proposed is organized at the following levels: General System; Specific System and Practical Case. The dynamics of the meta-system is multi-causal, from the general to the particular, and from the particular to the general. At each of these levels variables and restrictions are defined. Going from the general to the particular, the variables are progressively less abstract and have more restrictions: some shift from free variables to dependent variables. However, the low-level variables (practical case) can also influence the Specific and the General Systems. Thus, the meta-system has a hierarchical nature (the whole to the part), and an emergent one (the part to the whole). While the hierarchical nature is associated with deliberative decisions, the emergent nature is more associated with distributed behavior and self-regulation. The deliberative and distributed nature of the system will be more explicit when applied. The keyword for defining meta-system, as in natural systems, is feedback loop.

A PRACTICAL CASE, TETRA SCRIPT SYSTEM

The Tetra Script responsive system proposes a membrane to mediate interior and exterior conditions. It can be defined as a set of components that control internal daylight according to external factors (geographical location, year, month, day, hour, sky type) and internal demands (functional requirements of illuminance and visual contrast, daylight types and light-shadow patterns). Responsive derives from the Latin "*responsivo*" designating one that responds quickly and appropriately to a situation. The proposed system responds in real time, which justifies the use of such an adjective. This system was development during a PhD (0213) developed by the author of the paper. This article intends to reflect on previous research to draw useful conclusions for the development of other responsive systems.

This project required conceiving a meta-system to define how to generate and design a daylight control system. The meta-system is defined by successive approximation levels, starting from a generic

solution with a large search space. The space of solution is constrained by progressive definition of the variables, which become dependent in a less abstract definition. The meta-system has three levels: general system, specific system and practical case. The variables and factors used are progressively constrained to find a discretization or solution to a particular situation, in a pavilion that was constructed, testing a possible automation of the control system.

VARIABLES, DOMAINS AND RESTRICTIONS

System organization is described including the used variables, their domain and restrictions. The variables of the General System are more abstract, to define the search space and its focus: to develop architecture with a protective membrane that could establish a holistic relationship between inner and outer conditions and that could be customized through digital technologies. The method used seeks to use explicit algorithms and identify relevant parameters and has discarded the local topography and the physical context. This general system can be used to define other objectives, such as the organization of interior spaces or to establish a distributed network of building membranes.

The specific system has as initial input a continuous a NURBS surface, and its local topological space. To control the interior condition of a space the initial surface is populated with developable components. An algorithm mediates the conditions between the parametric variables. By defining the bounds of the specific system a family of solutions can be defined and instantiated (Figure 74). This family of solutions and the resulting objects can be used in oriented objects language, to define a class, defining its actions, properties and methods.

The practical case is an instantiation in a specific building. Tetra Script pavilion is an instantiation of a specific case, attributing values to the variables. To find these values, a static adaptation process is used. To manage the goals of the system after construction is used dynamic adaptation, which will be detailed further below. After setting the input surface, its geographical location is defined the number and characteristics of the components.

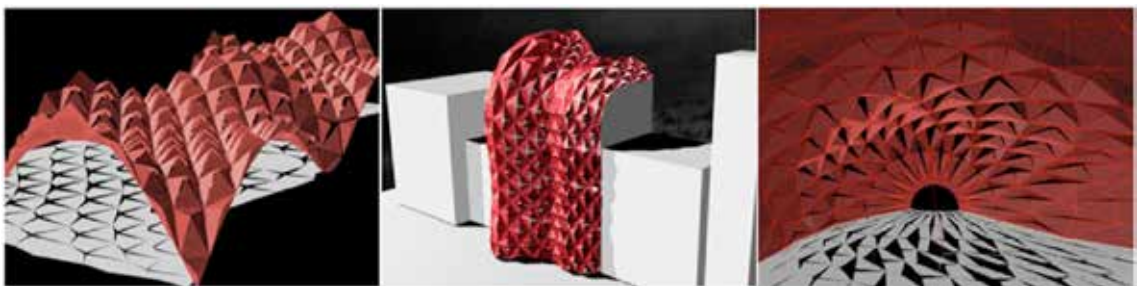

Figure 74 - Tetra Script System: instances of the same specific case.
Source: The author.

As a specific case, Tetra Script is defined with pyramid with quadrangular base, with mobile faces, easily manufacturable. Tetra Script pavilion is an instantiation of a particular system, restricting

the variables. The configuration process finds the best relationship among the variables to satisfy certain conditions, defining a progressively limited solutions search space. An emergent way to set the system would be to first choose a type of material, and then define the components, the base surface and, finally, the general system objectives. But, an emergent solution can also be achieved through interaction among the components using dynamic adaptation.

The meta-system levels are divided into sublevels. In the practical case developed, after setting the values of the general variables, a specific system was set containing sub-level groups of variables that, for space limitations, are summarized as follows. The interaction between each group of variables determines a solution for each individual case. The group of variables is defined thus: external variables of the object (such as geographic location, date, sky type and respective domains, constraints and dependencies), the specific variables of form (surface type, dimensions, component type and number), variables of the form in the practical case (surface area, parametric space, domain, number of pyramids, height and aperture value), and internal variables or functional requirements (illuminance, visual comfort, thermal comfort and space heuristics). To determine certain conditions, it is necessary to find an algorithm to control the relation between the parts and the associated variables.

SYSTEM METHODS: STATIC AND DYNAMIC ADAPTATION

This research proposed two methods to control the meta-system adaptations, which are referred to as static and dynamic adaptation. Static adaptation controls the geometric generation until the form is baked, manufactured and constructed. The dynamic adaptation controls the relationship among the parts after the system is constructed and operating. These methods allowed real-time adaptation of the system in the practical case developed. This methodology can be used to instantiate different solutions and to develop other systems. As described by the author in previous publications, these processes find parallels in living systems, particularly in adaptation through natural selection and through behavior adaptation.

	Variable	Domain	Restriction
General System	Architectural use	holistic membrane	digital customisation
	Algorithmic	parametric definition	topography/settlement
	holistic system	micro/macro interaction	disregarded
Specific System	Surface	continuous nurb surface	local parametric space
	Components	defined in the surface	developable
	Openings	component defined	movable openings
Case Study	Specific location	Porto, Portugal	41.158 N, -8.629 O
	Surface type	Spheroid	6 x 4 x 3 m
	Developable surfaces	Quadrangular pyramids	manufacturable material

In static adaptation, the relation among variables is established progressive discretization of values. As mentioned, the general system level defines the goals to be enabled by digital processes. To find a solution using the system, an asynchronous process was conducted using CAD-CAE-CAM-AUT digital processes. Digital processes were used to generate and manipulate surfaces using algorithms, to manufacture components, to test component types and groups, to simulate and assess environmental performance of the solutions generated, and to automate and develop strategies for the components. A diagram is proposed to describe the interaction among the digital tools and processes found in previous publications (HENRIQUES *et al.,* 2012). The search intended favoring the use of explicit algorithms, although it can be further improved.

The dynamic adaptation controls the relationship among the parts to ensure the systems' desired performance. After the construction of the Tetra Script pavilion, the variable that can be controlled is the degree of the opening of skylight panels, which thus determines the formal setting of the pavilion. There is a multitude of possible combinations of apertures for controlling the amount and type of daylight. The dynamic adaptation allows finding aperture settings that meet daylight requirements, including glare and visual contrast. A more detailed description of the process can be found elsewhere (HENRIQUES, 2012).

Heuristics are used to find space solutions with certain features that meet the desired requirements. Heuristics are a mathematical rationale used to identify good solutions in a short time, rather than optimal solutions that do not always exist and that take longer to be identified. The set of heuristics to describe behavior patterns is based on simple rules and typify possible solutions, thereby reducing the search space. The optimization research could provide better solutions, but results would take a long time to converge, since the search space of all possible configurations to undergo analysis is vast. The proposed heuristic search method includes qualitative and quantitative natural daylight properties. The 5 heuristics used are described graphically in Figure 75.

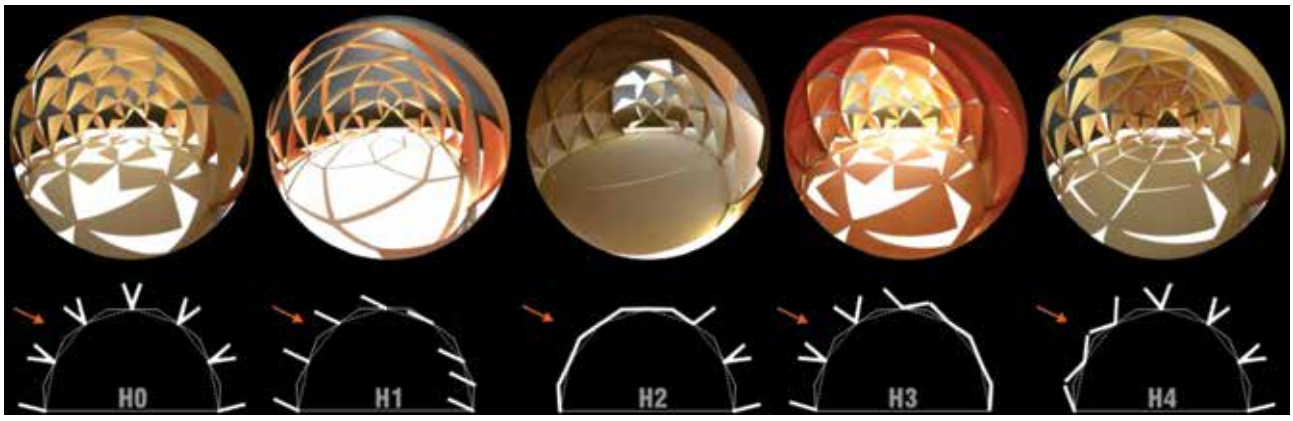

Figure 75 - Heuristics rendered preview (above) and schematic representation (below). From left to right: H0 uniform aperture, H1 maximum direct light, H2 maximum diffuse light, H3 incident sunlight, and H4 Hybrid low incident + diffuse light.

Source: HENRIQUES *et al.*, 2012.

The interaction among groups of variables is considered in a practical case. The variables considered are: the external variables (external to the object), the specific variables of form, the practical case variables and the internal variables of space or functional requirements. For each group, it is necessary to define the "sub-variables" domains and bounds. In other words, it is necessary to build a system that approaches a mathematical model establishing relationships and boundary conditions. Heuristics are defined parametrically, testing the boundary conditions throughout the simulation to find the system space of possible solutions. To find solutions using this system, it was necessary to establish the visual comfort requirements and external reference conditions.

The parametric system is used to find configurations, and, to assess performance, a daylight validated software (Radiance) is used. Simulations were performed considering all the variables described above. Values were assigned, and system performance tested through illuminance program evaluation setting the Tetra Script performance database. An interpolation method was developed in order to predict the illuminance behavior at other dates, times and in different sky conditions considered in the studies. This method is used to evaluate and choose the most suitable aperture setting for the required indoor conditions. A visual interface was developed to control the internal conditions of the pavilion in real time by modifying the opening of skylight panels.

SHARED CONTROL INTERFACE MAN / MACHINE

Algorithm control, feedback and adaptation. The user can choose what factors he values most to customize the space, defining the quantity and quality of light inside the pavilion through an interactive process. The customization was precisely one of the objectives of this research. To select a particular factor, the user is informed of the range of possibilities of the system to achieve the same amount of light with different qualities. This choice may be performed in real time using the proposed interface.

A control system is proposed to control the skylight apertures (Figure 76). The system uses two different inputs: from the user (manual) and from the computer (automated). The user can choose the activity by defining the minimal illuminance required. This information is transmitted to the algorithm that then computes all the possible configurations. The computer has instructions to obtain the time and location information from the computer that is running the program and both inputs - required illuminance and time-weather conditions - are fed into the heuristic search calculation, where values are interpolated. Then, the choice of the most adequate solution can be made automatically or manually. But, the significant feature of this scheme is to add a feedback loop using light sensors to update the database. This process would enable refinement of the expected values for each situation. Although this process is not yet implemented, it is expected that its use would allow the system to correct values and, in a way, "learn with experience." The meta-system has a dual nature, which is deliberative and inductive, thereby creating space for possibilities ("state spaces") enabling solutions that are beyond the property of each part, but result from the interaction of the parts. Thus, both

the metasystem, at different levels, as well as control algorithms, seek to enhance the immanent, the virtual, that only when explicit can become knowable, discovering new uncharted possibilities.

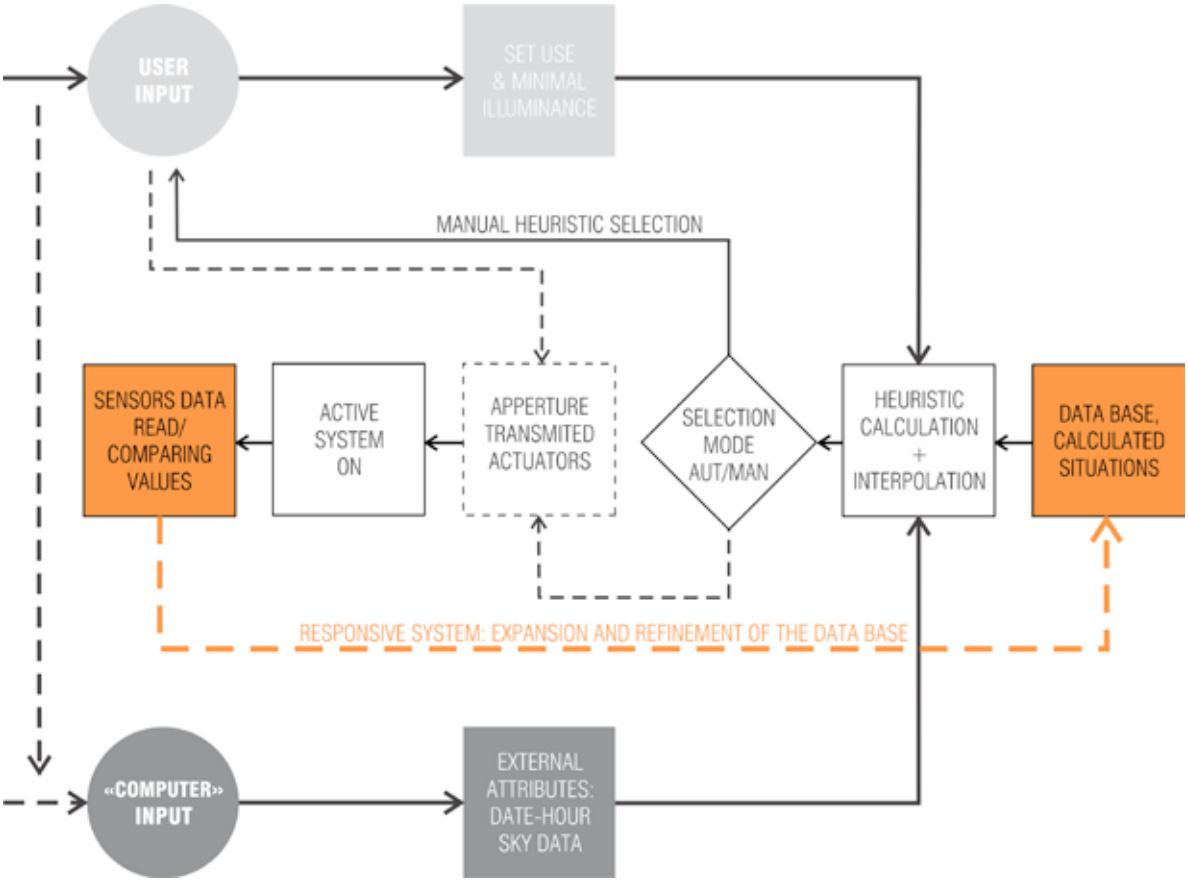

Figure 76 - Shared Control System man / machine Tetra Script pavilion.
Source: The author.

RESULTS AND DISCUSSION

This paper analyzed and synthesized contributions seeking operational concepts for the development of responsive architecture. A previous applied case study was analyzed looking for a general method to design responsive systems. This research wishes to contribute to a complex and wide task. What becomes evident during this attempt is the relevance of computational methods for the development and implementation of systems.

The creation of responsive systems requires meta-systems and the use of computation to construct a formal model that can approach a probabilistic model used in physics. While classical physics presents a model in which each object interacts alone, the probabilistic physics tends instead to value the interaction among the parts combined in a set as a model. Probabilistic physics also considers several causes simultaneously, ideally multi-causality that is absent from deterministic models of restricted causality (or single causality). The result of multicausal interaction is predictable

within certain parameters, but is not determinable a priori. To enter this discussion, architects need to know about organizing information or meta-systems and their methods. Otherwise, they can only access systems as a black box, entering information as an input receiving only the output. In this framework, the simple use of the computer - or computerization (as defined by Terzidis) is not enough, nor is it sufficient to define a system as a model of representation of the reality. Although the computer is still necessary as a tool, the use of computation to define meta-systems, defining methods and actions used to design and operate systems, becomes relevant.

ACKNOWLEDGEMENTS:

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CHAPTER 05

TRIDIMENSIONAL PARAMETRIC MODELING AND THE PRODUCT DESIGN PROCESS FROM A TEACHING AND LEARNING PERSPECTIVE

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TRIDIMENSIONAL PARAMETRIC MODELING AND THE PRODUCT DESIGN PROCESS FROM A TEACHING AND LEARNING PERSPECTIVE

MARCOS BORGES

ABSTRACT

This chapter reports some undergraduate Engineering Design Graphics (EDG) teaching and learning experiences linked to the Product Design Process (PDP) context. One of the assumptions is related to the EDG class-hour reduction observed over the years in engineering curricular around the world, faced to a Computer Aided Design (CAD) significant amount of re-sources and technology development speed verified nowadays in the PDP and engineering practice. For that, there is a brief historical description of the digital design aids from the first attempts to the present paradigm of parametric modeling. Besides it, there is a brief overview of engineering design methodologies evolution. Also, there is a discussion that links the EDG to the PDP from a teaching and learning perspective. There is argued that those areas are indissociable and the need for more integrated curricula approaches is fundamental for a CAD resources full utilization. From that theoretical discussion, the chapter presents the structure of a parametric modeling tool and its relation to the Computer Aided Engineering (CAE) resources, using some didactic examples to illustrate the concepts. Finally, the partial results from the experiments are reported and illustrated. Those results showed that it is possible to link the EDG to PDP in a tight class hour scenario, leading the students to a context-based learning experience.

INTRODUCTION

This chapter is divided into two main parts. The first one presents some reflections about the EDG and PDP current paradigms and its relations to the learning and teaching processes in engineering courses. One essential argumentation bonds EDG, PDP and specific engineering and

technology contents in a whole frame. Those bindings among areas intrinsically related aren't always found in engineering, architectural and design curricula structures.

Those thoughts started from classroom pedagogic experiments carried by the author on the Mechanical Engineering course at the Federal University of Juiz de Fora (UFJF) along many years. There was verified that technical drawing has been worked as content not contextualized with its targets as foundation knowledge (OLIVEIRA; BORGES, 2001).

Additionally, there are presented some reflections around recent EDG tools from a historical perspective of design representation digital systems evolution considering mainly the tridimensional parametric modelers. Those reflections are also associated with the concept of Parametric Design Thinking (PDT) proposed by Oxman (2017).

The second part of the chapter reports and illustrates the ongoing experiments that aim to identify relevant aspects related to the graphic expression and its interactions with the design process. Those experiments are linked more specifically to mechanical engineering technological artifacts. However, it is easy to glimpse the possibility of architectural and design adaptations. The reported experiments start from a brief description that sets the parameters for its realization and presents some partial results from a systematic observation and online questionnaires applied to the students over the years.

These partial and initial results were published previously by the author (BORGES, 2015. BORGES; SOUZA, 2015). Here these results are updated and enhanced by more deeply observations of the work developed by the students.

It must be emphasized that this work does not approach all the potential and resources of the nowadays tridimensional parametric modelers. Follow are some examples of those exclusions: manufacturing processes interfaces allowing fabricating parts for reductive or addictive manufacturing, namely computer numeric command, laser cut and tridimensional printers, among others. However, those resources must always be considerate since they act as links between EDG, design and manufacturing processes.

THEORETICAL FOUNDATION

EDG CONCEPTS AND CONTEXTUALIZATION

The EDG field and its foundation disciplines, as is the case of descriptive geometry, are considered by many researchers and educators as significant content for product design and technological innovation (FERGUSON, 1993; BARR, 2012; SUZUKI, 2014). The use of non-ambiguous technical representations of artifacts, from the first rough drawings to final and detailed working drawings provided by the graphic descriptions theoretical foundations and standardizations is indispensable on the investigation process of innovations among diverse technological areas.

Although the relevance that one must consider in engineering, architecture and design competencies for the under graduated students, there is verified an increasingly class hour reduction in the Graphic Expression area. It is more likely perceived in engineering curricula structure in a broad sense (LEAKE; BORGERSON, 2008), but also one can find distortions in architecture and design courses. In many cases, there isn't synchronization between computational tools evolution and the discipline syllabus inside curricula structure (GODOY; CARDOSO; BORGES, 2014).

Besides that, scenery of class hour reduction and increasing contents related to design process digital tools, there is verified in some cases a growing articulation between EDG, design practices and computational tools (LEAKE; BORGERSON, 2008). However, this association hasn't been the teaching and learning pattern on engineering courses. Disciplines like descriptive geometry, projective systems, and similar others had always shown a historical lack of contextualization and adherence to engineering and design process contents.

Researchers from the EDG area have been seeking means to establish parameters that allow for spatial reasoning understanding and evaluation and consequently construct better practices of teaching and learning. The research resulted in some assumptions that are similar in many authors. Sorby (1999) points the importance of working from the paper printed material, physical tridimensional models and with real parts from machines and equipment's to elaborate orthographic projections and isometric perspectives done by free hand.

Barr (2012) stands out that from fourteen items identified on a survey among professors as competencies constructed on engineering formation and related to EDG, three are highly scored on studies from 2004 and 2012. They are:

- Ability to create tridimensional solid models on computers.
- Ability to elaborate graphics representations by free hand.
- Ability to visualize and interpret tridimensional solid models on computers.

Danos et al. (2014) refer to the term graphicacy as a means to discuss the ability to communicate using images such as maps, diagrams, graphic symbols and technical drawings. The authors define these means of communication as bidimensional representations of tridimensional artifacts. The term graphicacy can be understood as the visual and spatial ability that are coupled to cognitive processes as is the case of mental elaboration of tridimensional models and the critical thinking about those elaborations (DANOS et al., 2014).

The visual media and language is thigh linked to PDP. Many authors refer to terms like visual thinking and graphic thinking as essential instruments on the design activities cognitive process (FERGUSON, 1993. LASEAU; 1989). Beyond these terms, Ferguson (1993) stresses the names "thinking sketch" and "talking sketch" as a means to reasoning and communicate the early design concepts.

The challenge nowadays is to stimulate the development of graphics, visual and spatial reasoning skills on the students, considering a very intense digital environment.

From this context, the structure proposed by Barr (2012) has the potential to act as a framework for relationship establishments among competencies that must be constructed linking EDG and PDP. Figure 77 represents those possibilities. It interconnects three main areas that must be accessed in an engineering curricula structure.

The Tridimensional Model Applications can be considered as typical tasks in a PDP process and are strongly linked to Computational Modeling that has the function to develop the geometric virtual representation of the product being designed. The EDG concepts act as foundations that allow the information and knowledge articulation among them. From a teaching and learning perspective, the way that those areas are approached in a curricula structure, can be an excellent means to construct competencies in visual and spatial reasoning and also in problem-solving (BARR, 2012).

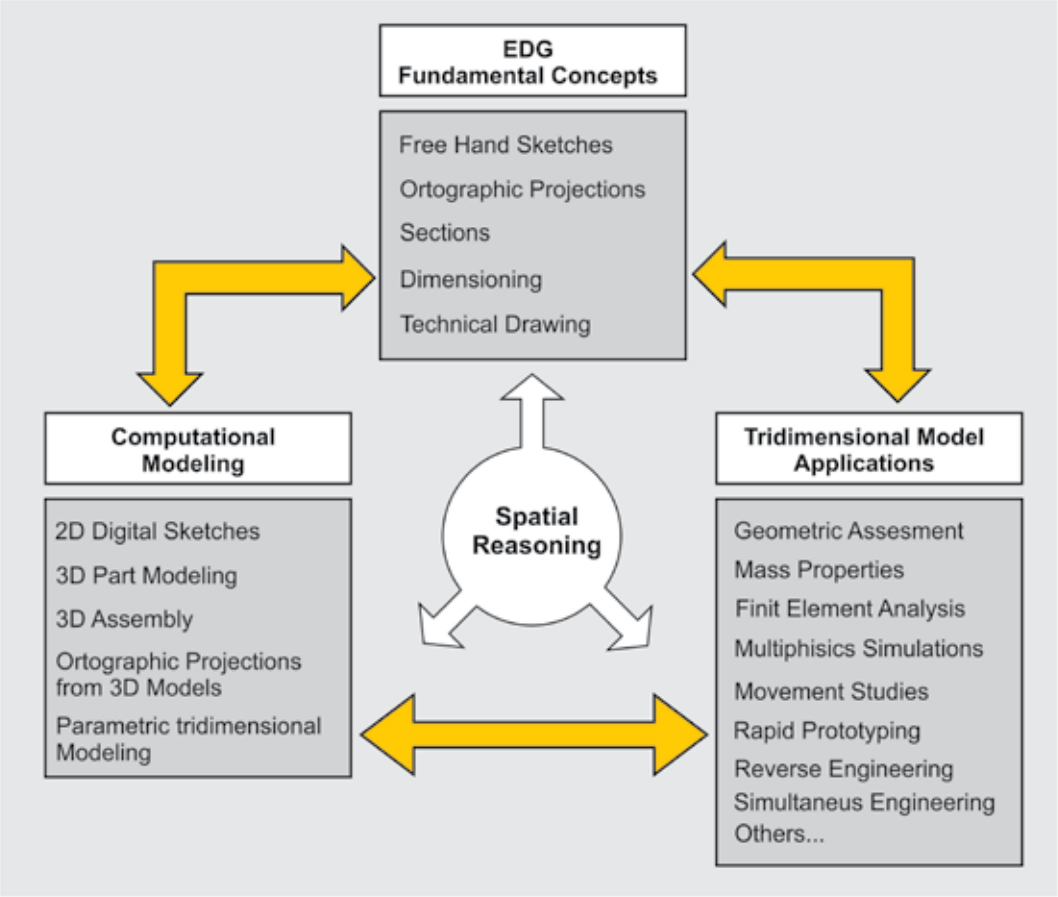


Figure 77 - Competencies around EDG.
Source: adapted from Barr (2012).

On a brief survey, one can verify that currently, the integrated environment is the trend in many digital design tools available on the market. The Computational Modeling and Tridimensional Model Applications items can be easily identified on them. That is the case of the software SolidWorks used in the experiments reported here.

Also, it is verified a significant number of parametric modelers in the market. The number of plug-ins and extensions that play specific tasks or analysis is higher yet. Sometimes those plug-ins are incorporated into the central platform contributing to the integrated environment trend.

The industrial products sector has a large number of artifact types ranging from home appliances to aerospace vehicles. From this context, the parametric modelers are grouped in two main categories as shown in table 1. For instance, the software CATIA is mostly used in the automobile and aerospace industry while SolidWorks is typical on generic products sector (BORGERSON; LEAKE, 2008).

Simple Packages	Advanced Packages
Inventor (Autodesk)	Pro/ENGINEER (PTC)
SolidWorks (Dassault Systéme)	CATIA (Dassault Systéme)
Solid Edge (Siemens)	NX (Siemens)

Table 1. Parametric Solid Modeler's examples.
Source: Adapted from Borgerson & Leake, (2008).

The fast and constant evolution of computer tools is stressing the need for a broader approach to the EDG teaching and learning processes. Many challenges must be addressed ranging from curricula structure to classroom methods and practices. Furthermore, the reduction EDG class hours contribute to a tight context to solve those problems. In that sense, this chapter aims to provide with some ideas.

FROM PAPER-BASED DESIGN AND EARLY CAD TOOLS TO PARAMETRIC DESIGN

The second half of the XX century witness the arising of a new way of EDG work. Digital media then becomes the active instrument for artifacts representation. The fact reveals profound transformations in many aspects related to the PDP itself, but mainly on the professional engineering practice and in the EDG teaching and learning processes. Those early transformations impacts are yet present in many cases. Many authors argue that the first CAD system was developed in MIT (Massachusetts Institute of Technology) by Ivan Sutherland as his Ph.D. thesis in 1963. It was named Sketchpad and is considered the first object-oriented graphics editor (PORTER, 1997). However, those early systems in the sixties were more appropriate for the information processing instead of its representation. The first CAD software demanded an enormous amount of computer processing. This fact associated with high costs and the learning process necessary to use the systems were barriers to its immediate adoption by engineers and architects. Some authors argue that commercial software did not immediately embrace the innovations brought by early CAD programs for almost three decades (TEDESCHI, 2014). Although those initial difficulties, the evolution of CAD systems is a remarkable trajectory that has profound impacts on the design process itself.

Figure 78 diagram aims to synthesize that historical evolution showing two milestones in the process. The first one is the transition from the hand-drawn practice to the first CAD systems. This shift can be considered a considerable paradigm change and in some instances can be regarded as an ongoing process since them. Also, the figure aims to relate the design thinking models settled by Oxman (2017) with the EDG evolution and its strong link with PDP.

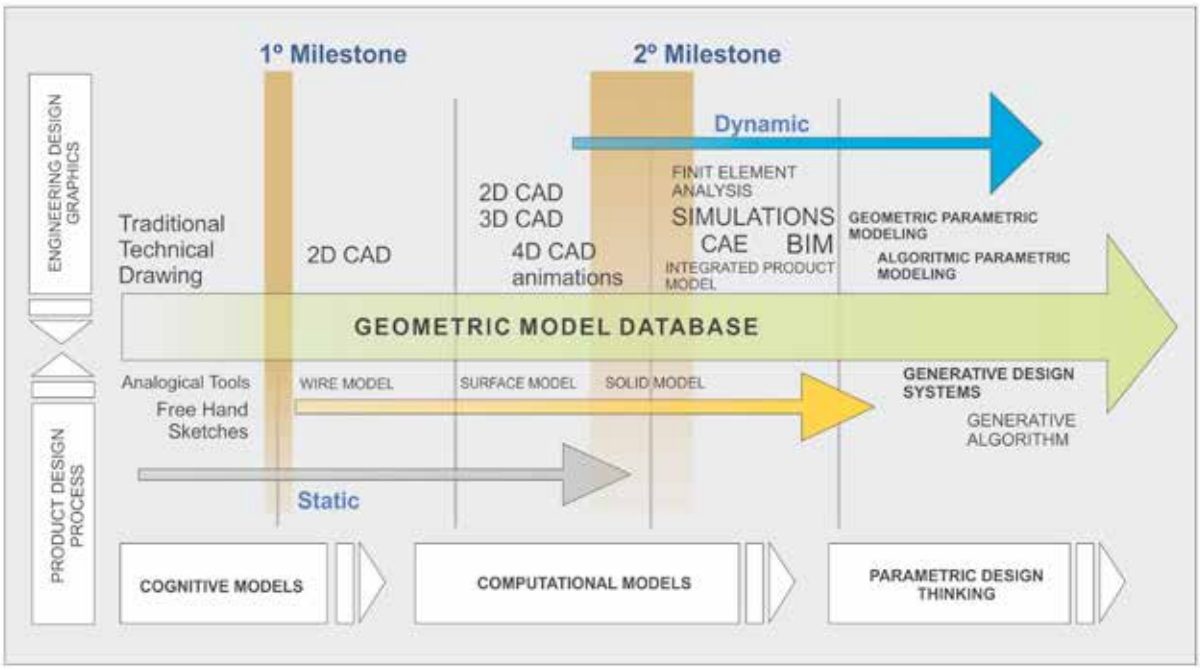


Figure 78.
Source: Author (2016).

The progressive evolution of CAD tools and computers processing capacity allowed the development of computational resources that set the foundations of a new way to approach design problems. Oxman (2017) calls it as the concept of Parametric Design Thinking (PDT).

The evolution on the side of design process models evolved from paper-based and early CAD practices explored by researchers in the second half of the last century (CROSS, 1982, 2000; SCHON, 1983, 1988), linked to Cognitive Models of design thinking. Those theories can be associated with the first milestone represented in Figure 78. The time lapse between the first and second milestones fits the assumptions of computational models in the sense that incorporates the evolution of CAD systems on a broader spectrum. For instance, there is the side of evaluation tools like Finite Element Analysis (FEA), among others. On another hand, that era witnessed the early researchers and developments on Artificial Intelligence (AI) and the rise of Knowledge-Based Design (KBD) concepts (OXMAN; GERO, 1987).

Those trends lead to the necessity of new contents being incorporated in a curricula structure that allows the link between geometric representation, algorithm structures, and code script

competencies. Those topics are usual on engineering courses and almost absent on the architectural and design side. Furthermore, there is a trend on the Architecture, Engineering, and Construction (AEC) sector to stay on the comfort zone of bidimensional and tridimensional representation with tools such as *AutoCAD* and *SketchUp*, considering at least the Brazilian context.

For the case studies reported in this chapter, it will be considered the concept of Tridimensional Parametric Modeling that is present in software like SolidWorks, Inventor, Solid Edge, among others. Those are tools linked to mechanical engineering design and represent current practice in the area.

PARAMETRIC TRIDIMENSIONAL MODELING

Almost all CAD software available nowadays has at least three kinds of geometric entities for tridimensional modeling. The first is the wire model that represents only vertices and edges; the second is the surface model that represents plans, and the third is the solid model. In most parametric tridimensional modeling tools, that model can be considered as the virtual counterpart of the real artifact. Those representations are capable of embodying physical properties of a specific material.

In that sense, the object-oriented characteristics of the tridimensional models expanded the traditional CAD representation to the design and fabrication processes. Those technical features indicate a fundamental role shift about those models. They can act now as an active element of the design process and not only a representation of it. The Tridimensional Model Applications described by Barr (2012) has exactly this function. This role added to CAD models on the parametric modeling is the basement for the second milestone represented in Figure 78.

Almost all parametric modelers like SolidWorks have a structure that encompasses three primary environments. The first is used to model a tridimensional representation of a unique component of an artifact. It is called Part environment. The second is the Assembly ambiance where the parts will be positioned relative to other pieces or previous assembled sets or sub-assemblies. The third environment is focused on the technical documentation of a project and allows the representation of a part or assembly bidimensional drawing. They are parametrically linked, so the modifications realized in any ambiance are automatically updated on the others (KUROWSKI, 2014).

Some authors argue that the modeling strategies are essential to permit efficient reuse and maintenance, linking the part to its manufacturing processes (FOGGIATTO; VOLPATO; BONTORIN, 2007). In that sense, there are some recommendations like modeling from a basic solid and add details further to permit rapid parametric modifications in features like holes, cuts, fillets, among others.

The primary sequence tasks to model a tridimensional part is to draw a closed profile and then apply some tridimensional modeling tool. Also, on a first overview of the software incorporated resources, one can identify a considerable amount of tools ranging from basic tridimensional operations like extrusion and revolution to more complex modules that allows the performance

analysis of a select part or assembly. However, in this chapter, the emphasis is on basic modeling tasks that are the base for performance evaluation and the fabrication of the component in another moment of the design process. Although this approach, it is important to stress that those evaluation tools like static loads simulations, temperature behavior, and computer fluid dynamics, among others, can act as powerful tools that have the potential to allow the experimentations of a large number of design alternatives in a reduced time lapse. This fact allows those systems to act as the possible translation of concepts like simultaneous engineering, integrated product model, product lifetime management, among others.

CASE STUDIES

Here are presented the experiments and equipment's that were modeled by student's teams. There were three equipment's from the UFJF Engineering School Technological Museum and one from the Fabrication Lab. The choice of those artifacts had no specific criteria except the fact that they were readily available and had a lower to medium complexity geometry and number of parts.

The students came from the primary cycle on a Mechanical Engineering course. On a survey, it was identified that almost 80% came from traditional second-grade classes and 18% had a technical formation with some experience on CAD tools.

One of the first tasks that the students must undertake in the project is to analyze the entire equipment and identifies which are the unique parts. This approach allows for a better understanding of the machine and opens the possibility to an equipment contextualization that leads to some knowledge of manufacturing processes. That characteristic can act as an extra stimulus. The primary sequence of modeling task is to identify the part, take measurements with a caliper rule and draw a freehand sketch to record the dimensions and begun to have a more in-depth understanding of it. The project is conducted by teams although there is the possibility to do it individually. Table 2 presents rendered images of the tridimensional model and a brief description of each equipment.

Compass: Equipment from UFJF Engineering School Technological Museum. Bounding box: Number of parts: 13.	

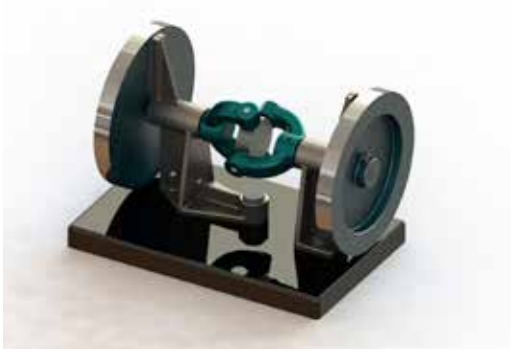
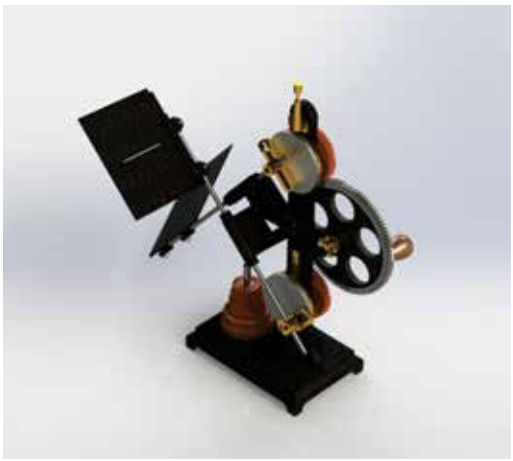
Policut Machine: Equipment from UFJF Engineering School the Fabrication Lab. Bounding box: Number of parts: 22.	
Universal Joint: Equipment from UFJF Engineering School Technological Museum. Bounding box: Number of parts: 14.	
Lisajous Machine: Equipment from UFJF Engineering School Technological Museum. Bounding box: Number of parts: 42.	

Table 2. Equipment's modeled.
Source: Author.

From the selected equipment's it was under carried an analysis that aimed to identify the most used modeling resources used and the main steps in the process. The method used for this task was analyzing the resources tree on the software interface. Figure 3 shows the interface for the universal joint part, and Figure 4 presents the resource tree fragment for this part.

The SolidWorks main interface is composed of three main parts. The modeling area that shows an isometric view, in this case, the 2D and 3D tools ribbons at the top and the resources tree in the left of the drawing area. Many subparts provide a lot of other tools like dimension and mass properties analyses, material properties table, among others.

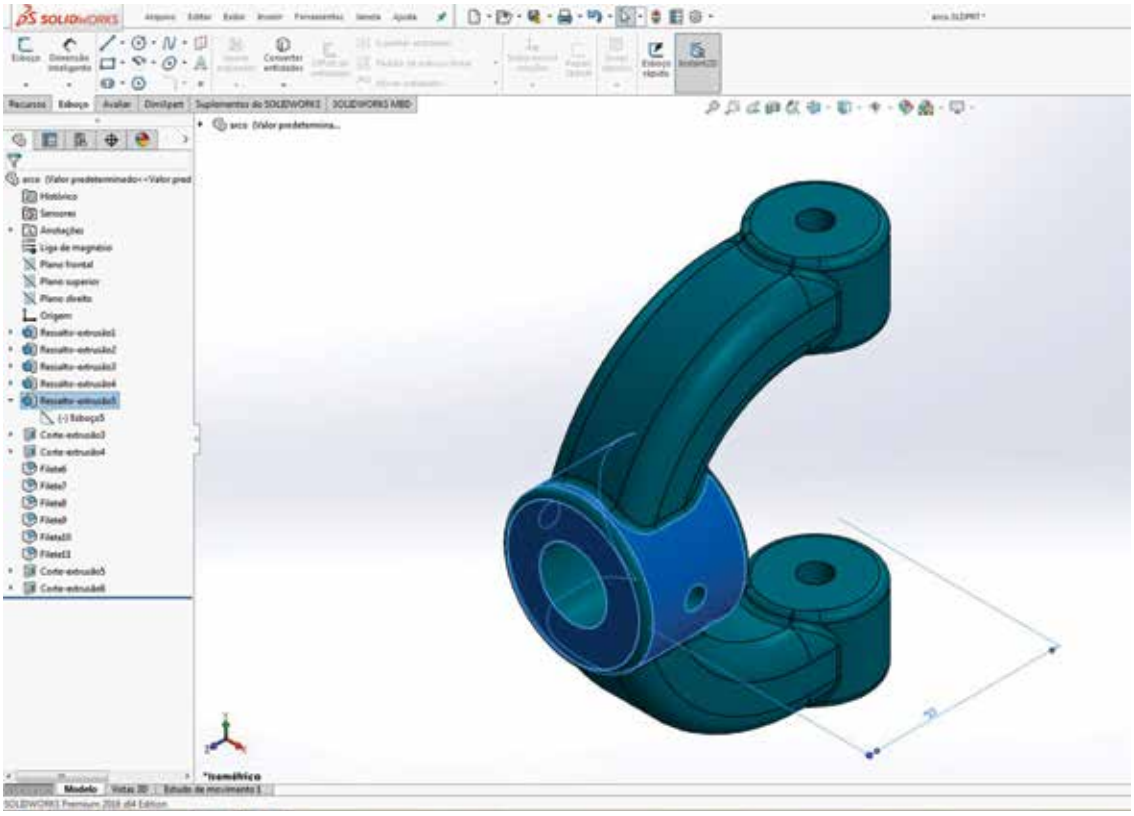


Figure 79 - Part interface.
Source: Author

The resource tree exemplified on Figure 80 has every step of the modeling process recorded. One can track the levels for a single part from the initial sketch to the complete piece with refinement resources added like holes and fillets. The software parametric functions allow the part edition and update at any moment.

Those characteristics allowed the modeling survey and analysis for the entire equipment's.

Figure 4 presents the resource tree fragment for the part shown in Figure 79.

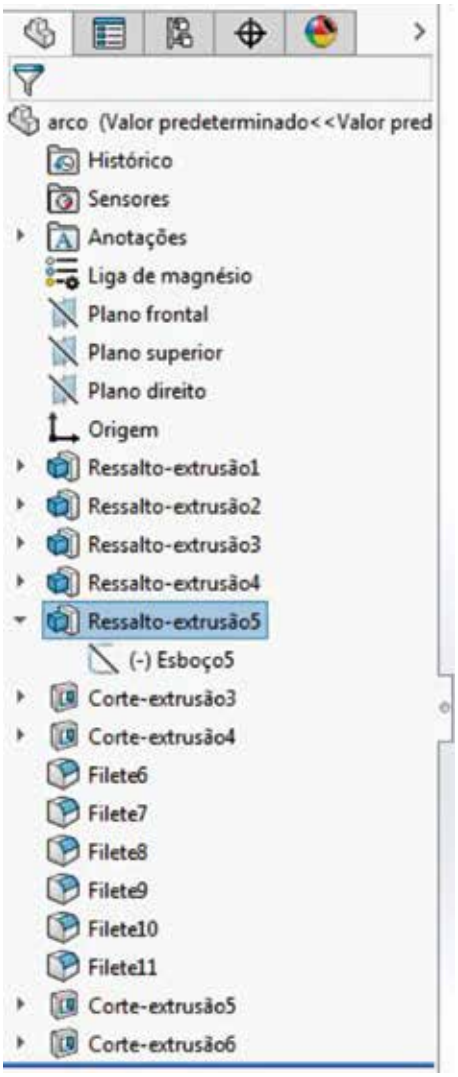


Figure 80 - Resource tree.
Source: Author.

Beyond that, the modeling resources were categorized into two main groups. They are Modeling Resources and Support Resources. For the specific equipment's analyzed there were identified about 11 items for the modeling process and five support means. The total resources available in the modeler are much higher than those presented here.

The Support Resources are characterized by means that aided specific modeling tasks; such is the auxiliary plans, linear and circular patterns, among others.

Table 3 quantifies the number of resources used for each equipment. Also, it is possible to verify the number of times a resource was used in the artifact. For example, the extrusion cut was the most used modeling tool in the Lisajous Machine.

Resource	Compass	Policut	Universal Joint	Lisajous Machine	TOTAL
Modeling Resources					
Revolution	5	0	6	33	44
Extrusion	32	57	43	91	223
Extrusion Cut	21	58	56	123	258
Revolution Cut	4	3	0	0	7
Shell	0	2	0	1	3
Loft	1	6	0	0	7
Domes	1	1	0	0	2
Sweep	0	2	0	0	2
Sweep Cut	0	2	5	0	7
Fillet	13	26	37	30	106
Chamfer	0	4	5	0	9
TOTAL MODELING RESOURCES	**77**	**161**	**152**	**278**	**668**
Support Resources					
Linear Pattern	0	3	0	0	3
Circular Pattern	2	0	0	0	2
Plan	0	15	0	0	15
Mirror	0	3	0	0	3
Helix	8	2	5	0	15
TOTAL SUPPORT RESOURCES	**10**	**23**	**5**	**0**	**38**

Table 3. Total resources used.
Source: Author.

The numbers showed in table 3 can be better visualized in Figure 81 and Figure 82 graphics. It helps to better identification of modeling strategies used by students. One that draws the attention was the Extrusion Cut. From that observation, it was verified for a specific part on the Lisajous Machine a significant mistake on modeling a gear. The team used the Extrusion Cut for each gear tooth instead of using the circular pattern resource. It demanded a much more extensive modeling time. This was important to adjust the time those contents are introduced in the discipline.

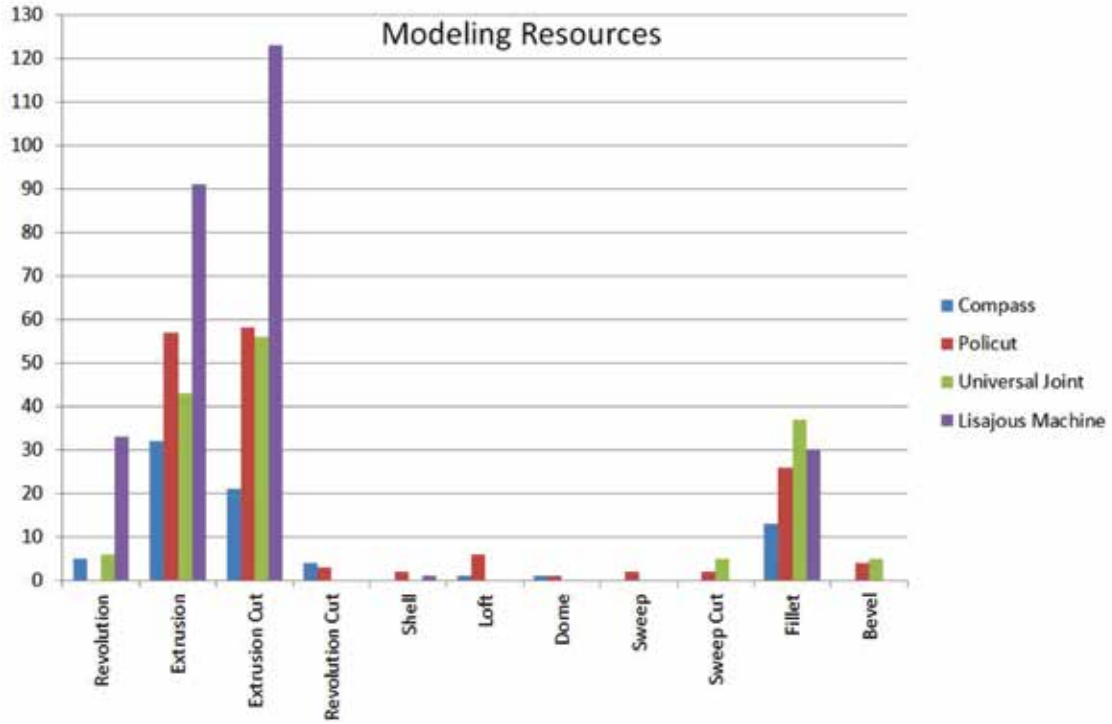


Figure 81 - Modeling Resources usage.
Source: Author.

The most frequent modeling operation was extrusion with more than 75% of the modeling operations followed by the revolution in less than 25% of the total transactions.

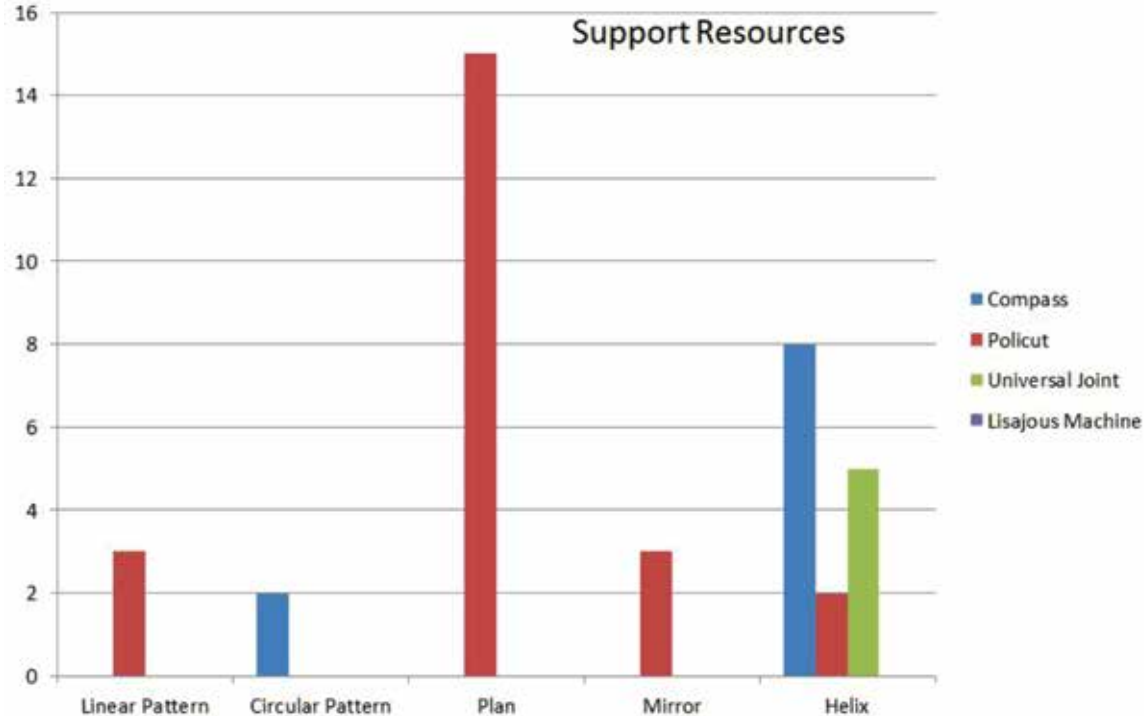


Figure 82 - Support Resources usage.
Source: Author.

From this survey, it was possible to identify the process adopted by the student's teams. Considering that are more than one way to model a part, it was possible to determine when the teams were more efficient or not. There is the fact that most of the modeling resources selected by the students are a direct result of the way the contents are presented in the classroom. Therefore, it is possible to enhance the teaching and learning process with more emphasis on topics that were neglected.

CONCLUSIONS

This chapter discussed some issues that involved the EDG teaching and learning process considering an extreme digital evolution scenario that impacts the way products are designed. It is necessary more deep investigations on the processes, but the studies show that is possible to address the challenge of reduced class-hours within this scenery. One strong argument to support those considerations is the method used. The students are stimulated to search the modeling tools that will aid the task of modeling an equipment part instead of being trained in each software resource without an application context.

Beyond that, one can observe that when the students face the challenge of modeling entire real equipment that is tangible and can be touched, measured and analyzed in person, there is much more stimulus for the task compared to work from books and printed material. Moreover, there is space for connect the EDG contents to other engineering and technological knowledge; such is materials science and mechanical elements.

On the other hand, there are some issues that must be addressed. They are related to the fact that the team work has the potential to benefit the student that don't interact and contribute to the final result. This must be treated more accurately, but one way to work around is to stimulate the teams to use some design management concepts.

From the curricula structure perspective, it is observed the need of more deeply transformations. These, for instance, can be in the direction of change the traditional technical drawing contents, removing the analogical drafting excessive hours by foundation concepts in free hand drawing, modeling tools, design management, among others.

Finally, the method used has the potential to bond EDG concepts and specific tools to the more current engineering design practices.

CHAPTER 06

CMS ENVIRONMENT FOR BUILDING MAINTENANCE MANAGEMENT

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CMS ENVIRONMENT FOR BUILDING MAINTENANCE MANAGEMENT

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ABSTRACT

The various transformations that have been taking place in today's productive world have demanded from company's greater productive efficiency and higher quality of their process and product, as a way to remain competitive and present in their market. However, in the Architecture, Engineering and Construction (AEC) industry, companies still find it difficult to manage their project processes more efficiently. The project process involves the participation of different specialists with different skills and knowledge, often from different companies, who meet for a certain period of time with the goal of creating a unique product or service. The lack of integration and even communication among those involved in a given project has been reported in the literature as one of the main causes of project failure. In this context, Design For X (DFX) emerges as a systematic product development integration application, including manufacturing and maintenance, designed to integrate the development of all elements in a product's life cycle from the outset. This enables the organization of all building and relevant maintenance information. The objective of this work is to organize project information to give feedback to designers about the maintainability of the proposed solutions. Thus, the application of a logical model for the management of maintenance information is presented. Conceptually, the model makes use of Web Orientation technologies using Content Management Systems (CMS) and identification tags (RFID). This combination enables easy, fast, decentralized and hierarchical access to information through mobile connection technologies such as laptops, smartphones and tablets, supporting building maintenance teams. In addition, it allows designers to confirm the fulfillment of a user's maintenance needs. One contribution of this work is the continuity of research in the field of intelligent tagging, Web Orientation, information traceability and retrieval as a way to assist as project feedback.

INTRODUCTION

The Maintenance topic has grown in importance today. This is because, over time, materials and buildings need maintenance in order to continue to meet the initially established performance conditions. Although maintenance is only performed at the building usage stage, it is important that information be collected throughout the entire project process. Maintenance personnel can, for example, provide information on the best access to installed equipment (LOVELAND; PARADIS, 2013). Not considering maintenance from the start of a design project has been responsible for a number of problems as will be seen later.

This demands a culture change. Lavikka *et al.* (2016) still points out that, in general, stakeholders in a project are mainly interested in delivering it on time and within the budget. They are not necessarily interested in understanding customer needs, whether they are owners, end users, or maintenance personnel. Thus, despite the increasing importance of maintenance, many companies still regard maintenance factors as of less significance (ARIS, 2006).

In order to support the integration of the various project needs in its initial phase, Design For X (DFX) can be used as a systematic product development integration application designed to integrate all elements in a product's life cycle from the outset. This enables the organization of all building and relevant maintenance information.

In addition, the publication of Performance Standard NBR 15575 (ABNT, 2013) in Brazil emphasizes the need for proper building maintenance and record keeping. This Standard even emphasizes the user's responsibility in performing such maintenance.

On the other hand, the complexity of new buildings with the addition of innovations, as well as new technologies, increases the amount of related information. This leads to the search for information technology resources in order to help handle a greater amount of data. There are software options available in the market in the scope of maintenance. However, high software cost, associated with software complexity, makes it difficult to apply it to small companies and even for building maintenance management purposes.

The objective of this work is to organize project information for to provide feedback to the designers about the maintenance of the proposed solutions. Thus, a logical model for the management of maintenance information is discussed. Conceptually, the model makes use of Web Orientation technologies using Content Management Systems (CMS) and Radio-Frequency Identification (RFID) tags. This combination enables easy, fast, decentralized and hierarchical access to information through mobile connection technologies such as laptops, smartphones and tablets, supporting designers in the project feedback

DESIGN FOR MAINTENANCE & MAINTENANCE PROJECT

A civil construction project, by its very nature, is dynamic, and its main characteristic is its life cycle, which is identified by a start date and an end date and a set of highly interdependent intermediate intervals. Cintra (2005) describes these macro-intervals as product planning, project development, construction, usage and recycling stages. While most of these stages may be considered of relative short duration, the long-term usage stage is where the building operation and maintenance activities are performed. This is the costliest stage in a building's life cycle, but also the one that benefits the most from structured information since it accumulates building information from its conception (NIST, 2006).

A building's project process pervades all stages. For Fabrício (2002),

> The project process involves all the decisions and preparations to subsidize the creation and production of a development, from the preparation of real estate operations to the creation of a needs and product design program to the development of production, the "as built" design and the assessment of users' satisfaction with the product (FABRÍCIO, 2002, p. 75).

Thus, a project process is broader than the product specialty design. It involves the participation of different specialists with different skills and knowledge, often from different companies, who meet for a certain period of time with the goal of creating a unique product or service. It involves all decision makers in a venture, from design to usage, not just architectural and engineering designers. Nevertheless, the lack of integration and even communication among those involved in a given project has been reported in the literature as one of the main causes of project failure.

In addition, poor consideration of the maintenance aspects at the beginning of this process can also lead to a number of problems such as: poor design functionality, poor constructive quality, poor building performance in terms of layout, choice of equipment, etc. (SANCHES; FABRÍCIO, 2008). In another paper, Melo Filho *et al.* (2012), present a survey with a small company in Recife (PE) that conducted the maintenance of plumbing systems on a construction site. The authors found that access to the main water tank downpipe installation in the building was achieved through a poorly illuminated 40-cm high span, which made it difficult to carry out the maintenance activities. For Gnipper (2010), this is a frequent situation, especially in old vertical buildings where water distribution systems under elevated tanks have a clearance of only 0.50m or 0.60m, which makes access for maintenance services difficult.

But this picture is beginning to change. For authors such as Antunes & Calmon (2005) and Melo Filho *et al*. (2012), maintenance should be considered at the beginning of the building design where the necessary procedures are established for its conservation and recovery.

This position is in line with a more current view of project development, the so-called Concurrent Engineering (CS), which provides for the early integration of production and operation needs since the design stage of a building (FABRÍCIO, 2002). CS is a concept originated from

the manufacturing industry (Concurrent Engineering), which considers that the various design progression-related activities should be, whenever possible, integrated and performed in parallel rather than sequentially (NAVEIRO; O'GRADY, 1997).

A key concept within CS is Design for X (Design for Excellence) which consists of techniques aimed at reducing the cost of a product throughout its life cycle. According to Huang (1996), the "DF" in DFX refers to "Design for...", and the "X" refers to the various phases in Concurrent Engineering, for example: DFM (Design For Manufacturing), DFA (Design For Assembly) (Design for Quality), DFS (Design for Service), DFD (Design for Disassembly), etc.

In this context, Sanches & Fabrício (2008) propose a tool which is directly associated to the maintenance, use and operation of buildings, which they named Design for Maintenance:

> [...] a series of positions to be taken in different stages of a project which provide support and guidelines for the Maintenance Project. Based on this, documents and manuals which were made easier by the high degree of maintainability achieved can be released and followed in the usage stage (SANCHES; FABRÍCIO, 2008, s/p).

According to NBR 15575, the term maintainability can be defined as:

> The degree to which a system, element or component can be easily maintained or refitted to a state in which it can perform its required functions, under specified conditions of use, when maintenance is performed based on certain conditions, procedures and prescribed means (ABNT, 2013, s/p).

Figure 83 shows the relationship between both concepts: Design for Maintenance and Maintenance Project. While the former focuses on a Design stage, the latter is concerned with the Usage stage, and should contain information regarding procedures and periodicity of the maintenance services.

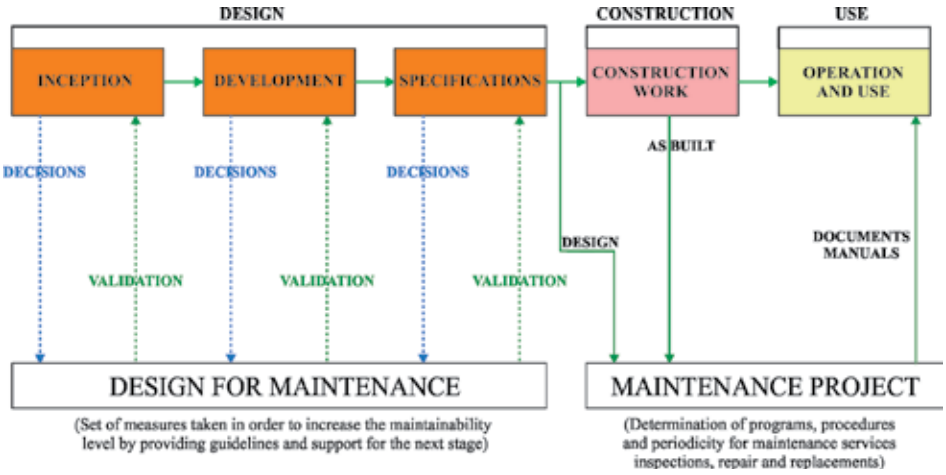

Figure 83 - Design for Maintenance & Maintenance Project.
Source: Sanches & Fabrício (2008).

MAINTENANCE MANAGEMENT

Materials and buildings deteriorate over time. This is why planning and performing proper maintenance is required. The maintenance of buildings consists of accomplishing tasks for the maintenance, restoration and improvement of all parts, subsystems, services and surroundings of a building in order to sustain its usefulness and value (EL-HARAM; HORNER, 2002).

Similarly, Kim *et al.* (2004), state that the performance evaluation of a building is necessary to decrease the demands for reconstruction or renovation, as well as to ensure a long service life for buildings. The later maintenance begins, the higher its cost and the more impaired the performance of the building will be.

Standards are established in order to regulate maintenance activities. At the international level, Gonçalves (2014) presents the main Portuguese and European references defining maintenance rules, requirements and procedures. These include EN 15331 - Critérios para a concepção, gestão e controle de serviços de manutenção para edifícios and NP 4483 – Guia para a implementação do sistema de gestão da manutenção.

Similarly, Brazil has Standards NBR 5674 - Manutenção de edificações – Requisitos para o sistema de gestão da manutenção (ABNT, 2012) and NBR 14037 - Manual de operação, uso e manutenção das edificações – Conteúdo e recomendações para elaboração e apresentação (ABNT, 2011).

NBR 5674 (2012) establishes the need to prepare a maintenance program that includes in its documentation a Use, Operation and Maintenance Manual for Buildings according to NBR 14037.

A maintenance program for buildings, according to NBR 5674,

> [...] consists of determining the essential maintenance activities, their periodicity, personnel responsible for its performance, regulatory reference documents and necessary resources, all referring individually to the systems and, when applicable, to the elements, components and equipment (ABNT, 2012, p.4)

Also according to this Standard, a maintenance program should contain a series of documents to guide the performance of maintenance activities as well as the records of all interventions that had to be carried out (Table 4).

DOCUMENTS
Use, Operation and Maintenance Manual for Buildings according to ABNT NBR 14037
Equipment Supplier and Service Provider Manual
Maintenance Program
Maintenance Planning, containing Planned and Actual Completed Work
Signed contracts
Catalogs, construction specifications, designs, drawings, procedures for maintenance services and technical proposals
Documents included in NBR 14037, Appendix A, including the qualification of the person in charge and revalidated proof of qualification
Technical Service Assignment Documents
RECORDS
Inspection report
Maintenance service records
Minutes of maintenance-related meetings

Table 4. Maintenance Program.

Source: Adapted from NBR 5674 (2012).

While these documents help guide maintenance activities, the records help provide feedback to designers regarding users' maintenance needs. The Use, Operation and Maintenance Manual, according to NBR 14037, must be supplied by the entrepreneur, whether as a developer or the constructor. It is a document that helps clarify user concerns regarding the actual conditions of appropriation of the built environment, gathering the necessary information to guide the operation, use and maintenance activities in a building. Hippert & Mattos Jr (2015) propose an itemization for this document in order to include the requirements provided in the Brazilian Maintenance (NBR 5674 and NBR 14037) and Performance (NBR 15575) of Buildings Standards.

NBR 15575 establishes requirements and performance criteria applicable to residential buildings as a whole or to their compounding systems. These requirements relate to safety, inhabitability and sustainability and include maintainability-related requirements. The latter, in general, refer to the need to provide easy access conditions for inspections and analysis of the Use, Operation and Maintenance Manual (HIPPERT; LONGO, 2017). Difficult access for facility maintenance is pointed out by the literature.

NBR 5674 also considers that maintenance system management should be guided by a set of guidelines establishing relevant information, and other kinds of information, and the communication flow. Structuring a maintenance management system requires organizing the maintenance information so that it can be retrieved for use.

By relating the necessary maintenance information to the interventionists throughout the design process, we can conclude that it is incumbent upon:

- Designers: to specify the materials, provide the drawings, specifications, designs and, upon completion of the construction, the as-built;
- Suppliers: to provide catalogs, material manuals, equipment, as well as to indicate maintenance actions regarding the supplied materials, components and equipment;
- Developer/Constructor: to provide the Use, Operation and Maintenance Manual for the building;
- Constructor: to provide information regarding all acquisitions such as manufacturer/ supplier data and associated warranty periods. In addition, the constructor should also provide the construction/installation dates of the elements, components and equipment used;
- Owner/superintendent: to record all inspections and maintenance actions in order to provide evidence of the interventions.

INFORMATION TECHNOLOGY

Throughout the design process of a building a great deal of information is produced making up a series of documents which, upon completion of the work, must be delivered to the owners and building managers. These latter are in charge of locating, organizing, accessing and keeping this information (MCGREGOR; THEN, 2003).

However, the increased complexity of the buildings has increased the amount of documentation that is produced. On the other hand, the need to obtain reliable and accurate information to deal with operational issues leads to the need to integrate this information (MCGREGOR; THEN, 2003).

In this context, the aid of information technology is needed, along with the information systems that will be used in the building maintenance management. Such management is part of a larger context called facility management (FM). For Alexander (2003), FM guarantees a better functioning of the building through a set of related systems and processes. It can be understood as the management of people, spaces, work processes and investments included in an organizational environment. In the field of building maintenance, its purpose is to establish administrative and operational guidelines to ensure a perfect functioning of the building (FERREIRA, 2005). According to Ma & Liu (2010), Facility Management has a significant impact on building performance.

Information Systems that can be used for FM are Computer-Aided Facility Management – CAFM, Computerized Maintenance Management Systems – CMMS, Computer-Aided Design – CAD, Integrated Workplace Management System – IWMS, Enterprise Resource Planning – ERP, and Enterprise Asset Management – EAM. However, these systems have a higher cost, especially for smaller worksite managers or even residential buildings, which leads to the search for open-source technologies in order to rationalize the implementation and system maintenance cost for management.

The open source concept arises from the ideal of free distribution, with the possibility of using and/or modifying its parts as long as the original author is credited (KATZ, 2011). According to Iwasaki (2008), open source culture is based on open code that can be run, copied, distributed, modified and improved by all users.

According to Avital (2011), the condition of freely distributing any product must go through three basic spheres: visualization, which concerns sharing; modification, considering the sharing of results and improvements made to the design; and use, which refers to sharing of the created property.

RFID AND NFC

RFID stands for Radio-Frequency Identification. It is a term used to describe a system that transmits information via radio waves. The RFID system consists basically of two hardware components, a transceiver (called the reader) connected to an antenna and a set of transponders or tags, where information is stored (MARTINS, 2011). The goal is to get the reader to read the information stored in the tag and send it to a computer (Figure 84)

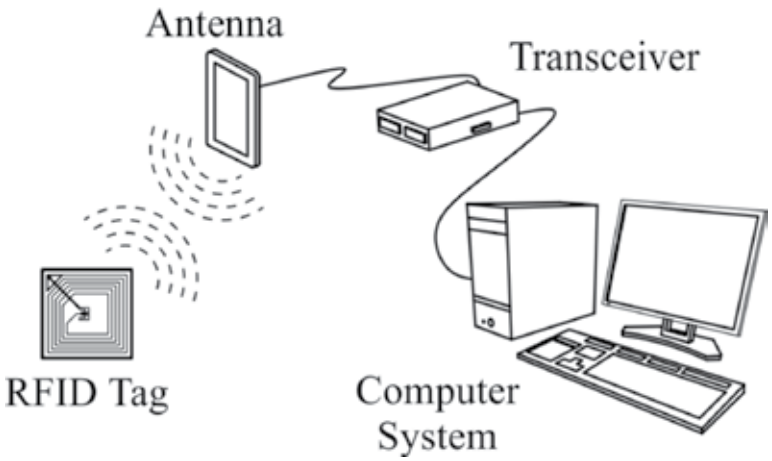

Figure 84 - RFID System.
Source: Authors.

Its operation starts with the reader sending a signal to a tag, which is activated and reflects back the signal or transmits its own signal. The signal is transmitted through a radiofrequency wave to which the tag is tuned to receive this wavelength and return the stored information, also by radiofrequency. The reader receives this information and sends it to a computer where some software must be capable of interpreting the received data.

Each tag has an identification that characterizes. RFID tags can take on the most varied formats. In addition, they may have different technical specifications, depending on the type of power supply they use to send the waves, and are therefore called passive or active tags (LI; BECERIK-

GERBER, 2011). The former harness the energy generated by the reader while the latter have their own internal battery to send waves.

The RFID system can operate in different frequency bands, which influences its characteristics, such as speed, maximum reading distance and materials. There are four frequency bands in which RFID operates: Low Frequency (LF), High Frequency (HF), Ultra High Frequency (UHF) and Microwave (MARTINS, L., 2011).

Near Field Communication (NFC) is a technology that allows transferring data in short-distance wireless communication by approximation. NFC is standardized by ISO 18092 / ECMA 340 (NFCIP-1), which specifies the interface and the wire communication protocol among coupled devices (ISO, 2013). According to this protocol (NFCIP-1), NFC has a radiofrequency operating interface working at 13.56 MHz and distances of up to 10 cm. In this configuration, NFC reads HF RFID tags.

Like RFID, NFC consists of three basic elements: a reader, an antenna, and a tag. Also according to the relevant protocol, system operation can take place actively, where both devices involved in the communication generate electromagnetic waves to carry data, and the passive communication mode, where one of the devices generates waves while the other uses the modulation that was received to retransmit data.

APPLICATION OF RFID IN CONSTRUCTION

RFID is one of the most promising wireless systems (CALIS *et al*., 2011). As a result of its ability to identify and track objects, RFID is being used in several applications: aviation, construction and facility management, logistics or security, etc.

Some examples of RFID application in construction are shown below. RFID Journal Brasil (2013) presents an RFID application for traceability of materials throughout the life cycle of a building. In 2007, the Hong Kong Housing Authority, an agency that implements public housing projects in the region, started a pilot program to examine the effectiveness of incorporating passive RFID tags into precast concrete façades used in their residential buildings. Then the agency went on to require all its suppliers to attach an RFID tag on each precast concrete façade, each door, aluminum/wooden window and metal security gate.

In another application, Martins (2011) proposes the use of RFID tags to assist in building maintenance. These tags will be placed on the maintainable elements and will contain all the necessary information to maintain it. The person in charge of maintenance can read the information contained in the tag by using an RFID reader (which has the ability to change the information contained in the tag). Tags must have rewritable memory in order to enter information on the actions that were performed. One of the advantages in this system is the possibility to standardize all the maintenance action information. One of the difficulties in this system is the investment that is necessary for its operationalization (software and reader acquisition).

In another application, Moreira (2017) developed an information model that used identification tags (RFID) and Web Orientation technologies using Content Management Systems (CMS). This combination enables easy, fast, decentralized and hierarchical access to information through mobile connection technologies such as laptops, smartphones and tablets. Moreover, the author used open-source technology, in order to reduce the costs of the implementation and the maintenance of the system. The proposed model allows a large range of applications. In this paper, Moreira (2017) presented three situations, as examples of the application of the model by a construction company: work safety, hydraulic and electric installations.

INFORMATION MODEL AND BUILDING MAINTENANCE

This paper deals with an adaptation of the model proposed by Moreira (2017) for maintenance issues. As previously described, maintenance information should be organized throughout the stages of the building design process so that it can be retrieved later in order to support the building maintenance actions, and afterwards the evaluation of the proposed solutions.

The following prerequisites were considered in order to adapt a model:

- Compliance with Brazilian Building Maintenance Standards (NBR 5674 and NBR 14037) regarding documents and records
- Compliance with Brazilian Performance Standard (NBR15575) regarding systems and their maintenance requirements.

Elements and components that require maintenance-related monitoring must have a remote RFID tag for system operation. Such tag can refer to each element and component or to a particular building environment. In this case, a tag could be installed at the entrance of that environment, in a standardized place.

RFID tags require recording their unique identification and link (weblink) that routes them to the server's CMS system. In addition, they must operate in a High Frequency (HF) of 13.56 MHz so that they can be read by a mobile device containing an NFC standard reading system (a smartphone, for example) (Figure 85).

The identification number that is read will reference an element in a CMS system database which should contain all the initially registered information and allow the recording of new information from the maintenance activities that were performed.

The centrally-built model enables decentralized and quick access to the information provided in the created environment. The logical structure to use the Content Management Software (CMS) environment takes the open source culture into account and makes use of mobile connection technologies such as laptops, smartphones and tablets. These technologies enable real-time data collection through Web orientation, i.e., access via intranet/internet links.

In order to implement the system, registration of the design and maintenance information in the CMS is initially required. Thus, for structural, floor, vertical wall, roofing and water/sewage systems (according to NBR 15575), the compounding elements, such as floor, wall, ceiling, doors, windows, bathroom fixtures, toilets/sinks, etc. must be determined and their characteristics such as supplier, guarantee, maintenance methods, among others, must be associated.

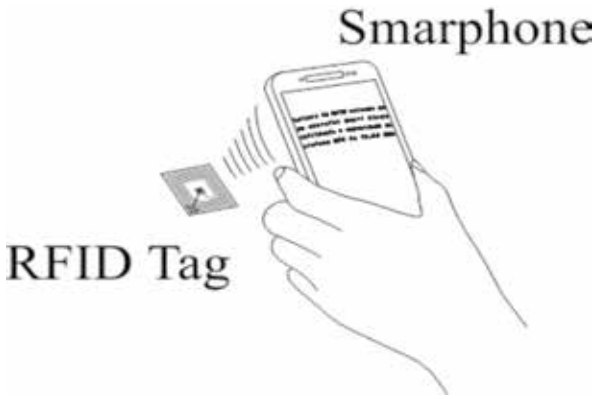

Figure 85 - Smartphone with an NFC Standard Reading System.
Source: Authors.

It is proposed that the system be initially modeled by the construction company since it is responsible for the delivery of the Use, Occupation and Maintenance Manual to the first owners of a building. Because the superintendent is responsible for managing the maintenance of the common areas, the superintendent must receive the initial model and proceed with system operation.

The company must have a technician who is responsible for the organization and treatment of materials and contents applicable to the CMS. This professional should also be responsible for preparing and filtering the technical materials that will be made available to the system, organizing the query contents for each level of access and for each configured smart tag. In addition, this professional is also responsible for recording smart tags.

SYSTEM OPERATION

After modeling the system and having registered the initial information, the system can be operated. To this end, the following resources are needed:

- Dedicated computer with Wi-Fi access;
- Mobile device for data verification and collection such as a tablet and/or a smartphone, containing an NFC reading system.
- HD RFID tags.

Access to the system is organized into two levels: administrator or manager and users. The former has access to all system information and is responsible for maintaining the system. In the case of a residential building, the manager is the superintendent or contractor, responsible for maintaining the common areas of a building. The system will, for example, make available the entire maintenance program that should be applied to the building in compliance with the existing regulations. For the required maintenance activities, work orders may be issued by the maintenance operators.

Users themselves can be the maintenance operators or designers. The former are those professionals or companies that will implement the work orders, i.e., they will perform the maintenance services. The designers are the professionals of a company that, in a post-work analysis, could have access to the database in order to confirm the maintainability of the design solutions that were adopted.

This way, the system will be made available to the manager with a previously registered access control. Maintenance managers and operators can be added to the extent they are needed to meet a change in the superintendent position and/or maintenance companies or personnel. System designers, i.e., structural, floor, vertical wall, roofing and water systems, will have already been determined by the construction company and may not be changed. Their access will only be allowed for querying the database.

The maintenance operator, when approaching the RFID tag with a mobile device containing the company dedicated software or any NFC standard reading software, chooses the type of information they want to receive and then do the reading. Through the (already modeled) CMS, which controls access levels, the system forwards the request to the database which returns the requested data, displaying it on the device itself.

The case of a façade maintenance is given as an example. The manager issues a work order regarding the maintenance of this building element. The maintenance operator, who is responsible for performing the work, receives this work order, checks the maintenance information required to do this job and heads for the stipulated location. With the mobile device, the operator then approaches the RFID tag, has the tag read, and gains access to all the information about that element. The operator can open the work order and perform the job, and once it is done, the operator can enter the information in the system. This information awaits validation by the manager so that it can be entered in the building maintenance database. Once validated, this information is now part of the intervention history.

Thus, all information related to the maintenance activities, such as operator, date, problems, etc. are recorded. This would allow designers, for example, to have access to the database and check the maintainability of the proposed solutions as a result of the demands. In addition, the system would meet a regulatory requirement that requests the registration of all maintenance actions.

FINAL CONSIDERATIONS

The increase in maintenance activities has been pointed out in the literature as a worldwide trend. In order to contribute to the accomplishment of these activities, maintenance must be

considered from the beginning of a building's design process. This is why it is necessary to better organize the design information so as to contribute to a more adequate building maintenance management as well as to feedback designers on the maintainability of the proposed solution.

This work contributes to the discussion of this topic by proposing a logical model for maintenance information management. The model, which is based on open source technologies, makes use of Web orientation technology, Content Management System (CMS) and identification tags (RFID) allowing easy and fast access to information by supporting maintenance teams in performing their activities. In addition, because it uses database, the information that is collected and filed can be used to build an activity history, thereby enabling the tracking and retrieval of the required maintenance information. Therefore, this work may also contribute to design feedback by allowing the analysis of the maintainability of the proposed solutions.

The development of a practical application for the model is seen as a continuity to this work. Furthermore, this model may also be integrated in the Building Information Modeling (BIM) platform. Designers would then develop their design projects using objects containing maintenance information as proposed by Mota (2017), which would further contribute to the maintenance activities.

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CHAPTER 07

CITYMETRICS: A (PARA)METRIC SYSTEM FOR ANALYSIS AND OPTIMIZATION OF URBAN CONFIGURATIONS

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CITYMETRICS: A (PARA)METRIC SYSTEM FOR ANALYSIS AND OPTIMIZATION OF URBAN CONFIGURATIONS

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ABSTRACT

This paper describes and evaluates the implementation of CityMetrics: a computational system that articulates performance evaluation metrics and algorithmic-parametric resources, in order to analyze and optimize the degree of efficiency and the possibilities of operation of geometric and algebraic configurations of urban areas. In this context, this article uses computational resources and algorithmic tools specifically designed to assess the performance of urban areas, from the perspective of objectively measurable principles of Transit Oriented Development (TOD), an urban development model aimed at more autonomous and sustainable cities. More specifically, this research aims at verifying how TOD's measurable, geometric and algebraic (and therefore programmable) attributes can be implemented through a computational model that uses optimization methods to support decision making in urban design processes. Thus, CityMetrics is intended to provide support to decision making in urban design tasks related to the organization of neighborhoods and cities, as well as to contribute to the improvement of analysis and proposition possibilities in urbanistic contexts.

INTRODUCTION

The scope of this paper refers to a context of intersection between computational resources - more specifically those that concern algorithmic-parametric logic - and the implementation of measurable attributes (or metrics) related to the performance of urban configurations, in order to contribute to the development of analysis and optimization methods that support decision making in urban design tasks.

In this context, Transit Oriented Development (TOD) is an urban development model that became one of the key planning paradigms aimed at creating compact, walkable, mixed-use communities centered on high-quality transport systems. As long as TOD makes possible the creation of vibrant livable communities without depending on an automobile for mobility, it is being

increasingly promoted in several cities of the world as a sustainable policy (CALTHORPE, 1993. VALE, 2015). Nevertheless, although there is no universally accepted definition of TOD, it is often described in a physical manner: an area of compact mixed-use buildings served by a multi-modal mobility network within walkable distance (VALE, 2015. SUZUKI *et al.*, 2013). In this logic, basic urban needs are easily accessible without demanding automobiles or spending large amounts of time in commuting, with the intention of supporting more autonomous and sustainable neighborhoods.

TOD advocates some few main features to an urban area: proximity to transport stations and a functional relationship with them, as well as compact, mixed-use neighborhoods that encourage walking, cycling, and the use of public transit by residents, employees, shoppers and visitors. In other words, it should encourage the use of public transportation by creating neighborhoods with compact urbanization, diversity in land use and urban design geared to the pedestrian – where one can walk to the stations and other amenities. Therefore, the primary principles of TOD consist of: (a) transit accessibility - locating amenities, employment, retail shops and housing around transit hubs; (b) walkability - the ability that a particular neighborhood has to connect housing and amenities points through distances that can be traveled on foot; (c) diversity - providing a mix of uses, densities and housing types in the same district, and; (d) density for mass transit - encouraging infill and redevelopment within existing neighborhoods, allowing the system to run efficiently (CERVERO; KOCKELMAN, 1997. DITTMAR; OHLAND, 2004).

Furthermore, TOD is a multivariable dependent urban development model, as long as it relies on geometric and measurable attributes (or metrics) for assessing its performance, and for planning more autonomous neighborhoods. Thus, it represents a kind of complex proposition, derived from some variables considered as crucial in achieving its objectives, what makes TOD a potential case for computational implementation (LIMA *et al.*, 2016).

In this context, this paper describes and evaluates the implementation of CityMetrics: a computational system for support in urban planning decision-making. This system is meant to calculate indexes that enables one to objectively assess and optimize urban configurations performance, according to principles derived from TOD. In this sense, CityMetrics seeks to analyze and improve urban configurations through the analysis of a set of TOD's measurable principles. More specifically, CityMetrics allows one to evaluate urban arrangements through physical metrics (*e.g.* distance), topological measures (*e.g.* connectivity, integration and depth) (HILLIER; HANSON, 1984.), and results of mathematical operations (e.g. algebraic, geometric) that can be configured as fitness functions in optimization processes, in order to achieve more efficient solutions for urban configurations within TOD scope.

Thus, this paper is structured in the following sequence: (a) a description and a presentation of CityMetrics, its strategies and the developed set of tools; (b) an implementation of the proposed system in two case studies, that deals with different approaches for improving a neighborhood within TOD principles; (c) a discussion about the obtained results, and; (d) an overall discussion and conclusions.

CITYMETRICS: STRATEGIES AND TOOLS

CityMetrics is a computational system that implements an algorithmic-parametric methodology (LIMA *et al*., 2017. LIMA, 2017), articulated through the following basic methodological strategies: (a) Visual Programming Language; (b) Generative Systems, and; (c) Optimization. Thus, conceptually, CityMetrics can be synthesized through the implementation of Generative Systems in Visual Programming Language, in order to use specifically developed (or adapted) algorithmic tools to articulate performance evaluation metrics and logic operations, providing indexes that can be used as fitness functions in optimization tasks. Figure 86 illustrates the articulation of the strategies that synthesizes CityMetrics' concept.

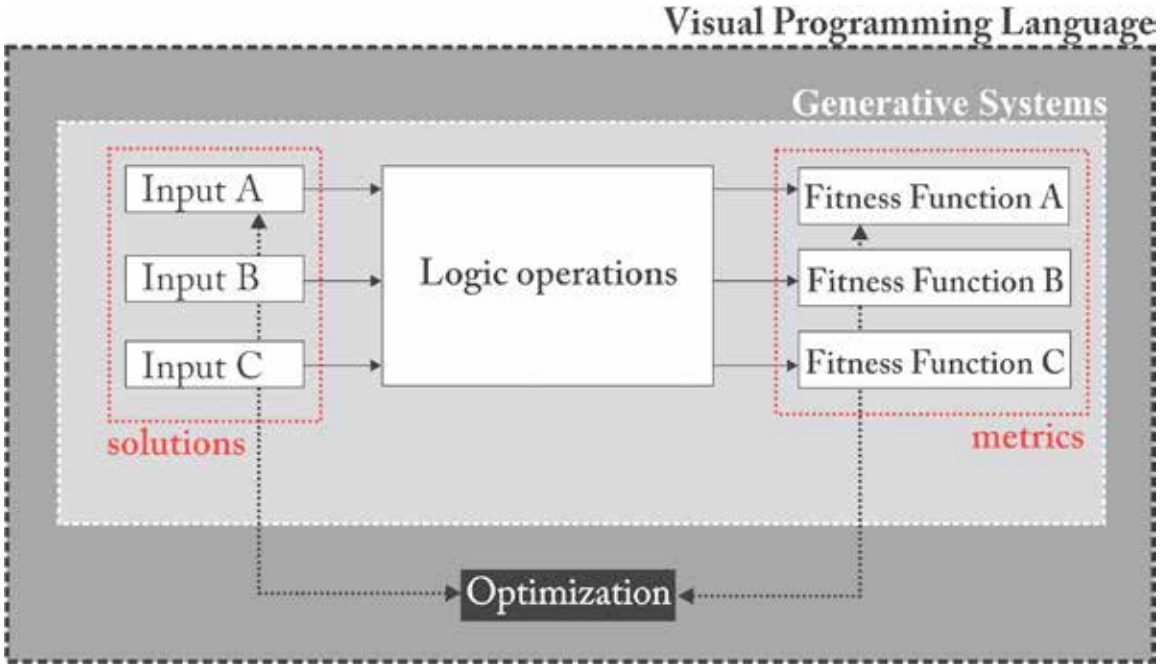

Figure 86. Diagram illustrating the concept of CityMetrics and the articulation of its fundamental strategies: The system uses computational resources to allow one to analyze and, therefore, optimize urban configurations performance, through indexes related to measurable TOD principles.

Source: Authors.

Therefore, CityMetrics is developed to measure and optimize urban configurations performance through metrics related to measurable principles, derived from Transit Oriented Development (TOD). In this sense, this system seeks to assist urban planners and developers on TOD oriented planning processes, as well as on urban planning tasks from contexts of a similar nature. More specifically, the core concept of CityMetrics is to use algorithmic tools to calculate urban metrics that can be used to analyze the performance of a given urban area, or can be set as fitness functions on optimization tasks. In this sense, the proposed system makes use of the following tools (LIMA *et al.*, 2017. LIMA, 2017): (i) Physical Proximity Calculator - measures the Physical Proximity Index (PPI), an indicator that calculates the smallest physical distances (considering slopes) between

the nearest target (station or amenity) and one (or all) origin(s) in a neighborhood; (ii) Topological Proximity Calculator – contemplates Space Syntax (HILLIER; HANSON, 1984) principles for calculating the smaller topological distances (number of steps) between a target (station or amenity) and one (or all) origin(s) in a neighborhood; (iii) Amenities Variety Calculator – performs the calculation of the average physical distances (considering slopes) between all targets (amenities) and one (or all) origin(s) in a neighborhood; (iv) Amenities Recurrence Calculator - calculates the ratio of the number of targets (amenities) and the total number of origins of an examined area; (v) Mixed-use Index (HOEK, 2008) calculator - computes the ratio between residential and non-residential areas in a location, in order to analyze its diversity; (vi) Spacematrix calculator – calculates Spacematrix density indicators (PONT; HAUPT, 2009) in order to support goals definitions and decision-making processes.

PHYSICAL PROXIMITY CALCULATOR (PPC)

Physical Proximity Calculator (PPC) is an algorithmic tool that measures the distance between a target (transport stations and/or amenities) and one (or all) locations(s) in a neighborhood (origins). In this regard, the proposed algorithm calculates the path(s) with smaller physical distance(s) between a target and one (or all) destination(s) in a district, considering slope(s) in the path(s). Thus, if a given plot (origin) is within 400m (5 min walk) from a target, it is assigned with a value of 1. The score decreases as the distance approaches 1.6km (20 min walk) and a 0 index is awarded for distances greater than 1.6 km.

PPC also makes possible to apply penalty factors (according to the acclivity) for estimating a score to classify the proximity to the station. For instance, in relation to a particular locality, if a station is 0.4 km away (5 min walk), then the maximum index (1) is assigned for this plot. If the station is a 1 km away from a plot, but with a 10% acclivity, then a 10% penalty is applied. It establishes a simple relationship to differentiate paths accordingly to their acclivity, but as long as it works on a parametric environment, it is possible to adopt other criteria for penalization. Figure 87 illustrates the calculation logic of PPC algorithm.

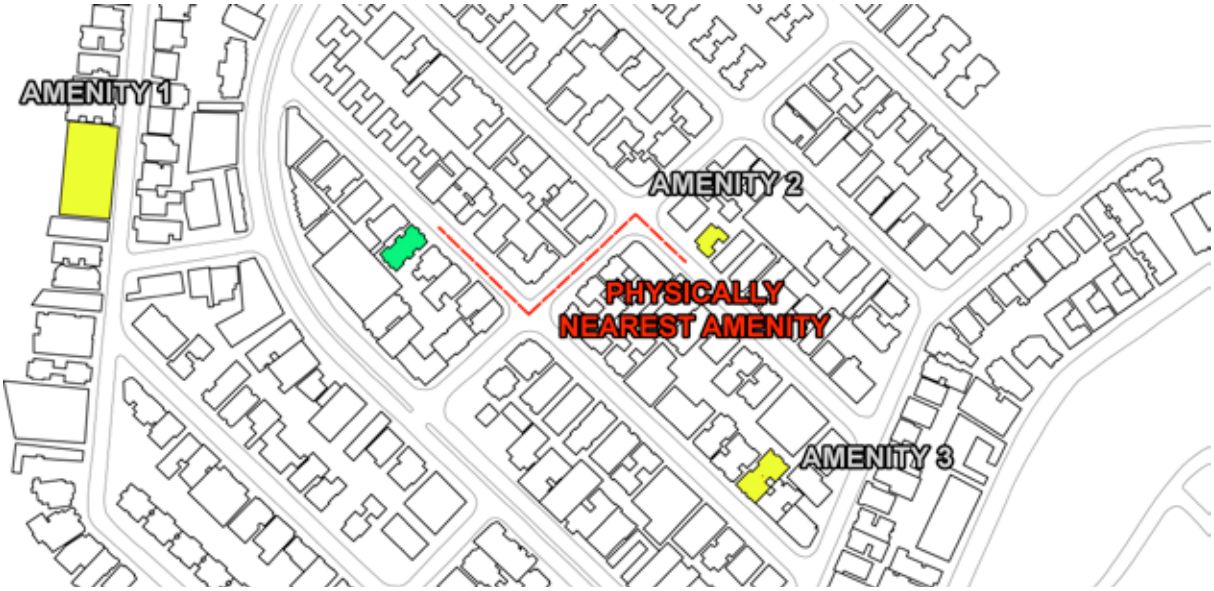

Figure 87 - PPC calculation logic. This tool calculates the shortest path (considering slopes) from a particular location (in green) to all amenities in a category (in yellow), identifying the nearest amenity to this location (considering physical proximity – distance in meters) and calculating an index based on its physical distance (in the above Figure, the amenity 2).
Source: Authors.

TOPOLOGICAL PROXIMITY CALCULATOR (TPC)

TPC is a tool that calculates proximity considering topological metrics, using concepts from Space Syntax theory (HILLIER; HANSON, 1984). This tool can be used in a complementary way to the tools that use the physical metrics. In this sense, the TPC aims to calculate: (a) the pathways with the smallest topological distances between origins and targets of a locality, and; (b) the integration/depth of the spaces of a given area. That is, this tool calculates the number of direction changes (topological steps) needed to reach one or more targets from a given origin, and also indicates which spaces are more integrated - which means identifying which streets are more accessible and, consequently, have greater relevance in the dynamics of an urban area. Figure 88 illustrates TPC calculations.

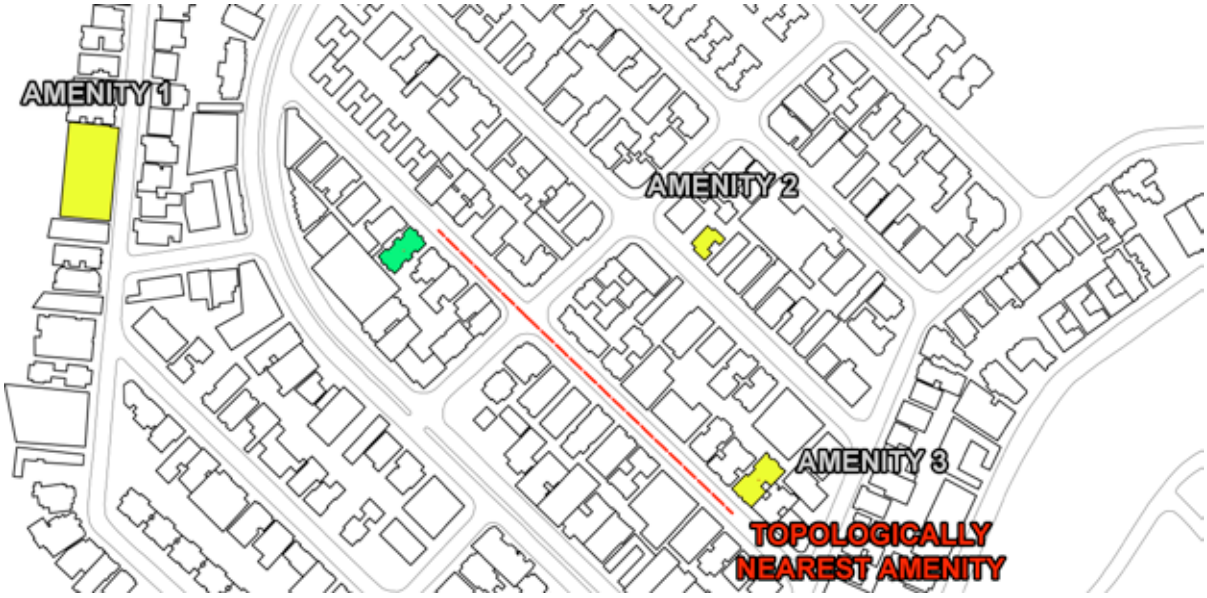

Figure 88 - TPC calculation logic. This tool calculates the shortest path (considering the number of changes of direction) from a particular location (in green) to all amenities in a category (in yellow), identifying the nearest amenity to this location (considering topological proximity) and calculating an index based on its topological distance (in the above Figure the amenity 3).

Source: Authors.

AMENITIES VARIETY CALCULATOR (AVC)

The AVC measures another important aspect for the evaluation of the walkability of a given location: the proximity between an origin and all the targets (amenities) within walkable reach. In this sense, this tool calculates the average distances between a given source and all the nearby targets in a given category of urban services. AVC algorithm works in a complementary way to PPC because, while the former considers only the distance to the nearest amenity, the AVC assigns an index considering the average physical distance between all the targets and the origin in question. Thus, while PPC measures the distance from the closest service to an origin, AVC considers the distances between the same source and all the targets reported in the same category, as shown in Figure 89. This index is important because it allows differentiating origins that have many close targets (greater diversity of services) from those that only have good proximity to a single target. To promote better walkability, it is also important to consider the diversity of the available services, and not just the proximity to a single target.

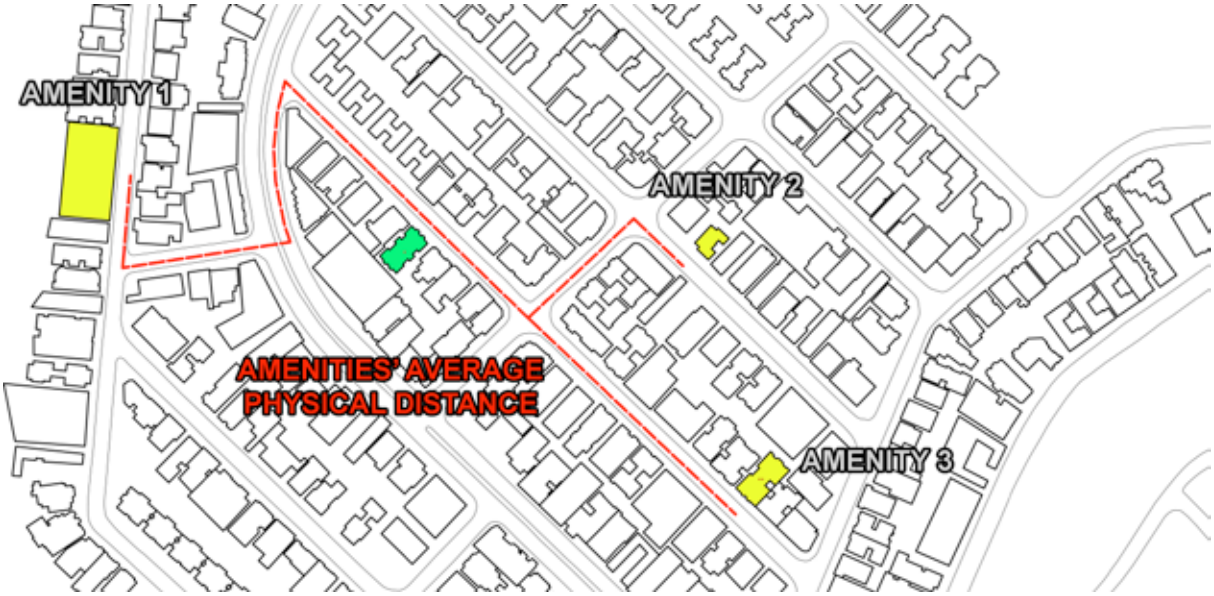

Figure 89 - The AVC calculation logic. This tool performs the calculation of the average physical distance from a particular location (in green) and all nearby amenities in a category (in yellow).
Source: Authors.

AMENITIES RECURRENCE CALCULATOR (ARC)

Amenities Recurrence Calculator (ARC) in another developed tool that aims to measure the walkability of a particular area, and works in a complementary way to PPC and AVC tools. While the formers calculate the lowest physical distance to the nearest target and the average physical distance to all targets, respectively, ARC has quantitative characteristics, as it calculates the proportion of the number of targets reported (in each category of services) and the total number of locations in a surveyed area.

This algorithm, which basic operation consists in counting targets within a radius of 20 minutes of walking and dividing this value by the number of lots in the same area, is important for analyzing the supply of services in each neighborhood, an aspect equally important to measure the capacity that a given locality has to connect dwellings and various urban services by distances that can be traveled on foot, as shown in Figure 90.

Figure 90 - ARC calculation logic. This tool calculates a ratio between the number of amenities in each category (in magenta) and the total number of locations (in green) in a given area.
Source: Authors.

MIXED-USE INDEX CALCULATOR (MXIC)

The Mixed-use index calculator (MXIC) aims to measure the diversity of a neighborhood. For this, MXIC incorporates the mixed-use index (MXI) concept (VAN DEN HOEK, 2008) that calculates the proportion between the sum of all the residential and non-residential areas of a locality, making a comparison of these proportions. The closer the ratio between areas is 50/50, the greater the diversity an urban area has. This algorithm has great importance in the context of CityMetrics, because it allows one to assess the diversity of a certain area before and after potential interventions. In some approaches, the MXI index may even be configured as one of the fitness functions of an optimization task, in the search for areas with greater diversity. Figure 91 shows the MXIC calculation base, and Table 5 presents its references.

Figure 91 - The MXIC calculation logic. This tool calculates the ratio between all residential areas (in green) and all non-residential areas (in magenta), seeking to assess the diversity of a given neighborhood, according to Hoek, 2008.
Source: Authors.

MXI value	0	50	100
Meaning	No house present	50/50 balance	100% residential use
District Type	Single use	Mixed-use	Single use
Examples	Office Park Factory Complex	City Center Semi Central	Newtown Suburbia

Table 5. Reference values for MXI.
Source: Adapted from Hoek, 2008.

SPACEMATRIX CALCULATOR (SPC)

The Spacematrix calculator algorithm implements codes for calculating density attributes from studied areas, informing three fundamental indicators proposed by Pont & Haupt (2009): Intensity - Floor Space Index (FSI); Coverage - Ground Space Index (GSI) and Network Density (N). Thus, once the required inputs are informed (contours of the analyzed area and its buildings, number of buildings floors, and design of the streets) the algorithm informs the FSI, GSI and N of an analyzed area. This tool has great importance in the context of CityMetrics, since it allows calculating and visualizing information about the density of urban areas in real time, allowing a dynamic evaluation of urban contexts studied and the proposed interventions / modifications. Figure 92 illustrates the elements that this algorithm uses.

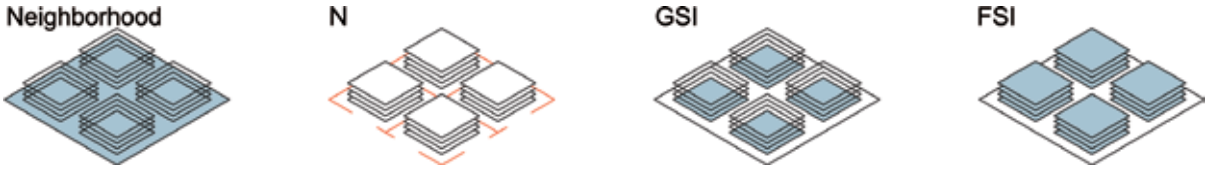

Figure 92 - Spacematrix inputs for calculation: total area of aggregation – in this case, a neighborhood; network of streets; occupation area and the total area of floors.

Source: Adapted from Pont & Haupt (2009).

EXPERIMENTS

This section comprises the description of CityMetrics' application in two different experiments for the same neighborhood: the existing district of Cascatinha, in the city of Juiz de Fora, Brazil (see Figure 93). The main goal of these experiments is to evaluate CityMetrics' potential to be used in a variety of contexts, situations and approaches. Despite of being a predominantly residential neighborhood, the chosen district has a great potential to be a more autonomous and sustainable urban area, presenting some features that make it an ideal sample for evaluation of the proposed system, such as: (a) a suitable extension for TOD implementation (approx. 1 km diameter); (b) relatively low density; (c) no transport station; (d) topographical complexity; (e) available areas for new buildings; (f) vicinity to important amenities such as a park, a hospital, a university, and a shopping center, among others; (g) closeness to the city center, and; (h) a good placement in the urban network, linking directly the city center to important city regions. This is a key scenario for assessing CityMetrics towards more efficient TOD oriented planning, because besides demonstrating typical issues of the sprawling city paradigm, a situation found in several cities around the world, it also presents some important features for evaluating the system implementation.

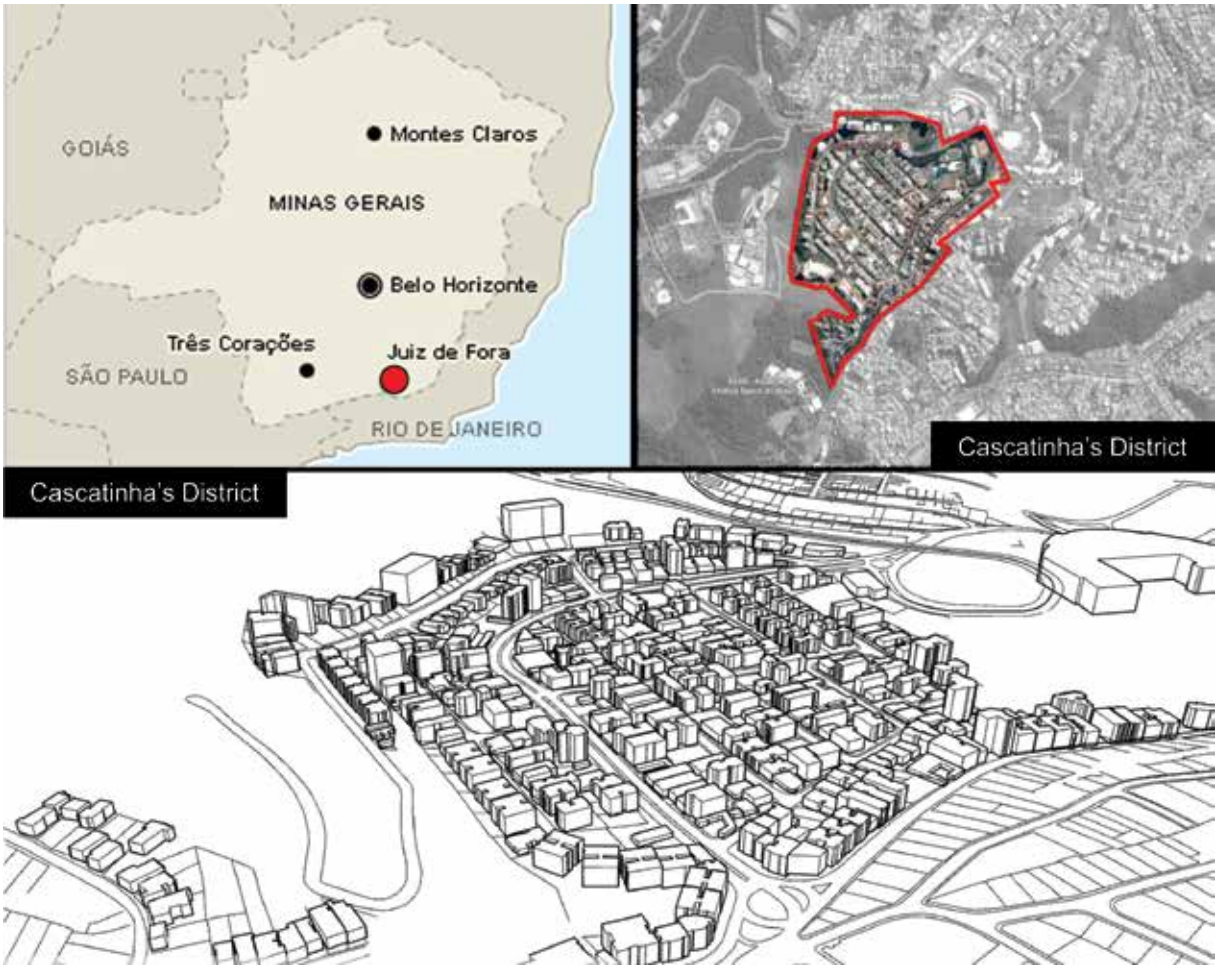

Figure 93 - The geographical location and a 3D model of the case study´s neighborhood. Source: Lima et. al., 2017.
Source: Author.

Within this framework, we create a Rhinoceros/Grasshopper parametric model of the selected neighborhood, to manage geometric and measurable features related to TOD principles. In that sense, the following information was obtained and transferred to the analysis model: (a) the footprints, number of levels, uses (residential and non-residential) and topographical positioning of each building inside the district, in order to measure distances, slopes, possible connecting paths, diversity and density indicators; (b) the location of each one of the amenities on the neighborhood, according to the aforementioned considered categories, in order to measure proximity, diversity and variety of amenities; (c) the identification of available areas for new buildings (vacant lots and non-consolidated places), seeking to provide room for new constructions and to modify the diversity of the district; the topographical network of neighborhood´s streets, with the view to consider slopes and distances for measuring PPC, AVC and ARC operations, and; (d) the design of blocks and lots, in order to provide density (Spacematrix) assessment.

Octopus, a Grasshopper plug-in for applying evolutionary principles to problem solving, was used to search for many goals at once, producing a set of optimized trade-off solutions between the

extremes of each goal. Thenceforth, CityMetrics tools used district data, emulated by mathematic entities, as input for simulation and optimization operations, aiming to increase transit accessibility, walkability and diversity related indexes, by the following workflows, described in sequence:

EXPERIMENT 1

Experiment 1 can be descripted by the following steps: (i) the search for the best location for inserting a transport station - as long as the district does not have one, using only Physical Proximity (PPC); (ii) the search for the best location for inserting only a single new amenity for each category, aiming to increase indexes related to walkability and considering only physical metrics - Physical Proximity (PPC), Amenities Variety (AVC), and Amenities Recurrence (ARC); (iii) the evaluation of different scenarios for vacant lots occupation, automatically calculating Mixed-use index for a more balanced distribution between residential and non-residential areas, and; (iv) the assessment of Spacematrix indicators, in order to evaluate different occupation strategies for available land and to help analyze the impacts of the proposed solutions within TOD scope. Figure 94 illustrates the approach workflow adopted in this experiment.

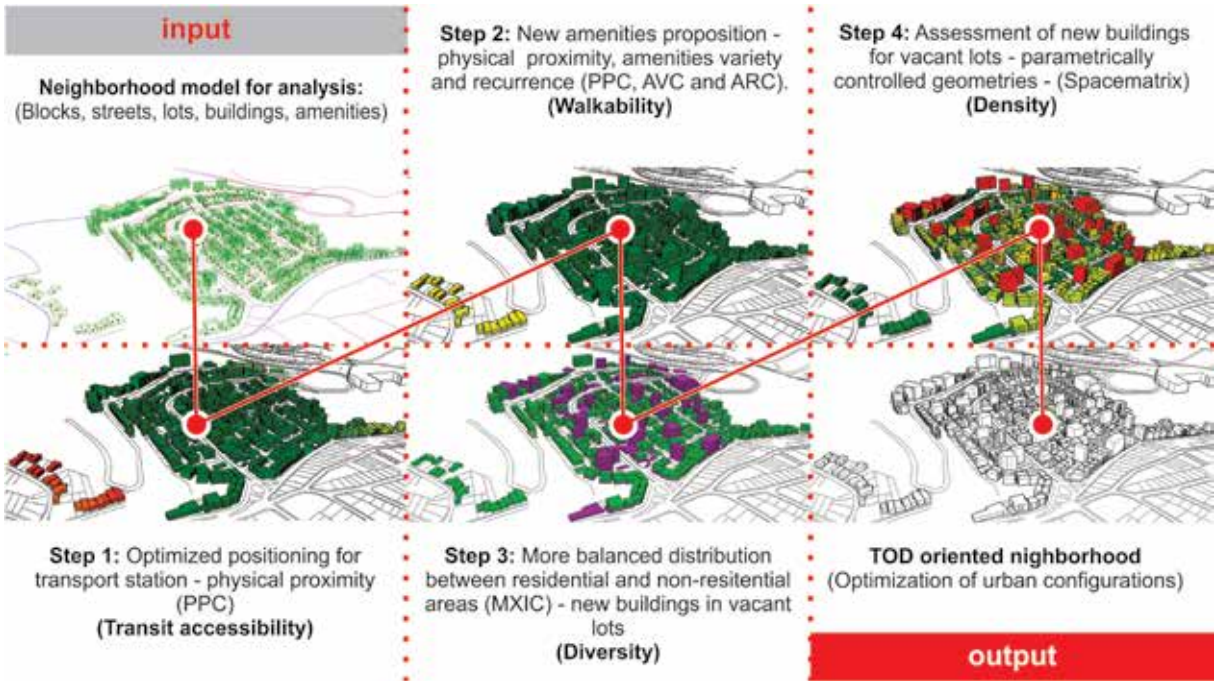

Figure 94 - Approach workflow adopted in experiment 1.
Source: Author.

EXPERIMENT 2

Experiment 2 can be synthesized by the following steps: (i) the evaluation of different scenarios for vacant lots occupation, automatically calculating Mixed-use index for a more

balanced distribution between residential and non-residential areas; (ii) a parametric assessment of Spacematrix indicators, in order to identify density limitations or potentialities within TOD scope. In this experiment, Topological Proximity Calculator (TPC) was used to measure the integration of each one of the available lots, allowing to indicate higher occupations for places with greater integration; (iii) the search for the best location for inserting a transport station, using both physical and topological metrics and considering the total constructed area of each lot. Thus, it was sought to prioritize the station´s proximity to places with higher potential to house (living or working) more people, and; (iv) the search for the best location for inserting a new amenity for each category, aiming to increase indexes related to walkability - Physical Proximity (PPC), Amenities Variety (AVC), Amenities Recurrence (ARC) and Topological Proximity (TPC) - with only a single new amenity for category. Figure 95 illustrates the approach workflow adopted in this experiment.

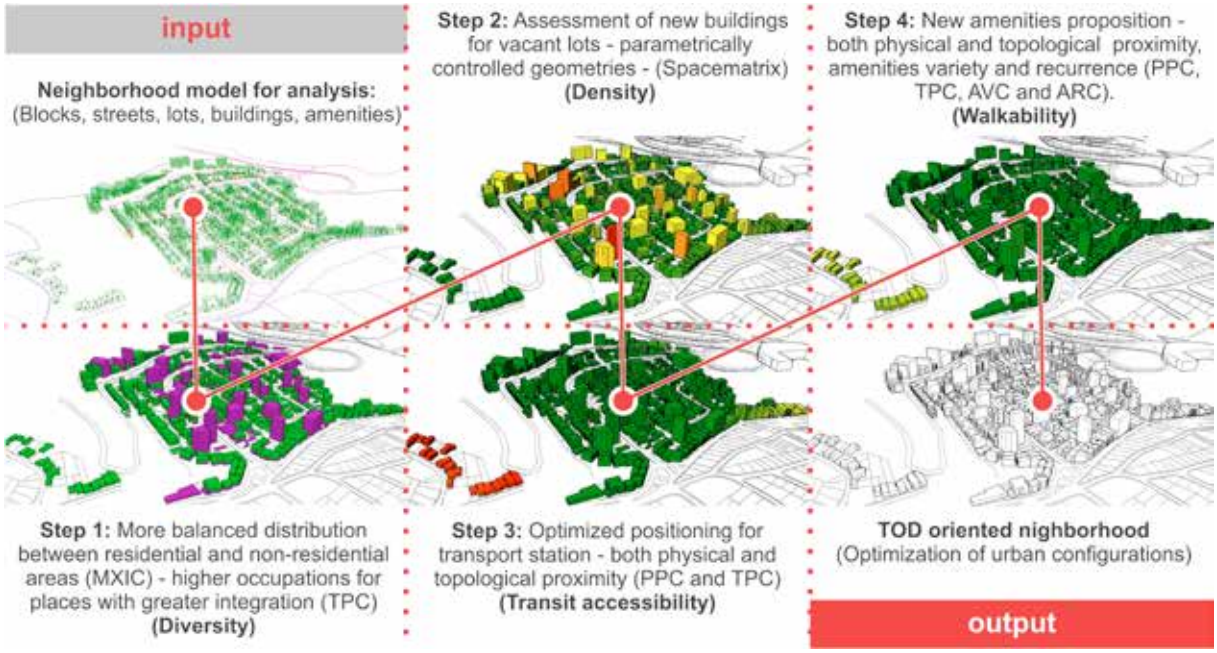

Figure 95 - Approach workflow adopted in experiment 2.
Source: Author.

RESULTS ANALYSIS

Experiments 1 and 2 consist of the implementation of CityMetrics in two different approaches in the same existing urban area. The difference between them, is that while the experiment 1 considered only physical metrics (PPC, AVC and ARC), in the experiment 2, both physical and topological metrics were used (PPC, TPC, AVC and ARC) for analysis and optimization of urban configurations. This modification allowed some rearrangements in the methodological structure of the experiment 2, which also considered weighted average calculations to obtain its solutions.

Therefore, the implementation of CityMetrics through different approaches indicated different changes (or solutions) to the arrangement of the neighborhood, both suggesting a better performance from the scope of TOD principles. In summary, the new settings provided: (a) an excellent Transit Accessibility, since the optimized insertion of a transport station permitted high average Station Proximity scores in both experiments; (b) a greater walkability for the district, in both approaches, as long as the optimized addition of new amenities provided an increase of the neighborhoods Physical Proximity, Amenities Variety, Amenities Recurrence and Topological Proximity indexes in all analyzed categories; (c) a neighborhood with more diversity, since the proposition of new buildings and their functions provided a more balanced Mixed-use index, seeking a greater equilibrium between residential and non-residential places, and; (d) a more suitable density for a Transit Oriented Neighborhood, since parametrically controlled urban geometries made possible to regulate density, in a manner that supports more people (working or living) closer to transport hubs. Proximity and diversity indexes increased after optimization tasks, suggesting that amenities became closer and more balanced within the new district´s arrangements.

In this context, in the experiment 1, we can observe the following characteristics: (a) a parametric regulation of buildings for vacant lots occurred in a direct and uniform relation - all proposed buildings had the same number of floors, despite of their diverse characteristics; (b) the solutions obtained were based specifically on aspects related to physical metrics, such as PPC, AVC and ARC for the positioning of the station and the new services, and; (c) the fitness functions adopted referred to the simple averages of the indexes of all the lands, which does not allow to consider different weights for plots according to their features.

In the experiment 2, the following aspects can be highlighted: (a) the introduction of the TPC algorithm allowed to calculate the integration of each available plot, which meant establishing different heights for the proposed buildings, so that greater occupation was proposed in areas of greater pedestrian recurrence; (b) we sought solutions that established trade-offs between physical and topological metrics, which allowed us to consider more indexes and different criteria for positioning the station and the new services - PPC, AVC, ARC and TPC, and; (c) the objective functions adopted referred to the weighted averages of the indices of all the lands, which allowed to consider different weights for lots, according to their total constructed area - prioritizing the positioning of the station (or services) in areas with potential to house (residing or working) more people.

Thus, the comparison between the results obtained in experiments 1 and 2 provides the following data: (a) the experiment 1 presents Physical Proximity indexes for the station and services equal or slightly better than the experiment 2, however; (b) experiment 2 presents a configuration that also includes aspects related to topological metrics, which is reflected in better Topological Proximity indexes (the lower the index, the less the distance) than experiment 1, with similar PPC and AVC rates. In addition, the experiment 2 use of the weighted average of the indices implied in solutions more directed to the areas with greater occupation and integration. Figure 96 illustrates comparisons between the results obtained in experiments 1 and 2.

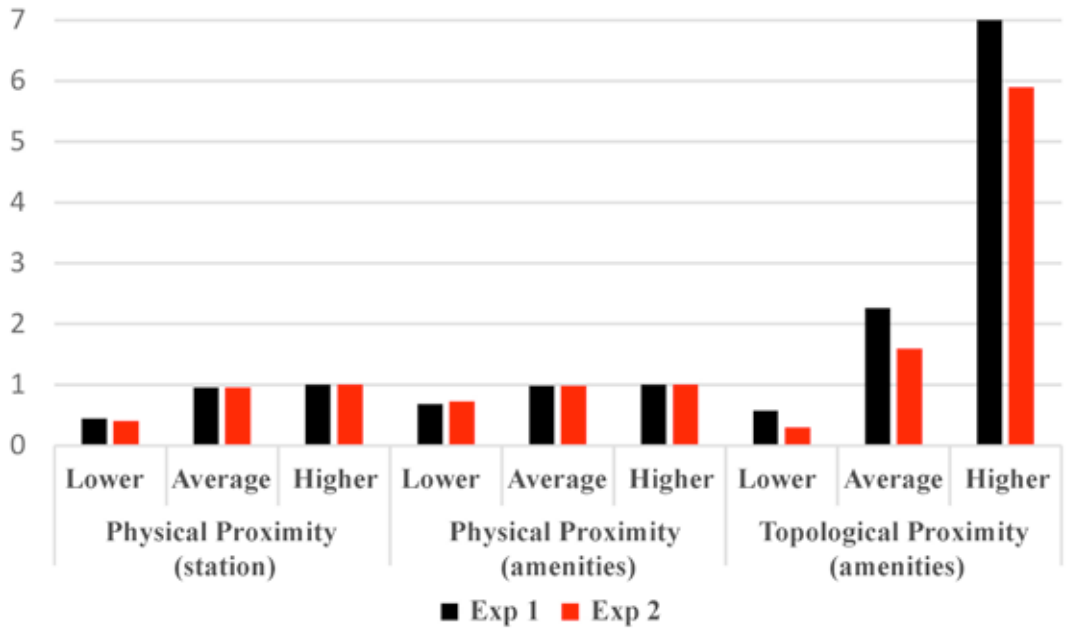

Figure 96 - Graph showing the comparison of results between experiment 1 (in black) and experiment 2 (in red). High Physical Proximity indexes related to transit accessibility and walkability in both situations. Significantly better (lower) Topological Proximity indexes in experiment 2.

Source: Author.

DISCUSSION AND CONCLUSIONS

The implementation of CityMetrics indexes as fitness functions on computational systems, has allowed the production of a huge variety of potential solutions, some more, some less suitable. The placement of different amenities, the simulation of different occupation scenarios for vacant lots, as well as the regulation of increasing density according to the distance to the station, provided many combinations and arrangement possibilities. Considering that this range of potential solutions allows the enlargement of analysis, discussion and intervention possibilities, contributing to more efficient urban practices, this approach relies on a logic of interaction and feedback, aiming at supporting an efficient design process that allows greater dialogue between the different actors of the process.

In this sense, it is vital to think about the employment of a flexible digital environment, capable of responding to changes throughout its implementation. In this context, CityMetrics proved to be helpful in order to provide dynamic assessment and optimization of principles derived from TOD. The positioning of the station, in both approaches was supported by optimization tasks that allowed to identify, among hundreds of options, the solution that provided the lowest average distance between the station and all other lots. Density indicators play an important role in this system, as long as they enable the visualization and evaluation of different scenarios for vacant areas occupation, guiding interventions and giving hints from building potential and mix of uses distribution. The Mixed-use index and Spacematrix indicators proved to be useful in the algorithmic

implementation of this approach, given that they consider objective features for measuring diversity and density, respectively.

Despite the usefulness of a computational tool for supporting TOD oriented urban planning processes through evaluation and optimization of specific urban features, we identify some limitations in the presented methodology. We recognize that CityMetrics does not fully incorporate the diverse features that can influence the measurable principles of an urban area, and for this reason, we emphasize that it is meant to be used as an instrument of recommendation. In addition, considering that CityMetrics essentially relies on a computational implementation of objectively measurable attributes as performance measurement metrics, it can be stated that the proposed system has the potential to support urban projects of other natures and purposes (and that extrapolate the scope of TOD) by adapting or including other measurable attributes for performance analysis and optimization.

CHAPTER 08

CONSTRAINTS BASED GENERATIVE SYSTEM AND PARAMETRIC TOOLS AS SUPPORT ON THE ARCHITECTURAL DESIGN PROCESS

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CONSTRAINTS BASED GENERATIVE SYSTEM AND PARAMETRIC TOOLS AS SUPPORT ON THE ARCHITECTURAL DESIGN PROCESS

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ABSTRACT

This chapter explores the use of digital tool, specifically parameterization and generative systems, as support methods on the decision making process in architecture. The object of study were design algorithms developed focusing on design constraints. At this research, a practical approach was adopted, through the development, application and analysis of algorithms in three distinct levels of design: architectural detail, architecture and urban occupation. With emphasis on fire safety regulation and on Juiz de Fora/MG city's building code, the studies showed that it is possible to create digital tools aiming the automation of the repetitive tasks related to legal constraints. Besides from architectural objects and details, it was also possible, to use the models for simulating urban occupation. Thereby, it was noted the potential on the use of digital tool as support on the space analysis and creation, pointing that constraints based parameterization tools and generative systems could lead to better and more efficient processes since design solutions can be developed and tested seemingly on real time.

INTRODUCTION

This chapter explores the use of digital tools as support on decision making throughout design process. It addresses the potential use of parameterization and generative systems on the

automation of legal constraints on architectural objects. Most of the studies presented here were developed within a Master's Degree course on Built Environment at Federal University of Juiz de Fora. More information on each study is available through their specific publications (SANCHES, 2017; SANCHES *et al.*, 2017).

Focusing on automation of legal constraints through algorithms, the content discussed here addresses three different levels of design complexity. At the first level, it focuses on architectural details, with the development of three-dimensional representations of elements required by fire safety regulations. At the second level, it addresses regional building codes of the city of Juiz de Fora / MG, aiming on parameters with significant impact on the architectural form. At this point, focusing on buildings, the 3D objects are generated based on urban standards for building height, floor area, and total area allowed. Finally, at the third level, the algorithm focuses on urban environments producing possible scenarios of occupation for city regions.

For a better understanding, this chapter can be divided in five sections. Initially it explores the theoretical basis for the studies, focusing on the impacts of the computer on the design process, from a passive design tool to the active role it exercises with BIM, parameterization and generative design systems. The following three sections present the algorithms for the different levels of design complexity (architectonic detail, building and urban environment), presenting the development as well as the results obtained for each one of them. Finally, the last section, presents a discussion of the whole process seeking to establish a critical analysis of the digital design tools for either production and analysis of architectural and urban spaces.

MATERIALS AND RESEARCH METHODS

Based on a Systematic Literature Review (SLR), it was possible to identify main reference works and authors, as well as most common research methods and results on generative design systems studies. With the review, carried out in the Periódicos CAPES and CumInCAD databases, it was possible to identify a tendency for applied experimental studies mainly through development and use of design algorithms followed by the process analysis. It was also found that although generative systems are a recurring theme in architecture, even in analog forms, as shape grammars, the studies on them have increased with digital supports, usually exploring different software, such as *Grasshopper/Rhinoceros*, *AutoCAD*, *3DsMax*, *Ecotect* and GIS. (SANCHES *et al.*, 2018)

In agreement with the SLR results, the research presented here can be characterized as a qualitative experimental and explanatory study. For this type of study, Prodanov & Freitas (2013), indicate the direct designation of an object of study, a way of observation and a control situation. The objects of study, in this case, were design algorithms specifically design constraints based architectural forms generation. It was set as a way of observation, the development and application of the algorithms in hypothetical sites and products, backed up by real design possibilities. Lastly, the numerical and visual validation of the 3D objects created by the algorithms were used as control

situation. Based on those standards, a practical approach was carried out through the development, application and analysis of design algorithms, for three different levels of complexity.

Almeida (2008) sets that coding an algorithm starts with the problem's organization in three steps: input – indispensable data for problem solving –, processing – procedures leading to result –, and output – initial problem's solution. The formalization of these stages occurs through specific representation methods; one of them, which was chosen for this research, is the flowchart, a representation through conventional geometric symbols, expressing logical reasoning with which the problem is solved (ALMEIDA, 2008).

Based on those definitions, the research development took place in three stages. At the first stage, the legal standards were extensively analyzed seeking to establish inputs, outputs and processes presented in them. The next two stages were the coding of the algorithms and the simulation/validation of its use.

Regarding the software used in the study, specifically at the architectural detail level, Microsoft Excel is used for calculations and Rhinoceros/Grasshopper converts this data to 3D figures. For the architectural and urban levels, for usability purposes the whole algorithm is created exclusively in Rhinoceros/Grasshopper avoiding multiple platforms.

SHORT LITERATURE REVIEW

The Architecture scenario has considerably changed, as depending on the increasing integration with digital tools not only as representation platforms, but also as design supports. According to Howell & Batcheler (2005), the original premises of Computer Aided Design (CAD) systems was the automation of design drawings, focusing on 2D representation through graphic elements. With the development of 3D tools, the focus changed for objects visualization and finally, at the final stage, there are the Object Oriented CAD systems (OOCAD), which are capable of representing the behavior of building elements. At this scenario, the Building Information Modeling (BIM) can be characterized as the most advances of the OOCADs. Eastman *et al.* (2014) define BIM as a modelling technology and a set of processes to produce, communicate and analyze construction models.

The basic difference between conventional 3D models and BIM is the use of parametric objects. In this case, the design objects do not present fixed proprieties, but actually parameters and rules determining its geometry allowing form updating and context changing by the user. In addition, it establishes the integration between design elements at various levels in a nonredundant and consistent way. With the objects carrying out attributes such as structural materials, acoustic and energy data, among others, it allows a sort of tests and simulations, which would not be possible in other type of 3D models (EASTMAN *et al.*, 2014).

Shea *et al.* (2005), present parametric modeling as a transformation in the role of computers in the design process, from a drawing assistant to an active tool in the process, being able to produce design solutions through data processing, geometric constraints or dimensional relations. In this

case, a next step in this transformation of computers from passive tolls to active players in the design process, would be the digital based generative systems.

> A generative system is an indirect design method in which the designer does not worry about a particular solution for a specific problem in a specific context. He (or she), seeks to find a design solution somewhat generic that would be able to solve similar problems in different contexts. (CELANI, 2011)

Generative designs are a practice in which the designer uses a system with some level of autonomy, to produce design solution. (ABRISHAMI *et al.*, 2013). A set of abstract definitions of possible design variations capable of producing objects are the main characteristic for such systems (FISCHER; HERR, 2001).

The tools discussed above are usually seen as part of BIM system and according to Aien et al. (2015), this different way of thinking 3D models, are significantly changing the way we manage city information, however, such models still focus on physical and functional information, leaving legal aspects aside. Although, as there are, already, some specialized systems to store site registration data and other legal aspects, the next step in search for greater usability of city models may be the integration of physical and registration data. (AIEN *et al.*, 2015).

Issa *et al.* (2009), affirm that simulation is a promising field of BIM technology since it allows greater exploration and refinement of construction projects and even buildings operation. In a scenario of raising interest in sustainability, it would be a significant tool to determine the environmental impact of design decisions. Lastly, with the crescent complexity of architectural objects, 3D modeling becomes a source of studies regarding means and construction methods. (ISSA *et al.*, 2009).

STUDY AT ARCHITECTURAL DETAILS LEVEL

FIRE SAFETY RULES AND REGULATIONS

At the architectural detail level, the study focuses on fire safety regulations due to its deterministic nature ad relatively low degree of complexity for coding. Regarding regional specificities, Fire Departments of each Brazilian state are responsible for fire safety standards, commonly through Technical Instructions (IT). In Minas Gerais State case, the Technical Instruction 08 – IT08 (CBMMG, 2010) is the reference regarding escape routes design for any kind of building.

The process stated by IT08, is a composition of two phases. The first one is the input of design data in a sequence of reference tables to define number of exits and type of stairway. The second one is the design of stairway's specific details like ducts minimum size and its proportions (Figure 97).

REPORT ON THE ALGORITHM DEVELOPMENT – DETAILS

As stated before, at this level, the algorithm takes advantage of Microsoft Excel and Rhinoceros/ Grasshopper integration to fit specific needs of both types of operation present in the process.

At first, the tables presented by IT08 containing the reference database were set into Excel in order to automate the necessary classifications based on user data inputs. The parameters defined in this stage are population, required number of escape routes, type of ladder and air inlet and outlet ducts dimensions, as well as their openings in each floor. Based on the Excel outputs, the second part of the tool is developed in Grasshopper/Rhinoceros software and performs a series of geometric operations to simulate a 3D representation of stairwell and inlet/outlet air ducts (Figure 2). With the coded tool, the user can consistently and continuously visualize the building`s legal requirements, since it is possible to generate instant answers for every scenario in study.

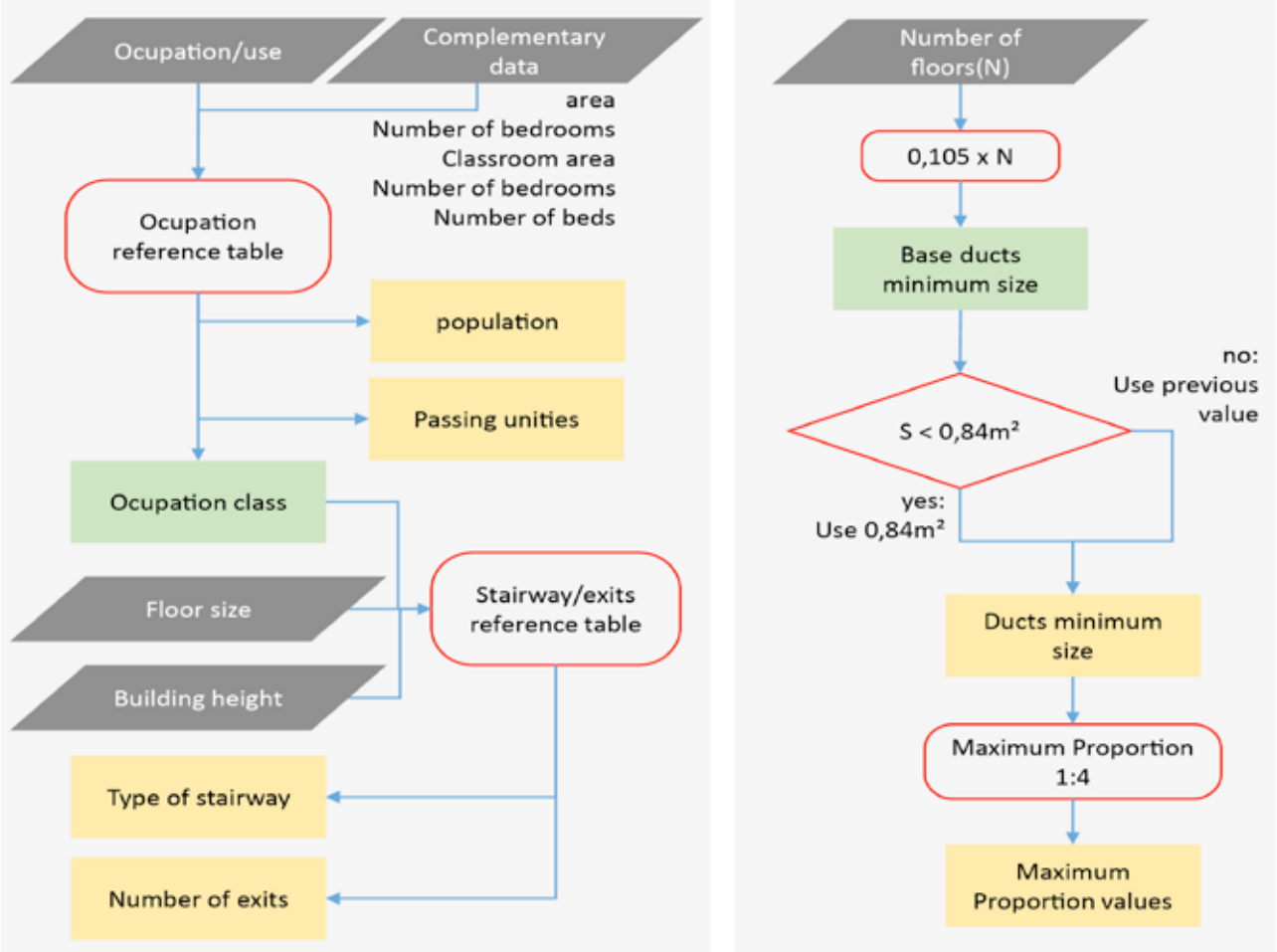

Figure 97 - Flowcharts representing fire safety requirements application process.

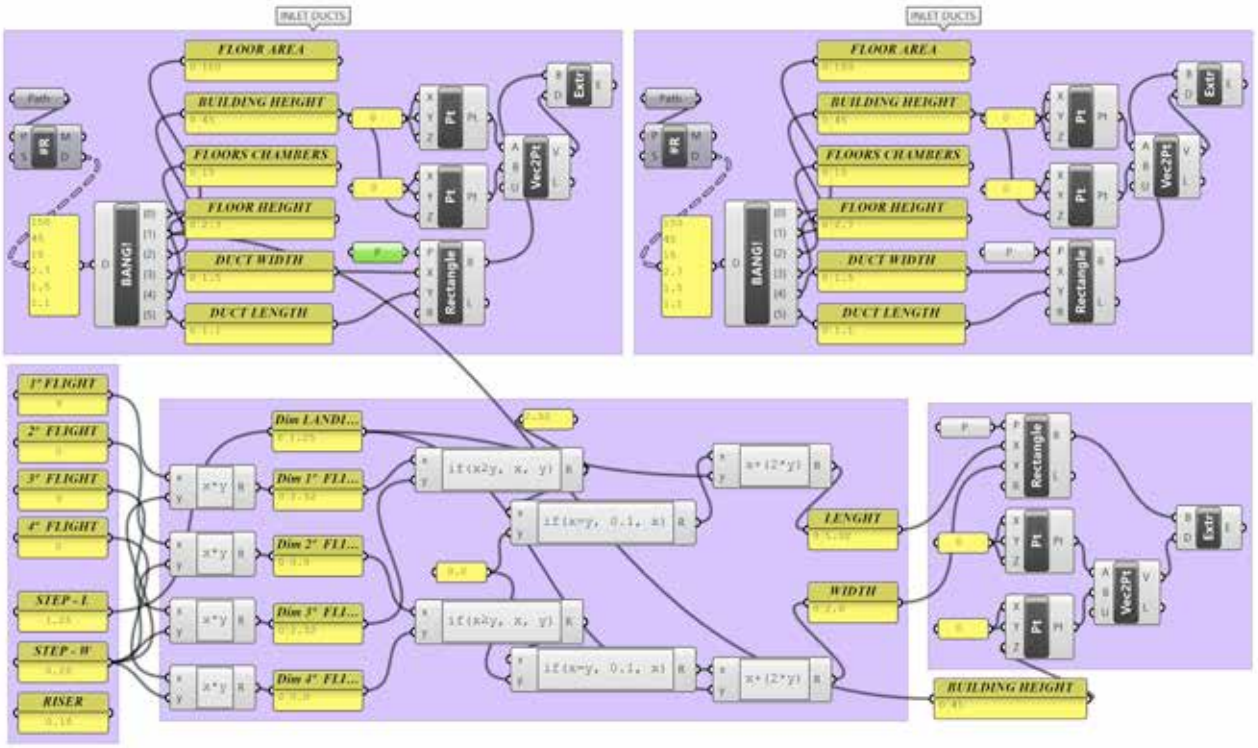

Figure 98 - Algorithm used in Grasshopper to create de inlet/outlet ducts and the stairwell.

SIMULATIONS AND RESULTS – DETAILS

In this phase, the research focus on the study for two hypothetical buildings to explore the tool in conditions similar to real projects in the city of Juiz de Fora. Since the use of a building determines various standards, one of the buildings were commercial/services and the other residential and the product parameters adopted for each case are described below (Table 6):

	Residential	Commercial and services
Floor area	150m²	150m²
Building height	33m	45m
Number of anterooms	11	15
Floor to ceiling distance	2,7m	2,7m
Number of bedrooms	3	-
Area	-	120m²

Table 6. Parameters used on the simulations.
Source: The Authors.

The values resulting from the operations on the digital tool (Table 7) could be validated by conventional methods and the 3D objects were proved correct from their measurement. Thus, the research points out that it is possible to create digital tools addressing fire safety rules and regulations.

	Residential	Commercial and services
Population	6	18
Type of stairs	smoke proof	smoke proof
Number of exits	1	1
Ducts area	1,155m²	1,575m²
Width	0,537m	0,627m
Length	2,149m	2,510m
Chosen Width	1,10m	1,50m
Chosen Height	1,10m	1,10m
Duct opening height	0,70m	0,70m
Duct opening width	1,20m	1,20m

Table 7. Result obtained with the digital tool.
Source: The Authors.

Considering the digital process as a whole in comparison with conventional methods, both the calculations and reference table's assessments and operations were instantaneous. Although there`s the need for different platforms, Excel and Rhinoceros/Grasshopper, process of testing design hypotheses in 3D, practically, instantaneous with the changes on input data. It is worth mentioning that the presented results are three-dimensional forms materializing one of the possible solutions for the legal requirements related to a specific fire safety equipment, and not at all, a definitive solution or even the disposition of such objects in a project. (Figure 99).

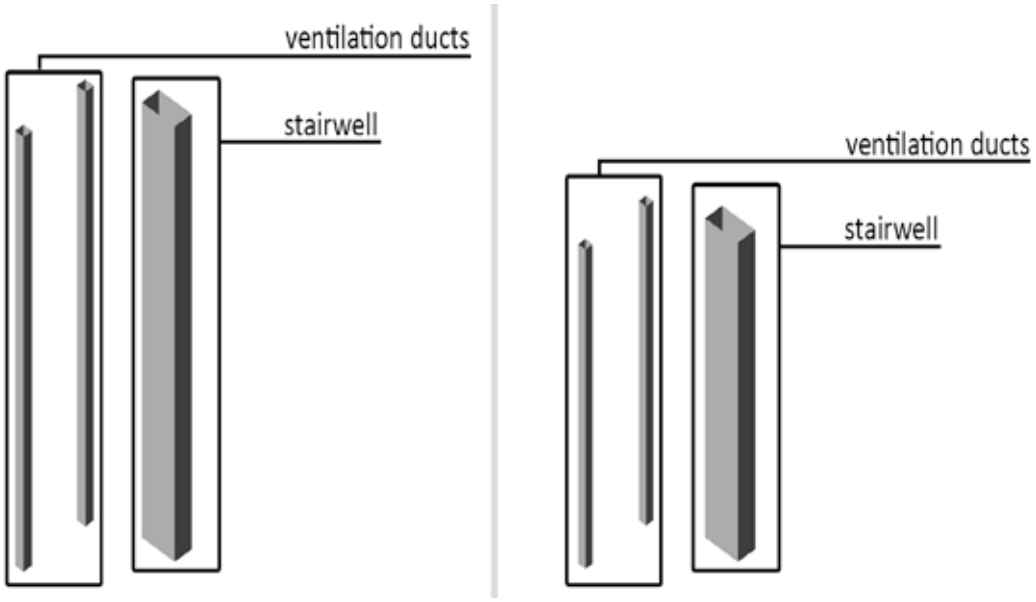

Figure 99 - 3D model: commercial study and residential study.
Source: The Authors.

STUDY AT ARCHITECTURAL LEVEL

JUIZ DE FORA URBAN CODE

The City of Juiz de Fora has 120 years of urban code history, but, from the first exclusively health-related requirements to the city`s 1986 "Legislação Urbana Básica", the standards were largely due to technological characteristics of the city and not to a specific urban space quality program. Only from 1986 ahead, the parameters aiming better occupation of the urban area were adopted as official design constraints. At this update the building code started to consider different occupation models with different levels of restriction for its sites (CARDOSO, 2015).

In a generic approach to the Juiz de Fora`s buildings and urbanization code, as well as in other cities, is possible to affirm that the design decisions need to be validated through a series of assessments and operations following prescriptive and repetitive patterns. The standards and regulations are also based on the relations between a series of legal requirements. In that case, the site`s location, size and form, together with the building`s specific intended use, program and typology define the parameters to apply on the architectural object.

REPORT ON THE ALGORITHM DEVELOPMENT – ARCHITECTURE

At this design level, specific studies on the current legal requirements have been developed, seeking to identify procedures for inputs, processing and outputs that are responsible for the generation of building shapes allowed by city standards.

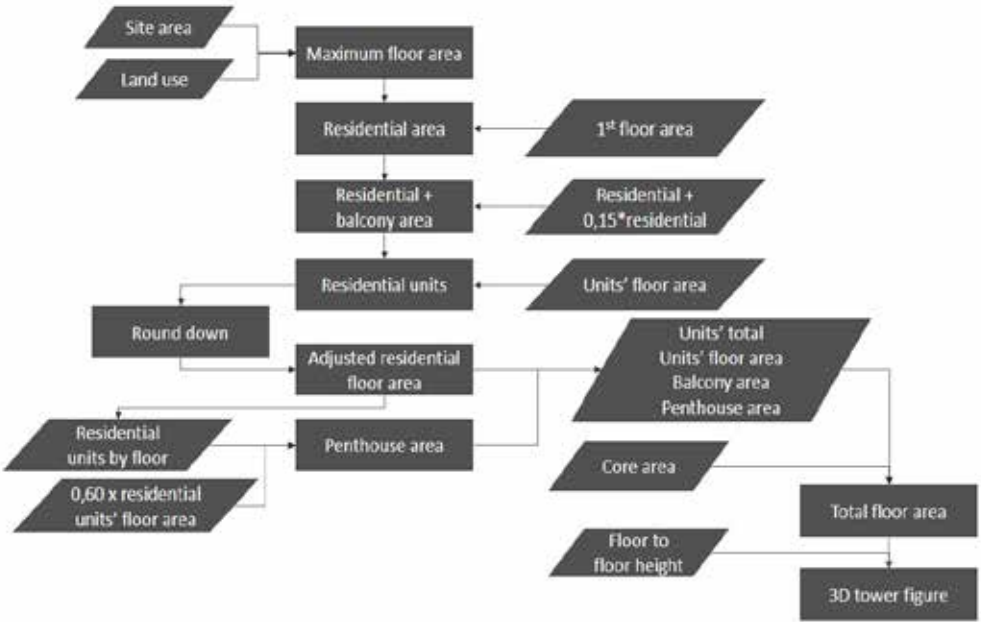

Figure 100 - Flowchart regarding the process of volumetric study generation for towers.

Initially, the building code's parameters were organized based on their impact on the architectural form. After that, the input parameters for site and product were identified in order to establish the interaction between them and the operations later to be performed. Proceeding with the analysis, the viability studies process were mapped aiming to determine the sequence of operations to be included in the algorithm code. Afterward, in order to simplify the transition to the digital medium, the data were set through flowcharts similares to the structure used in Grasshopper (Figure 05). At the end of the process, a design algorithm was produced for individual sites application, partially addressing the product definitions, which vary for each case being studied, and the constraints of the legal standards.

SIMULATIONS AND RESULTS – ARCHITECTURE

With the algorithm coded, hypothetical sites were used to test the tool and validate the solutions obtained. Due to the complexity of data, the user interface is based on geometrical and numerical inputs. The geometrical inputs set directly on Rhinoceros, are related to the environment and representing the site and the nearby streets. The numerical inputs are made on Grasshopper and are related specifically to the product in study, like gross floor area, gross floor area for each unity, units per floor, floor-to-floor height. (Table 3)

Site	Building-building street length	12 m
	Site dimensions	12,00 x 30,00 x 15,00 x 30,00
	Site area	405,00 m²
Product	Gross floor area – ground floor	150 m
	Gross floor area per unit	80 m
	Units per floor	2
	Floor-to-floor height	3,06 m
	Core area	36 m²
	Parking spaces per unit	2
	Parking spaces per unit - penthouses	3
	Parking spaces estimates area	25 m²

Table 8. Site and product data used on the simulations
Source: The Authors

Based on those inputs, the algorithm created one possible occupation for the site with its maximum potential allowed by the legal standards. As the building code presents different types of occupation models, the tests were performed for each one of them (Figure 101).

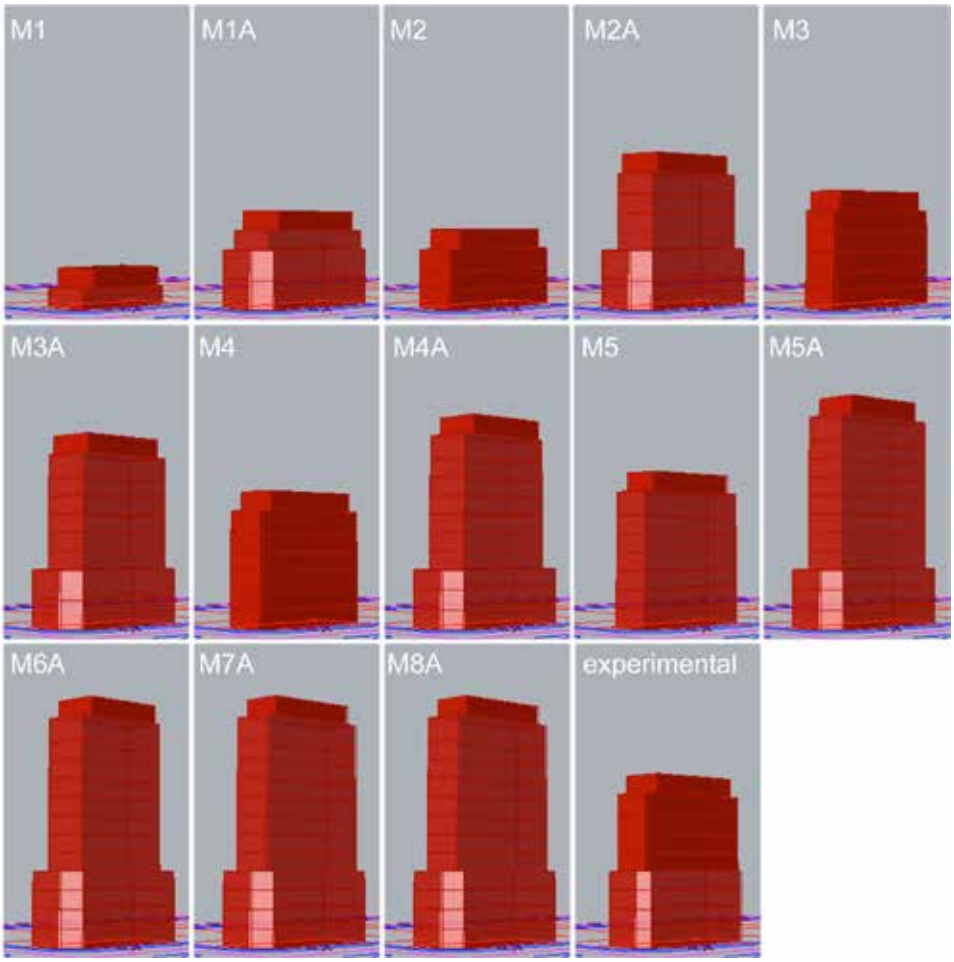

Figure 101 - Simulations for the hypothetical site with each occupation models allowed by the building code.
Source: Authors.

STUDY AT URBAN LEVEL

SPECIFICITIES FOR THE STUDY ON GROUPS OF SITES

To adequate the algorithm to the use at the urban level, many adjustments were coded to make possible the creation of 3D models for multiple sites at once. With the changes, the new version of the algorithm can be used to simulate more complex and wider areas, including city contexts. It also expands the data generation for each study listing population and number of vehicles.

REPORT ON THE ALGORITHM DEVELOPMENT – CITY AREAS

With the crescent complexity of operation on the algorithm, it was necessary to establish groups of commands responsible for specific tasks throughout the process. Groups for data inputs, algorithm flow controls, environment recognition, calculations, 3D shapes generation and positioning

were created (Figure 102). Specifically, for this version, it was created a group responsible for the reports on gross areas for each building, gross area by type of use, average gross area by unit, total parking spaces and estimated population.

It is important to state that, due to the indefinite number of sites, in order to stimulate the diversity of forms existing on the urban space it was necessary to develop random ways to generate the products data. For future studies, these values can be defined through genetic algorithms in an evolutionary way, and with that, to extend the possibilities of the simulations.

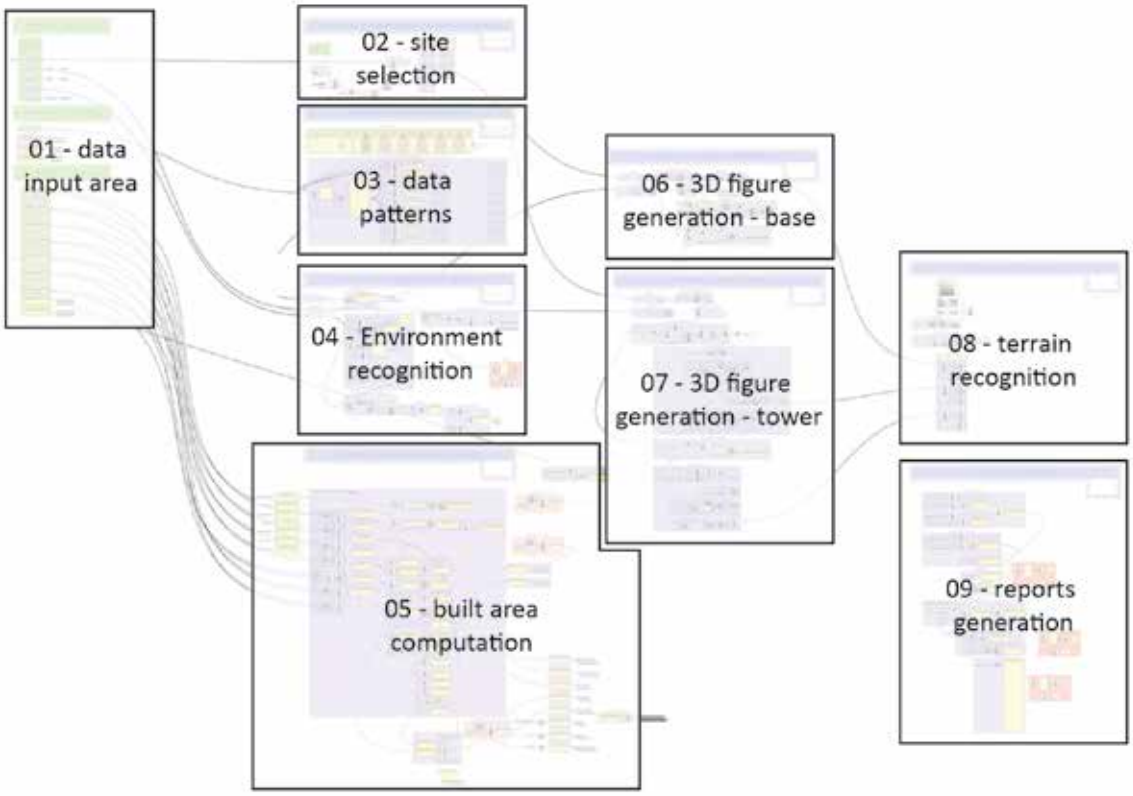

Figure 102 - Algorithm groups map.
Source: Authors.

SIMULATIONS AND RESULTS – CITY AREAS

Throughout the coding of the urban level algorithm, the essays were based on a real fragment of the city of Juiz de Fora. The area selected present important particularities for a better exploration of the algorithm`s potential, like varied terrain, different width of streets and intersecting corners at different angles. The Figure 103 shows the area selected for the studies.

Figure 103 - Area chosen for the algorithm tests.
Source: Authors.

The Figure 104 below presents two different simulations for the same area. For that study, the product data were generated randomly in intervals defined by the user. Both scenarios are using the same occupation model M8A, which is the most permissible one present in the buildings code. The difference between them is that the first one considers the maximum height allowed in the city and the second one keeps the same values as before, only ignoring the maximum height allowed. With this study it was possible to clearly identify the impact of the limitation of height for the sample area.

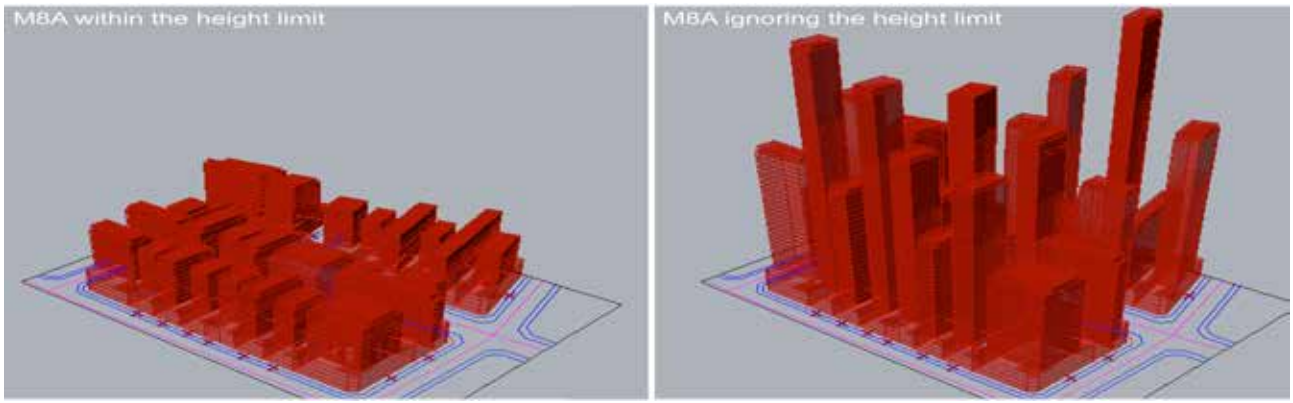

Figure 104 - Results with and without height limitations.

ANALYSIS

Throughout the design process, applying the legal constraints to an object involves a large number of comparisons with reference tables and a sequence of operations for each design hypothesis to evaluate. From the architecture detail to the city design level, the algorithms produced during this research were able offer instant answers for a large part of the design problems depending

only exclusively on the input of values. In this case, through recognition of design constraints and a systematized problem-solving approach, a design algorithm can automate repetitive tasks allowing the designer to focus more on the creative action.

Regarding the tool itself, it is necessary to establish its differences for each level of design. The crescent complexity of the problems addressed are clearly noted either on the use and the results obtained. At the architecture detail level, the responses are presented in a direct way since both the products and the legal scenario are very strict. At the architecture level, the form generation is based on relatively simple operations, whether algebraic or geometric. The complexity presents itself with the extended sequence of operations and the need to adapt to all possible scenarios paired with the multiple decisions throughout the process. At the urban level the complexity is related to the multiple site recognition. At this level, the algorithm presents itself as a generative system with the autonomy to generate values originally informed by the designer. By creating possible scenarios of occupation for the area in study, it can bring important information on the impact of the decisions on urban planning.

Code checking is another possible use for digital tools. In spite of the convenience posed by this type of process for the designer, if compared to the process explored in this research, it involves a different approach to the algorithm coding. It is necessary to change the focus from the form generation based the environment and legal standards to form recognition patterns and subsequent comparison with legal standards.

FINAL CONSIDERATIONS

It is worth mentioning the complexity of the design problem and in consequence the difficulties on its full automation. As mentioned before, regarding legal constraints, the process of creating an architectural object follows a path that can be mapped, but although based on simple operations, it is punctuated with usually subjective design decisions. Those design decisions, without reasoned actions can make any solution possible and consequently the number of solutions would be infinite. In that case, would be interesting to explore the genetic algorithms as evaluating methods for the large number of solutions.

Based on this research it is possible to state that, beyond complex forms experimentation, parameterization and generative systems, can be an important support on design process based on the constraints presented by rules and regulations, since it presents instant responses for each possible scenario inputted by the user.

The insertion of technical and legal requirements at the beginning of the design process may be a path to better and more efficient designs, since it makes clear the restrictions that at any moment may be applied to the objects. Besides, in terms of management, with the crescent implementation of BIM systems and, by consequence, the need for interoperability and coordination between team members, the possibility of registering a design decisions' history can contribute faster processes and better solutions for the design problem.

CHAPTER 09

CONCEPTS OF BUILDING INFORMATION MODELING

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CONCEPTS OF BUILDING INFORMATION MODELING

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ABSTRACT

In this chapter, the concepts and knowledge that surround the BIM platform (Building Information Modeling) will be explored. This design methodology has been adopted around the world due to its ability to optimize the AECO industry's design processes. Among the benefits already evidenced with the advent of this platform were the increase in productivity, compatibility, collaboration and improvements in coordination between project agents, followed by reduction of expenses, time, rework and waste during the entire building life cycle. However, such benefits are only achieved by making profound changes in the AECO industry, ranging from changes in the design process to the emergence of new work structures and responsibilities. Because of this, the implementation of BIM has many challenges to be solved for the full use of its benefits.

INTRODUCTION

The Building Information Modeling platform is one of the most influential innovations (SUCCAR; KASSEM, 2015) and one of the main AECO design process catalysts (ANDRADE; RUSCHEL, 2011). The studies related to BIM show impacts in the managerial, operational and organizational areas of the life cycle of the buildings.

In the studies of Eastman et. al (2011), some of the benefits from adopting of this platform are identified as: 1) Increased construction quality and performance; 2) Automation of the design process; 3) Generation of compatibilized graphical documentation; 4) Improvement of interdisciplinary collaboration among project agents; 5) Simulations and project analysis in the first phases of the project; 6) Anticipation of solutions; 7) Approach between the design and construction phases; 8) Use of digital projective models for the production of real elements; 9) Improvements in the management and operations of buildings; and 10) Integration between operating systems and facilities management. In addition to these benefits, many can still be identified according to the direction of BIM-related studies.

However, the implementation of the platform requires paradigm shifts already consolidated in multiple spheres of the AEC industry and the growing demand for BIM projects in the world increases, consequently, the demand of professionals qualified to perform in functions related to it. This requires specific qualification of the Stakeholders and new looks regarding the industry as a whole (UHM, LEE; JEON, 2017).

The large impact of the use of BIM, although one of the great advantages of its adoption, can also indicate a fragmentation in the development and adoption of the platform. Many studies are carried out with the aim of analyzing researches developed in the past to propose new trends for future developments in BIM (LI; WU, *et al.*, 2017).

Furthermore, research on BIM has adopted, in recent decades, differentiated terms that relate to the platform (Figure 105). Such terms may have conceptual or descriptive nature and may be attributed to research organizations, industry or software developers (SUCCAR, 2009).

The precursor terms to BIM - published between the mid-1970s and the late 1980s - give emphasis to the production of projects with computer aid. According to Gaspar and Ruschel (2017), the terms “Building Design System”, “Building Description System”, “Integrated Building Model”, “Design Data Model” and “Integrated Product Model” indicate a targeting of object-oriented modeling studies.

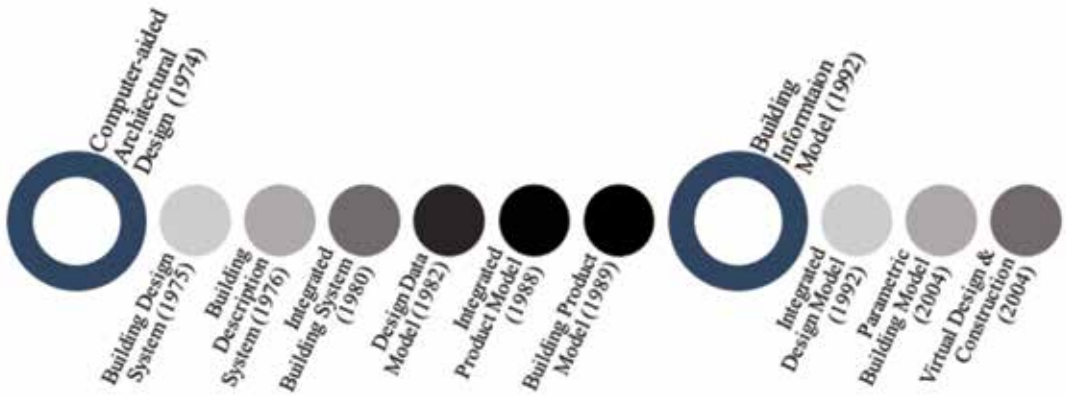

Figure 105 - The evolution of term Building Information Model.
Source: Adapted from Gaspar & Ruschel (2017).

The first appearance of the term “Building Information Model” occurred in the 1990s in the surveys of Nederveen & Tolman (1992). However, the direction of the term was still object-oriented modeling. Only in 2009, researcher Bilal Succar, in his work “Building information modeling framework: A research and delivery foundation for industry stakeholders”, assigns to the term a broader sense related to the design and construction processes (GASPAR; RUSCHEL, 2017).

Other terms such as “Parametric Design Model” and “Virtual Design & Construction” emerged after the “Building Information Model”, but today the term “Building Information Model” along with its “Building Information Modeling” variant are predominant (GASPAR; RUSCHEL, 2017).

In this chapter, concepts and work related to BIM will be explored to identify its context in the AECO industry today.

TRANSITION BETWEEN THE PARADIGMS CAD AND BIM

The architectural production passed through two technological revolutions (Figure 106) in the last years (XU, 2016). The development of the software industry in the 1960s marked the first revolution when CAD (Computer Aided Design) (COSTA; FIGUEIREDO; RIBEIRO, 2015) was launched in the following decade. With the adoption of this resource, projects, previously developed from manual designs, began to be developed with the aid of electronic drawings.

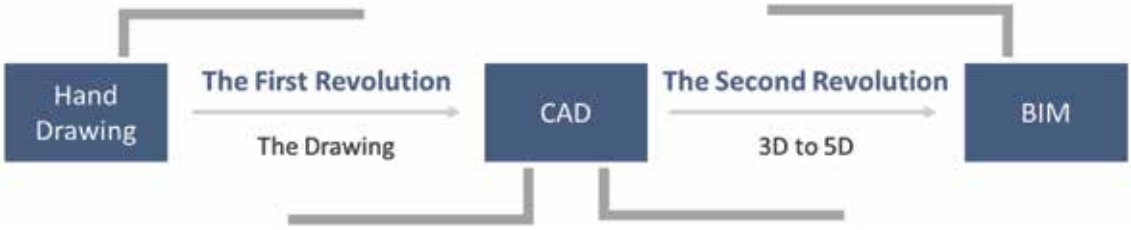

Figure 106 - Information Change in Construction.
Source: adapted from Xu (2016).

The development of projects in the computer guarantees to the designer a better quality and efficiency in their projects (COSTA; FIGUEIREDO; RIBEIRO, 2015).

The technology used in CAD software is the vector drawing that makes use of mathematical operations to generate geometric objects. These objects are lines, arcs, ellipses, etc., which, together, represent the constructive elements through 2D projections, as well as in manual drawing (RUSCHEL; BIZELLO, 2011).

In projects made in CAD it is possible to use resources that optimize and speed up the production of drawings such as: 1) Layers, to assign common characteristics to diverse objects; 2) Templates, to the standardization and creation of new projects; 3) Blocs, ready-made drawings of common elements - such as doors, windows, equipment, etc. - used to optimize the production of graphic documentation and; 4) association of non-graphical information, such as spreadsheets, with graphic elements (RUSCHEL; BIZELLO, 2011).

The features offered by the CAD platform show the direction of the use of the platform to the graphic representation. In fact, design companies have adopted and mostly adopt the CAD platform as a type of virtual drawing board. Even with the introduction of 3D features on the platform in the late 1960s, design processes resembled conventional manual processes (RUSCHEL; BIZELLO, 2011).

It is important to note that the transition between the CAD and BIM platforms was not due to the evolution of 3D modeling resources, but rather due to a change in paradigms and a view on the constructive design.

In the CAD platform, the focus is on the graphic representation of the elements, in the BIM platform the focus is on the database linked to the building digital model (EASTAMAN; TELCHOLZ, *et al.*, 2008).

The expansion of the use of technology for the entire building life cycle through BIM characterizes the second technological revolution of the construction industry (XU, 2016). Today, increasing project demands require the generation of many data and information on construction already in the design phase. Through the analysis and generation of accurate data, the BIM platform can meet this demand once the three-dimensional model becomes a construction database (LIMA; SOARES; BORGES, 2011).

The design requirements have made CAD systems evolve into more rational systems that automate the whole design process through new technologies. These two factors lead to changes in the entire structure of the AECO industry, thus characterizing the transition from the CAD platform to the BIM platform (LIMA; SOARES; BORGES, 2011).

Currently, the BIM platform can be implemented in multidisciplinary fields of knowledge. It is used to integrate, analyze, simulate and visualize geometric and non-geometric information of a project. This innovation has been progressively adopted in AECO industry enterprises (LI, WU, et al., 2017).

BIM: THE NEWEST PARADIGM OF AECO INDUSTRY

The transition between CAD and BIM platforms is one of the main paradigms of the production of contemporary architecture (OXMAN, 2006). The implementation of BIM feature has taken progressively larger proportions reaching national and market scales being in this large proportion, referenced by Kassem & Succar (2017) as “Macro BIM Adoption”. Among the advances of the AECO industry, BIM is ostensibly prevalent in the areas of practice and research (PÄRNA; EDWARDSA; SING, 2017).

Specifically, in the field of research, studies are mainly found on implementation policies and BIM project processes. In a smaller number, studies can be found relating BIM to information technology where improvement methods are explored for interdisciplinary collaboration and optimizations of computational platforms such as: 1) retrieval of information; 2) visualization; 3) data exchange; 4) interaction; and 5) interoperability (LI, WU, et al., 2017).

Many definitions about BIM can be found in the surveys about the platform. However, two jobs are referenced in many papers about BIM: 1) the book “BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors “ From Eastman et al. (2008); and 2) the magazine article Automation in Construction “Building In-formation Modeling Framework: The research and delivery Foundation for industry stake-holders” of Succar (2009) (LI; WU; *et al.*, 2017).

It is important to point out that other works are also referenced - just as the cited works referenced some others to define their BIM concepts. However, to elaborate a definition with clarity and precision, the cited studies will be used.

For Eastman *et al.* (2011), BIM is *"[...] a modeling technology and an associated set of processes to produce, communicate and analyze building models."* The direction of this work, widely referenced by the market and the academy is geared to the technological resources of the platform.

For Succar (2009), BIM is: *" Building Information Modelling (BIM) is a set of interacting policies, processes and technologies generating a "methodology to manage the essential building design and project data in digital format throughout the building's life-cycle."* As mentioned earlier, in his works, Succar (2009) broadens the meaning of the platform taking it to a level beyond technological resources.

The fields delimited by Succar to identify the BIM domains are known as TPP - Technology, Process and Policy. In these fields, the researcher identifies which products are generated in each one of them and which are its main players of them. In this way, this job facilitates the identification of knowledge related to BIM. Because of this, the TPP fields identified by the researcher will be used as reference for explaining the concepts related to BIM in this chapter.

TECHNOLOGY

The technological field established by Succar (2009) includes all players - as software development organizations - related to the development of software, hardware, equipment and network systems necessary for the development and improvement of efficiency, productivity and handling of the AECO industry.

Azahar, Khalfan & Maqsood (2012) relate BIM to a technology capable of simulating building in virtually 3D, thus creating a database that can be transmitted during the building's life cycle.

The definition of the author above has a close relationship with digital tools aimed at the development of projects where two main technological strands are applied: 1) parametric modeling; and (2) interoperability.

It is important to report that the design software does not contemplate all the competencies and requirements of the BIM platform. There are, in addition, other tools for coordination, management and analysis applied to different stages of building's life cycle.

PARAMETRIC MODELING

During the design process of a building, changes in geometry are realized in the search for better solutions, adapted to the context of the designed artifact. One of the resources that optimize the realization of these changes in the BIM platform is the parametric modelation (ANDRADE; RUSCHEL, 2011).

Although the greater complexity of parametric objects in relation to conventional digital objects and the consequent need for designers to use this modeling method, the smart behavior of these elements brings multiple benefits in terms of the compatibilization and optimization of projects production (EASTAMAN *et al.*, 2014).

The use of this type of modeling leads the designer to create the structural elements virtually through the filling of data that define their physical and functional characteristics. The objects created have their delimited behavior by the parameters assigned to them, whether fixed or variable parameters.

According to Eastman *et al.* (2011), parametric objects have four main characteristics:

- Topological structure: establishes, through the parameters assigned to parametric objects, its physical structure in the digital environment and its relations with the other elements. These relationships allow the connections between the constructive elements to be coherent by respecting three conditions: what can be connected; what kind of connection and how to compose the connection within its varied contexts.
- Properties and attributes: In addition to the physical characteristics, parametric objects may contain non-graphical properties attached to them for performing various analyzes and simulations. These properties include: material specifications; building's performance parameters; properties for assembly; and space properties.
- Generation of 2D documentation: parametric objects are defined only once in the project. Therefore, their instances have the same characteristics according to the type of information that is attached to that object (such as thicknesses and types of lines, identifiers, properties, etc.). This feature allows the extraction of two-dimensional views (plants, cuts, elevations, etc.) with all the rules of technical drawing conventions, built in quickly and always compatible, since all instances of a constructive element respond in the same way, presenting the same visual characteristics in all the projections necessary for the presentation of the architectural project.
- Scalability: The scale and level of detail of architectural designs can overload BIM systems making designing impractical. Although the project´s BIM tools do not incorporate information management capabilities into multiple files, they offer two solutions to optimize their processing: memory-based systems (objects loaded simultaneously into computer memory); and file-based systems (update and close multiple files simultaneously). The choice of one of the methods cited is based on the scale of the projected artifacts.

Within the BIM design process, parametric modeling is presented as an optimized form generation method since it allows fast and compatible changes in complex architectural entities that

present a high degree of manipulation difficulty considering the methods of creation of conventional forms (ANDRADE; RUSCHEL, 2011).

INTEROPERABILITY

Interoperability is, jointly with parametric modeling, one of the technological resources that gives support to the BIM platform and through it it's possible to develop more integrated levels of collaboration among project agents throughout the building´s life cycle (ANDRADE; RUSCHEL, 2009).

In the BIM context, in the AECO industry, interoperability operates as a means of identifying data that can be exchanged between distinct applications for performing tasks during the development of the various phases of the design process. Interoperability eliminates duplication of data, facilitating the automated workflow development.

BIM platform applications basically offer four types of data exchanges: direct link, proprietary exchange file format, public domain exchange file formats, and XML-based exchange formats (EASTAMAN, 2014).

The first happens when a direct connection between two applications occurs, a binary interface format is used (example: GDL, MDL). The proprietary exchange file format is formats developed by commercial organizations to interface different applications (examples: DXF, 3DS). File formats for public domain exchanges involve an open standard building model. These carry properties of objects, materials, relations between objects, as well as geometrical properties. They are essential interfaces for use in construction management analysis and analysis applications (examples: IFC, CIS/2). The formats based in eXtensible Markup Language (XML) exchange are extensions of the HTML format, which is the base language of the Web. They allow the creation of user-defined schemas (examples: XML, gbXML) (ANDRADE; RUSCHEL, 2009, p.81).

The standardization of information and data exchange protocols is essential to ensure good collaborative practices with the BIM platform, thus avoiding duplication of data. Internationally, the main protocol used is the Industry Foundation Classes (IFC), an object-based, non-proprietary data model.

The IFC was developed by buildingSMART as an open data interchange format. The model, although being the first project developed by the organization, undergoes continuous upgrades aimed at improving the AECO industry's suitability (buildingSMART, 2018).

BuildingSMART makes other efforts to improve the exchange and standardization of information in the AECO industry. The organization has partnership with the ISO (International Organization for Standardization) and its advances are carried out in accordance with the established norms. According to the organization:

The goal of buildingSMART is to enable the sharing of information across the lifecycle of any built-in environment resource among all participants regardless of the software application

they are using. Machine-readable data of good quality must be available for use during the design, construction, maintenance and operation phases (buildingSMART, 2018).

The IFC format is one of five pattern types developed by buildingSMART. Each one performs a function to support the exchange of data between AECO industry project agents (Table 9).

What it Does	Name	Standard
Describes Process	IDM Information Delivery Manual	ISO 29481-1 ISO 29481-2
Transport information / data	IFC Industry Foundation Classes	ISO 16793
Change Coordination	BCF BIM Collaboration Format	buildingSMART BCF
Mapping Teams	IFD International Framework for Dictionaries	ISO 12006-3 buildingSMART Data Dictionary
Translate processes into technical requirements	MVD Model View Definitions	buildingSMART MVD

Table 9. Five basic methodology standards.
Source: adapted from buildingSMART (2018).

The standardization of IFC information is still supported by the Information Framework for Dictionary (IFD) and Information Delivery Manual (IDM). According to Andrade & Ruschel (2009):

> [...] the IFD, is the development of an international library of objects for the AEC/FM industry that is IFC compliant and can be used to obtain more detailed information inside and outside a building project. [...] the IFD is an alternative identity for the conceptual model of ISO 12006 Part 3. With the IFD it is possible to create an identity to the object (unique identity) which facilitates interoperability. The IDM, [...] is a standard that defines which specification of use an object should have (ANDRADE; RUSCHEL, 2009, p.81-82).

The BIM Collaboration Format (BCF) "is an open file XML format "bcfXML" that supports workflow communication in BIM processes" (buildingSMART, 2018). BCF enables the user to fully control the management cycle through tracking and error-sharing (buildingSMART, 2018) on distinct digital platforms.

These resources, in constant development, aid the coordination and the compatibility of the projects in BIM, being essential to the collaboration of the project agents. Interoperability opens possibilities among project agents regarding the export of geometric models for different analyzes, export of quantitative data with model data, and communication between designers that can access information on key issues for project decision making (ANDRADE; RUSCHEL, 2011).

PROCESS

The second field determined by Succar (2009) is the process. In this field are grouped the agents that design, construct, manufacture, use, manage and maintain the buildings. In this field are included the players involved in properties, deliveries and operations of buildings and structures.

Nowadays, the figure of the individual designer is more and more rare. The Increasing of market demands for service execution in less time and with a lower error rate contribute to the formulation of specialized work teams that do not necessarily need to occupy the same physical location (FILHO; FERREIRA, 2010).

Traditionally, in the AECO industry, the integration of the project phases occurs after conception, which engages subsequent decisions in the project that is already mostly consolidated (ANDRADE; RUSCHEL, 2011).

The adoption of the CAD platform did not change this workflow; however, the adoption of the BIM platform allows the identification of design incompatibilities in pre-mature phases of the project, making the process more integrated (BARISON; SANTOS, 2016).

Although not a common practice of the AECO industry, the integrated design allows for better articulation between the design, construction and operation phases of a building. There is an increase in the time to generate the concept of the product, in its early stages of design, however, some activities can be developed concomitantly during the process of production of the architectural artifact (FILHO; FERREIRA, 2010).

The integration of all the players of the building project through a single digital model allows the anticipation of issues and the optimization of team collaboration, thus creating an integrated project model (BORGES, 2016).

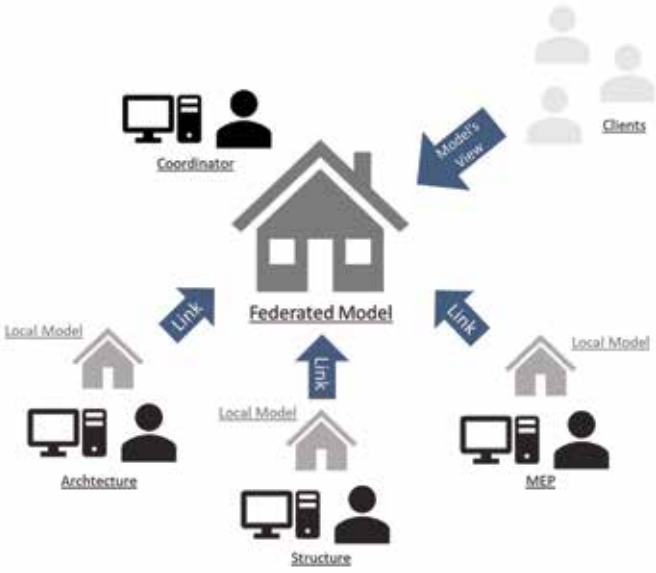

Figure 107 - Federated Model.
Source: Adapted from Manzione (2013).

The combination of disciplines in project development does not necessarily require the use of a single digital model. On the contrary, most activities occur in distinct models with information required by each knowledge area, however, such models have the same database present in an initial model that provides data to different applications (ANDRADE; RUSCHEL, 2011).

Today, cloud computing capabilities has revolutionized the market. The creation of work groups interconnected by the internet allows the exchange of a large volume of data in an automated way. In this current context, the BIM platform allows the creation of integrated project management groups where project agents can collaborate through shared directories in the cloud. This innovative resource assists decision-making by agents throughout the building life cycle (PÄRNA; EDWARDSA; SING, 2017).

In the pre-construction stages, BIM models, individually produced by designers specializing in specific design disciplines, are integrated into a federated model (Figure 99) where tests are performed to identify interferences between disciplines (PÄRNA; EDWARDSA; SING, 2017)

These models are used to coordinate the designers and to reconcile the projects of the design disciplines. Through the cloud features, models can be loaded into directories shared between designers and loaded into coordination-oriented software where clash detection analysis occurs. Identified interferences are communicated to the designers through the coordination platforms or, currently, can be transmitted through the BCF to the designer's computational platform.

This structure of work demands new functions and, consequently, new competencies of the project agents. The identification of these competencies and functions is essential for the development of teaching references, evaluation of functions and contracting of project agents.

BIM ROLES

Some studies related to BIM are dedicated to the exploration of the occupations that the players take charge in the development of constructive projects with the use of the platform.

With the adoption of BIM, new work structures can be adopted as the structure of development of competencies and functions for educational institutions suggested by Uhm, Lee & Jeon (2017). There is a relationship between the teaching and BIM work structures that is identified by the authors themselves, so the functions can be attributed to the market.

Uhm, Lee & Jeon (2017) identify eight work functions related to the BIM design process. They are: (1) BIM Project Manager; (2) Director; (3) BIM Manager; (4) BIM Coordinator; (5) BIM designer; (6) Senior Architect; (7) BIM MEP Coordinator; and (8) BIM Technician.

The term BIM is not assigned to the roles of "Director" and "Senior Architect" be-cause, in spite of the importance of these agents in the development, control and decision making of projects, the main role played in BIM projects is the manager, responsible for functions, coordination and compatibility of the entire project process. The "BIM Coordinator" function, in this way, is related

to a group of BIM consultants. The functions of BIM Designer include architects and engineers who perform the function of elaborating the projects related to the specialties linked to the constructions.

In addition to the project functions, the authors identify 43 BIM-related competencies assigned to three different levels that differentiate BIM functions: essential, common, and specific.

The essential competencies are the knowledge bases related to BIM, relating to all working groups, however, they are not necessarily low difficulty skills. The authors list the following competencies as essential: (1) speaking skill; (2) engineering and technology related knowledge; (3) technical vocational education; (4) BIM-related work experience; (5) work activity of interacting with computers; and (6) work activity for establishing and maintaining interpersonal relationships (UHM; LEE; JEON, 2017).

In addition, common competencies are linked to most BIM functions, however, they are not required for all work groups. Functions like BIM Project Manager and BIM Designer do not share common skills, for example. They are: (1) work style of cooperation; (2) design knowledge; (3) post-secondary degree; (4) work of evaluating information to determine compliance with standards; (5) work activity of thinking creatively (6) work of documenting or recording (7) work of communicating with supervisors and peers; (8) work activity of guiding, directing, and motivating subordinates; (9) work activity of providing consultation and advice; and (10) organizational context to monitor data on quality/costs /waste /etc (UHM; LEE; JEON, 2017).

The specific competences are linked to one or more functions according to their placement in the work structure. The structure proposed by Uhm, Lee & Jeon (2017) can be rearranged according to the teaching requirements and levels of knowledge required and is a malleable framework of the BIM function structure.

The designations and functions of BIM project players have been studied in recent years and great advances have been made in this area. However, even today, BIM training centers are focused on tool management, leaving aside the processes and methods of collaboration, coordination and project compatibility (UHM; LEE; JEON, 2017).

POLICY

The third and last field cited by Succar (2009) is that of politics. It includes organizations, researchers and groups that creates regulations for the standardization, regulation and contracting of activities and deliverables related to BIM. Some organizations, such as the American Institute of Architects (AIA), the NIBS, buildingSMART and ISO, have published documents that are referenced in BIM studies to this day.

The efforts of BIM-related regulations revolve around classification systems for the standardization of terms in construction (such as ISO 12006 - Building construction - known as the BIM standard), which do not necessarily only affect the projects in BIM, but the AECO industry

as a whole; Contract references with clauses and terms essential to BIM project contracts; and Implementation guides and design practices.

In general, the policies around BIM are linked to regions and institutions and are adapted to the demand and evolution of implementation of them.

BIM IMPLEMENTATION

The studies of Succar (2009) are also widely referenced regarding the implementation of BIM. The stages of implementation (Figure 108) proposed by Succar (2009) are divided into phases. The main difference between the two is that the stages propose radical changes in the domains of the BIM (TTP) fields, while the phases propose complementary changes.

There are also two main variables to be considered in the implementation stages: (1) Data flow; and (2) Phases of the project life cycle.

According to Succar (2009), the data flow is affected by changes in BIM technological paradigms. With the advent of the new platform, the type and variety of computational tools, the types of deliverables, and new protocols for data exchange can be adopted. Each level of implementation has variations in these requirements.

Figure 108 - stages of implementation BIM.
Source: Adapted from Succar (2009).

However, the phases of the project life cycle maintain their majority structure - design, construction and operation -, however, the components and relationships between the phases are modified according to the maturity of the implementation.

In Pre-BIM, Succar (2009) identifies the traditional situation of the AECO industry where there is little interoperability and there are a limited number of computational tools to aid the project. The focus of the industry is the two-dimensional representation of the building, few or no data is attached to the digital representations of buildings and the workflow is asynchronous and linear.

In the first stage of consolidation of BIM, the implementation of parametric modeling is carried out to generate models with automated 2D documentation and integrated 3D visualization (SUCCAR, 2009). It focuses on the technological resources of aid to the project in BIM and the elaboration of digital models. In this way, the previously geometric models become entities with their own behavior.

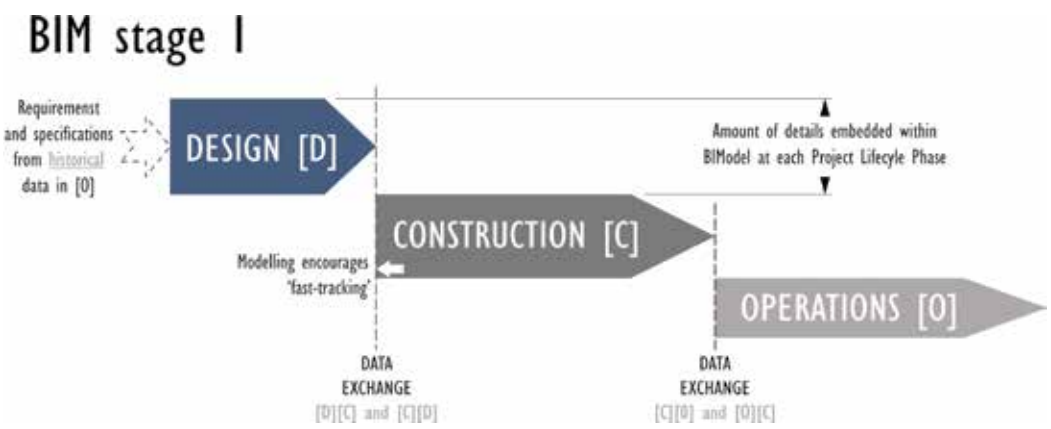

Figure 109 - BIM 1.0.
Source: Adapted from Succar (2009).

Efforts are concentrated in a single design discipline and there are few changes in the design process (Figure 110). The products generated at this level of implementation are three-dimensional models and their graphic documentation in general (plants, cuts, elevations, quantitative, etc.), being known as BIM 1.0 (SUCCAR, 2009).

The second stage of consolidation (BIM 2.0) is directed to the first activities aimed at multidisciplinary project collaboration, so two or more disciplines exchange data at this level of implementation. The impact occurs in at most two stages of the design process that is still asynchronous. However, the products generated are 4D and 5D models with time analyzes already made compatible through Clash Detection systems. Changes in project processes (Figure 102) are still of low impact and the focus is collaboration between teams at this implementation stage (SUCCAR, 2009).

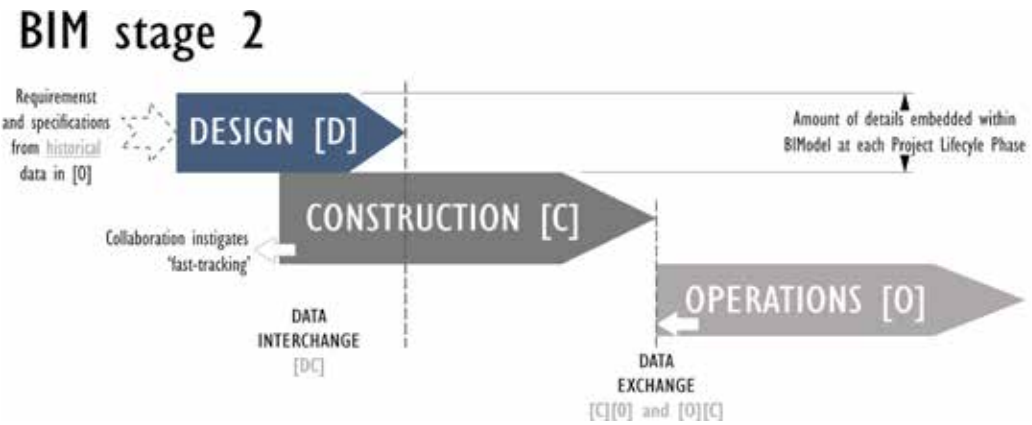

Figure 110 - BIM 2.0
Source: Adapted from Succar (2009).

In the last stage, BIM 3.0, the design process becomes simultaneous, integrated, shared and recursive (Figure 111). At this stage all project disciplines are involved in all stages of development. It is possible to identify, in this context, a workflow where all steps are connected to a single digital model that has all the multidisciplinary information - model nD - (SUCCAR, 2009).

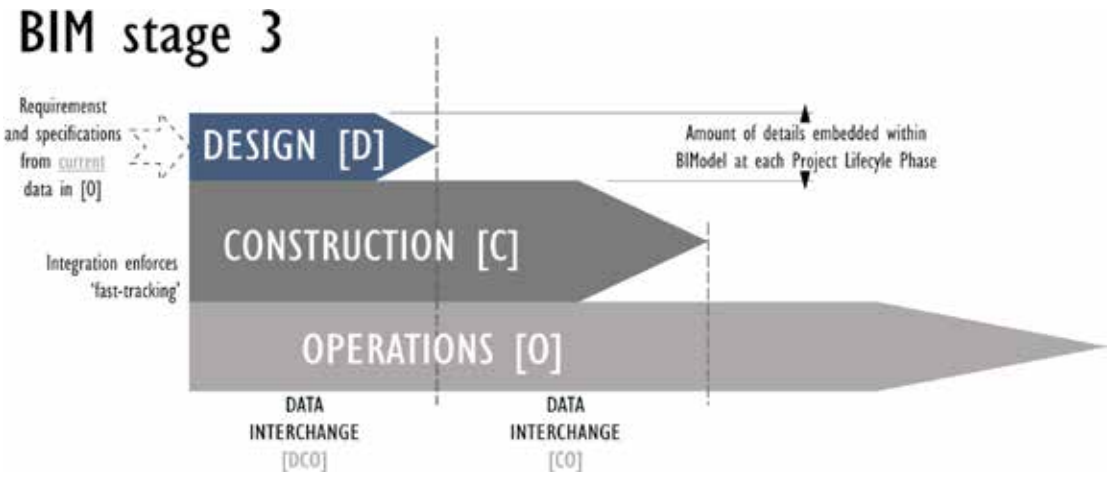

Figure 111 - BIM 3.0.
Source: Adapted from Succar (2009).

Simultaneous engineering-related production process practices can be identified at the end of the development of BIM's deployment in the AECO industry. According to Succar (2009) IPD (Integrated Project Delivery) is the point where "... fusion of technology, processes and policies, integrating people, systems, and practices into a collaborative process" occurs.

IPD was a term developed by the AIA (American Institute of Architects) in 2007 and is a long-term vision of BIM as an interrelationship of technologies, processes and policies (SUCCAR, 2009). Manzione (2013) complements saying that the IPD is a response to the demand for changes in contractual practices regarding the use of BIM.

By definition, IPD is therefore a project delivery approach that has six basic characteristics: (1) approaches favorable to the collaborative design process; (2) inclusion of the construction and delivery phases of the buildings; (3) multidisciplinary collaboration from project design; (4) open exchange of information among all agents involved in the design process; (5) team success linked to project success; (6) use of technology as an analysis tool to aid in the search for solutions in the process of finding solutions (MANZIONE, 2013).

Manzione (2013) still identifies four aspects of the conventional design process that justify the adoption of IPD in the BIM project process: (1) little dissemination of good ideas; (2) the limitations of conventional contract arrangements that reshape innovation and interdisciplinary collaboration; (3) coordination difficulties related to the restrictions of the contract itself; and (4) non-visualization of the project as a whole forcing isolated solutions in their specific areas.

It is important to emphasize that the adoption of IPD is closely linked to the adoption of BIM itself. Oliveira and Pereira (2011) identified in their studies that the use of BIM only in its first stage of implementation as a 3D modeler without any type of alteration in the project processes, collaboration between teams and contractual means, does not bring significant advantages to AECO agents who end up leaving the Plataforma due to difficulties of use. Therefore, the use of the BIM platform brings with it, changes related to the IPD approach (MANZIONE, 2013).

BIM IN BRAZIL

In Brazil, few actions were carried out in the public sphere requiring the development of projects using the BIM platform. Despite this, it is possible to mention some initiatives such as: (1) the development of the OPUS system (Sistema Unificado do Processo de Obras) by the Brazilian army in 2006; (2) the development of the BIM library for typologies of the *"Minha Casa, Minha Vida"* program by CONTIER ARQUITETURA in 2010, required by the MDIC (Ministério do Desenvolvimento, Indústria e Comércio Exterior) in conjunction with ABDI (Agência Brasileira de Desenvolvimento Industrial); (3) the licensing made in 2010 by CDURP (Companhia de Desenvolvimento Urbano da Região do Porto do Rio de Janeiro); (4) bidding for the development of projects of 270º regional airports organized by ANAC (Agência Nacional de Aviação Civil) through Banco do Brasil in 2014; and (5) bidding for the construction of two hospitals by the Government of State of Santa Catarina in 2014. This last action led to the creation of the " Termo de Referência para desenvolvimento de projetos com o uso da Modelagem da Informação da Construção " in the state of Santa Catarina that requires the use of BIM for AECO projects since 2015 (KASSEM; AMORIM, 2015).

Regarding the standardization of the use of the BIM platform in Brazil, in 2009, the Special Study Commission on Construction Information Modeling, ABNT / CEE-134, was created through an initiative of the MDIC. The main functions of this committee were: (1) to translate ISO 12006-2 Organization of information about construction works - Part 2: Framework for classification; (2) develop a classification system for construction; and (3) develop guidelines for creating BIM components. The first stage has already been completed since 2010 when ABNT NBR ISO 12006-2: 2010 was launched (Construção de edificações - Organização de informação da Construção Parte 2: Estrutura para classificação de informação) (CATELANI; SANTOS, 2016).

Currently, ABNT/CEE's efforts are focused on the second stage mentioned above through the development of ABNT NBR 15965 - Sistema de Classificação da Informação da Construção. For this, the ABNT NBR ISO 12006-2: 2010 standard and the North American classification system, OmniClass, were used as reference.

ABNT NBR 15965 will be divided into seven parts and composed of 13 tables. Its main objective will be the standardization of nomenclature used in the AECO industry processes, specifically Brazil, through a face-to-face classification that uses the "... combination of several terms, with their corresponding codes, derived from different tables, for the complete discrimination of a component, resource, process or result generated "(CATELANI; SANTOS, 2016). The standardization of information in the BIM project is of paramount importance to ensure constant data flow, and this is a necessary effort to achieve the use of design practices such as IPD.

The *"Grupo de Trabalho de Componentes BIM"* (GT) was also created in 2012 to develop the third phase of the work of ABNT / CEE-134, which is still open (CATELANI; SANTOS, 2016).

Based on a survey carried out in the database of the Brazilian Association of Technical Standards (ABNT), the ABNT Catalog, it was possible to identify 4 parts of ABNT NBR 15965 and the standard ABNT NBR ISO 12006-2: 2010 currently in force. Since the establishment of ABNT / CEE-134, five standards related to BIM have been elaborated: (1) A ABNT NBR ISO 12006-2:2010 - Construção de edificações - Organização de informação da Construção Parte 2: Estrutura para classificação de informação; (2) ABNT NBR 15965-1:2011 - Sistema de Classificação da Informação da Construção Parte 1: Terminologia e Estrutura; (3) ABNT NBR 15965-2:2012 - Sistema de Classificação da Informação da Construção Parte 2: Características dos objetos da Construção; (4) ABNT NBR 15965-3:2014 - Sistema de Classificação da Informação da Construção Parte 3: Processos da Construção Civil; (5) ABNT NBR 15965-7:2015 - Sistema de classificação da informação da construção Parte 7: Informação da Construção..

In addition to technical regulations, some bodies, such as the AsBEA (Associação Brasileira de Escritórios de Arquitetura) and the CBIC (Câmara Brasileira da Indústria da Construção) have developed works related to BIM.

While in the technical standards the content is directed towards the standardization of information, creating a unique language among AECO players, the ASBEA guides provide suggestions and guidance related to the practical procedures of implementing BIM in the work routine of an office as: definition of implementation plan; definition of work team responsibilities; information on minimum requirements for software and hardware supporting BIM technology; information on team training; tips on how to organize files and folders on servers; procedures related to team collaboration; activity mapping and timeline; and methods of quality analysis of the models (ASBEA, 2013) (ASBEA, 2015).

CONCLUSIONS

The implementation of BIM requires profound changes in the AECO industry. Despite this, its successful implementation offers diverse benefits to all AECO industry project agents.

Many challenges still need to be overcome and a closer look at multidisciplinary collaboration is needed to avoid the continuity of traditional design methods in the work developed at BIM.

In the market there are still misconceptions regarding the platform. Companies implement BIM design software and use them as CAD tools optimized for the generation of automated 2D documentation. Others show resistance to BIM due to the investments in structure and training that must be made for implementation and that there are still considerable risks in relation to implementation.

CHAPTER 10

THE ENVIRONMENTAL ANALYSIS AND THE BIM SYSTEM

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THE ENVIRONMENTAL ANALYSIS AND THE BIM SYSTEM

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ABSTRACT

A growing process of integrating digital environmental analysis tools into the BIM system is recognized as a result of three-dimensional modeling, the potential of parameterization between geometry / information and interoperability between software and actors. This chapter deals with the dynamics of environmental analysis when integrated with the Building Information Modeling (BIM) system and proposes an investigation about decision-making strategies immersed in this environment during the design phases of the architectural design. So, how to deal, with a multidisciplinary approach, the conformation of the building elements – in the digital environment – to enable an adequate environmental performance of the architectural object? The results of this paper focus on the decision-making issues facing the complexity of the environmental analysis variables, inferring the relation between geometry and information regarding the modeling, parameterization and interoperability of the BIM system.

INTRODUCTION

Nowadays, the building design process aimed at meeting environ-mental requirements disposes a broad digital media support. The architectural design under these conditions fits within the context of complex problems involving different levels of importance and difficulty. These problems make it possible to achieve many solutions, and sometimes can present internal conflicts. Given that this dialectical scenario involves decision-making process it increasingly requires the use of digital tools. Some authors believe that, in this process, the way we recognize and evaluate results is a key issue (FERNANDEZ; LAVIGNE, 2009, p.33).

Regarding this problem, the present aim is to open a dialogue considering the environmental analysis and the Building Information Modelling (BIM) system. It seeks to highlight the role of the

designer as the protagonist and responsible person for the set of decisions that feeds the complex system of analysis together with digital tools. The methodological procedure onset follows a bibliographic re-search oriented to three themes: the building design process in Brazil, digital strategies for environmental analysis and the BIM system. The next step is to assess the dynamics of environmental analysis in the BIM system, by means four pre-established parameters: modelling; interoperability; database; and actors involved.

In summary, a reflection on the issues inherent to BIM is presented, under the perspective, who works with the environmental issues involved along the building design process. Therefore, it can be considering that the complex thinking and uncertainties inherent for the assumption process and also for the theoretical basis of this discourse.

COMPLEXITY AND UNCERTAINTIES IN THE PROCESS OF ARCHITECTURAL DESIGN

Essential for the debate with challenges of decision-making, is to consider the complexity and uncertainties inherent the relations established in the design process. These points are very important when we must deal with an increasing volume of information, criteria and variables, due to the advent of digital tools embedded in the process of architectural design. The problem is the key element that triggers a process that demands decision making. From the perspective of cognitive psychology, the "mental process of problem-solving consists of discovery, analysis, and solution" (KLEINMAN, 2015, pp.81-82). The process of solving a problem is neither inflexible nor linear and remains exposed to a constant process of feedback – aimed at correcting deviations to achieve the target result (VASCONCELLOS, 2015, p.213).

There are, however, two categories of problems: the well-defined and the ill-defined. Whereas well-defined problems have clear objectives and are amenable to direct methods, ill-defined problems cannot be solved using a specific method and they may require a combination of strategies for the investigation stages (KLEINMAN, 2015, p.83). Ill-defined problems involve different objectives, which may result in more than one solution and, therefore, are considered difficult to de-fine (SIMON, 1996). Within this category of problem there is an inter-relation between the different objectives, where the favouring of one of them interferes in every other objective considered in the equation, either positively or negatively. Solving these problems require dedication to better understand them and probably reduce their extent making their interpretation possible.

We often face problems considered *"ill-defined"* in the practice of architectural design. This is perhaps due to the number of variables, constraints and changing priorities throughout the design process, which exposes the elements in question to conflicting positions (SIMON, 1984). It is common to come across a similar situation in the process of choosing a simple window (at least apparently). There are different levels of priority for: size; technical characteristics; response to

climatic conditions; thermal, light, visual, acoustic and olfactory efficiency; costs; implementation and as many other factors as should be considered. Considering that the design process remains in constant motion of complex relations, it is natural to realize that contradictions will coexist.

"The danger of inconsistencies or gaps in this process is minimized in part by the capacity of architects and their abilities to identify the problem, which depends on their training and professional experience, as well as their ability to organize the process (...)" (SANTOS, 2012, p.47). Therefore, we assume as a premise, that the problem in architecture tends to resemble a plot, a tangle of elements connected in multiple directions.

DESIGN COMMITTED TO THE ENVIRONMENTAL PERFORMANCE OF BUILDINGS

It is common sense among several authors that all environmental requirements cannot be treated the same way and that the environmental problem in architectural design is a complex exercise (FERNANDEZ; LAVIGNE, 2009, p.33). There are concerns in different levels of importance that may generate multiple and sometimes contradictory responses, making the decision process even more difficult. The design of a building is composed of a myriad of parameters related to one or more elements, and *"even a relatively small number of parameters will give rise to many combinations"* (CLARKE, 2007).

Since the 1990s, environmental performance related to the architectural design is shown as an emerging issue. The study of environmental performance has been a challenge due *"use of comping simulations, both as a central tool for assessing the performance of the architecture itself and for integrating architecture and engineering of pre-existing systems (...)"* (GONÇALVES, 2015, p.237).

Computer simulation is a powerful mean for an analysis process (HENSEN; LAMBERTS, 2011). Multiple scenarios can be generated to different fields of knowledge, from games to engineering problems. The complexity related with simulations comes from the number of variables, information on the model, the calculation method, the time cut, and the software's interface and structure. However, computers only work for what they have been programmed, noticing that *"(...) simulation as a technique to understand and predict the behaviour, and predates digital computers"* (SIMON, 1996, p.13).

Recognizing the challenges inherent in environmental performance related to the architectural design of buildings; and also the data-management potential for software currently available, it is possible to identify in BIM technology an important tool to process information and to aid decisions. Thus: (I) as a tool, BIM works with a three-dimensional digital model and acts as a catalyst for information; (II) developers use the inter-software plug-in system to ensure interoperability and readability of information; (III) the BIM system links the geometry data to the most diverse information through parametrizable resources, generating a model with potential

for different types of simulation; and, (IV) both benefit from the rapprochement between actors involved in the design process through an inclusive and integrated process. Thus, on this dialogue, the items chosen and the parameters defined are justified.

BUILDING INFORMATION MODELLING

First of all, we should understand the term genesis and the evolution of the meaning of Building Information Modelling, *i.e.*, the BIM. Occasionally, the origin of this term is associated with the building product model, employed by Charles M. Eastman in his publications, from the late 1970s (KUBBA, 2012). However, despite linguistic and theoretical similarities, BIM was recognized as such only fifteen years later. The onset of BIM in 1995 caused *"an international movement for new collaborative tools and the creation of a unique data exchange format, the IFC format"* (MAURY, 2015, pp.89-90). The organization responsible for this movement was the International Alliance for Interoperability – IAI, now known as Building SMART.

Information added to the building digital model of the building and its way of sharing are decisive elements for understanding the primary meaning of BIM. After two decades, the meaning and applicability of the BIM have been extended (Figure 112), comprising *"the management of the digital three-dimensional model and the modalities of data and information exchange among the actors involved"* (CELNIK, O.; LEBÈGUE, 2015: p. 91). Nevertheless, free exchange of data through the IFC format is not yet dominant.

Figure 112 - Illustrated synthesis of the elements that currently determine the BIM system.
Source: Authors.

At present, to understand the meaning and applicability of BIM re-quire an emphasis going from the software structure to a set of actions that impact the design work process. More comprehensively, BIM is understood as an integrated work structure, capable of associating the design, implementation and management of the building and its elements. Hence, we may consider the BIM as *"(...) a process of work and collaboration between actors of a design under elaboration, based on specific tools that allows the de-sign and operation of a digital model, simulating the building as being constructed and operative"* (CELNIK; LEBÈGUE, 2015).

The digital model is established through a set of three-dimensional models, modelling data parametrization and information provided by the user. Therefore, according to these cited authors,

BIM is considered a *"digital database with an integrated structure, informed by the architecture, engineering, construction and operations industry, which consists of parametric 3D objects that allow interoperability"* (KENSEK; NOBLE, 2014).

3D MODELLING

When considered as a three-dimensional modelling, the BIM is added to information related to time, space and specifications that are increasingly common and *"allows a greater degree of coordination considering structure, services and the envelope of the building"* (LOVELL, 2010). The system proposed by BIM encourages constant feedback of information among people involved, collaborating for an active and participatory profile of the design team.

According to Eastman *et al*. (2014), the potential of these tools lies on the ability of parametric modelling, which guarantees autonomy and operability by the user, but still depends on the developer companies for interoperability. The model for simulation can be simplified geometrically (Figure 113), without ornaments, but it requires dedication and precision to model information: *"the quality of the results of simulation depends on the accuracy of the model"* (HENSEN; LAMBERTS, 2011).

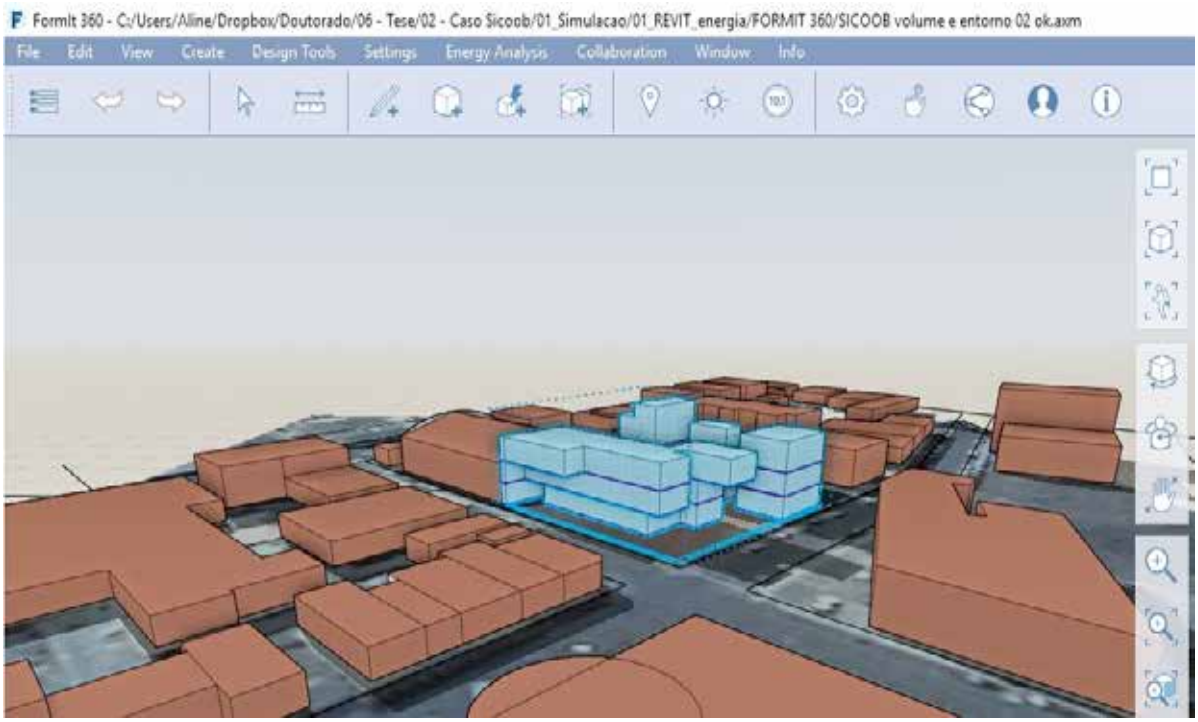

Figure 113 - 3D model under development of conceptual mass in the For-mIt 360 / Autodesk software for energy analysis and insolation.

Source: Authors.

The information valued related to a design process tends to grow along with the degree of technical or formal building complexity. Professionals are becoming increasingly specialized, and

this fragmentation of information and knowledge compels a distancing from the perspective of complexity needed for the design.

Overlapping layers from different designs as: electrical, hydraulic, heating, ventilating and air-conditioning system; landscape, safety, automation, accessibility, create complex interactions and suggest *"the need for an integrated approach to design"* (KRYGIEL, 2008, pp.54-55). Problems arise when information gathered from various sources is not sufficiently integrated. Properly managing information is determinant to minimize time and costs in the implementation stages (KUBBA, 2012).

Likewise, the 3D model is at the heart of relations and dialogue established among the actors. Thus, our main question is about the way each people visualizes, interacts and responds to the questions can be depicted from the model. The individual characteristics of each one has an influence on model generation, and the model needs to reflect the interest and requirements of each user. We highlight, however, that the objectives, parameters and decision criteria must match the interests set by the group.

INTEROPERABILITY

The debate on interoperability must reach at least two spheres that are directly linked: the first deals with the physical environment of the design process and refers to the exchange of information between ac-tors; the second is immersed in the digital environment and focuses on alternatives for exchanging digital tools. The intersection between both environments (physical and digital) incorporates the most important trade-off stage for this debate, *i.e.*, between actors and tools.

Two core questions come from the fact that BIM system proposes a concentration of information on the design of the 3D model which can be shared and receives interferences from the several actors involved in the several stages of the building life cycle: (I) direct dependence of the design on the three-dimensional model; and (II) connection and incorporation of all design actors into the same work sys-tem.

Clearly, for each question that can be raised there are advantages or disadvantages. In summary, the model design characteristics of con-centration 3D, and parametrizable, provide greater dynamics in favour of alignment and overlap between different designs; and also extends the possibility to use the model for the subsequent phases, as construction, restoration, requalification and/or retrofit.

Modelling in the BIM system allows more coordination between building information in the design, implementation, and use/activity phases. On the other hand, it results in heavy files that demand greater processing capacity of computers. Furthermore, modelling can be understood as underutilized, when layers of the design (structure, facilities) are designed in a non-parameterized two-dimensional system, making integration difficult to the three-dimensional model BIM (LOVELL, 2010).

Until today, not all software use the same format of data exchange, which is worsened by the increasing number of software used by the actors in the design process due to their specifications. In

summary, the system can be defined in two formats of data exchange: 1. Closed BIM (used by Autodesk, Bentley and Nemetschek); 2. Open BIM (IFC standard) that ensures the interoperability and durability of three-dimensional models. Both aim at a greater dynamic between the constant exchange of data and information during the development and implementation of the building design.

The Closed BIM format works under partnerships between software developers. For example, environmental analysis software such as the French model *ArchiWizard*, which are activated through plug-ins installed in *Revit*, *Archicad* and others. Thus, the exchange of data is directed throughout different software. However, there are already recognized problems of interoperability and rework to reinsert or check sent data.

The Open BIM system, known as Open BIM, has its technical basis in the *BuildingSMART IFC 2.0* certification procedure. It offers a transparent design flow, with the exchange of data made possible regardless of the software used. Thus, its objective is to avoid multiple data entry and consequent errors. As a result, "the Open BIM allows the integration of the design actors without imposing the purchase of one or another onerous platform" (HOYET *et al.*, 2016).

DATABASE

The set that makes up the digital 3D model adds data to its geometry. Normally, these are data related to information on types of materials; costs; thermal and physical properties and others. Modelling in the BIM system allows more coordination between building information in the design, implementation, and use/activity phases. On the other hand, it results in heavy files that demand greater processing capacity of computers (LOVELL, 2010).

In the digital environment, the transfer of data and information focused on the digital model must be clear and precise through different software adopted by the design team members. It is assumed that the database should be collective and collaborative, in which *"the semantics used in the description of components must be updatable and shareable (...)"* (HOYET *et al.*, 2016).

Moreover, the database of construction elements must be systematized and standardized, containing technical features that can be edited to meet the demand and objectives set by the designers. Specifically, the environmental analysis depends directly on the database linked to the design, be it the climatic database or the physical and mechanical properties of materials.

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ACTORS INVOLVED

The BIM system has here, as one of its premises, the interoperability between data, software and actors involved. Information sharing is the essence of both the integrated design and the participatory process, making the integration of different actors involved easier in the development of the design process (KUBBA, 2012; MARTINS, 2011).

Each group of design actors binds to a set of data needed throughout the process. For example, regulatory actors define normative data; suppliers collaborate with the composition of materials and their properties; designers – as decision makers – define geometry and articulate data and the choice of design solutions. Thus, the model adds information in a compatibilized and integrated way. The system proposed by BIM encourages constant feedback of information among the actors involved, collaborating for an active and participatory profile of the design team.

Finally, the designers and other actors are responsible for providing input data, the analysis and interpretation of the results of the simulations and, consequently, the results from the decisions made. Professional ethics and commitment to design guidelines must, therefore, guide this entire process.

ARCHIWIZARD CASE: FRENCH ANALYSIS SOFTWARE INTEGRATED WITH THE BIM SYSTEM

France has an advanced system of guidelines and standards focused on the design, implementation and verification of building efficiency. The standardization that involves thermal efficiency of the building is one of the most outstanding, due to the impacts on energy consumption and comfort inside environments. The first thermal regulatory standard, RT 1974, came into force in 1975. In contrast to the oil cri-sis, the country has invested in research and awareness to fight the fragility of energy. The most recent version is the Standard RT 2012, which feeds digital tools of environmental analysis in use in France (MOLLE; PATRY, 2011, p.5).

The RT 2012 *"(...) was drew up to respect the countries environ-mental commitments following Grenelle I and II Laws"* (MOLLE; PATRY, 2011, p.9). The standard applies to new buildings and new parts of buildings previously built. It defines that the average energy consumption of these buildings should be 1/3 from the previous standard, RT 2005; *i.e.*, a limit of 50 kWh/m2/year. In addition to this parameter, RT devotes attention to three main demands involving global energy performance: (I) bioclimatic design; (II) low consumption of primary energy; (III) good comfort conditions (MOLLE; PATRY, 2011, p.9). Therefore, its importance as a technical basis for digital tools of environmental analysis is considered.

The list of current analysis and simulation software applicable to projects in the area of architecture and urbanism is quite extensive. In France, some groups stand out in the development

of software focused on analysis and simulation: *Graitec*, with software for metal structures and reinforced concrete; *Clima-Win*, for thermal analysis; *Archiwizard*, for thermal and energy performance analysis; *Attic +*, for quantitative; *Élodie*, for life cycle; *Auralies* and *Phanie*, for environment simulations (CELNIK, LEBÈGUE, 2015).

In 2013, the close relationship of the School of Architecture with *RayCreatis Group* – Raytracing Software Solutions responsible for the development of *Archiwizard* software – favoured the implementation of this tool in the academic environment. This was done through re-search and investigations developed by professors and postgraduate students in the LRA (Laboratoire de Recherche en Architecture) or in undergraduate education through the ENSAT School of Architecture Toulouse. Under *Graitec's* management, since the end of 2016, *Archiwizard* software has no longer available the *Esquisse* version.

ARCHIWIZARD: THE SOFTWARE

The *Archiwizard* environmental analysis software – AWZ – is a good example for the discussion, since it is suitable for analysis in the study stage of the design process and its operation is similar to the others with this profile. To clarify the argument, we must inform that the AWZ is a French software, adapted to the current regulation RT 2012, and it uses the Energy Plus as algorithm for thermal simulation. Weather data can be added via *.epw formatted files or selected based on the *Meteonorm* database.

AWZ imports three-dimensional models from other software such as *SketchUp*, *Revit*, or *Archicad*, regardless of whether they adopt the BIM system or not. Once imported into the software's own platform, is possible to program the building envelope based on various digital catalogues of building components; perform thermal simulations, natural lighting, solar energy, renewable energy; and produce simplified results, easy to read through a user-friendly platform.

The interoperability feature adopted is done through plug-ins. This fact draws attention to the unilateral flow of information. The data are sent to the AWZ to change the geometry, to incorporate information, to select materials and their characteristics, in order to investigate different environmental questions. However, plug-ins do not allow the generated output to be forwarded back to software which help the de-sign process.

Information incorporated into the geometric model, *e.g.*, still in *Revit*, when sent to the *Archiwizard* (AWZ) should be reworked, since each platform handles information differently. For this reason, it is common to use simple software to create only the geometry, such as *SketchUp*, since information can be entered directly through the plat-form available in AWZ.

The three-dimensional digital modelling can be elaborated in different software generally adopted by professionals in the field of architecture, who work with a virtually universal language of graphic representation. This model must be exported to AWZ so it can be worked with, studied

and simulated (Figure 114). Its results must help decision making by re-feeding different steps of the architectural design. The interface is easy to visualize and automatically updates after each change.

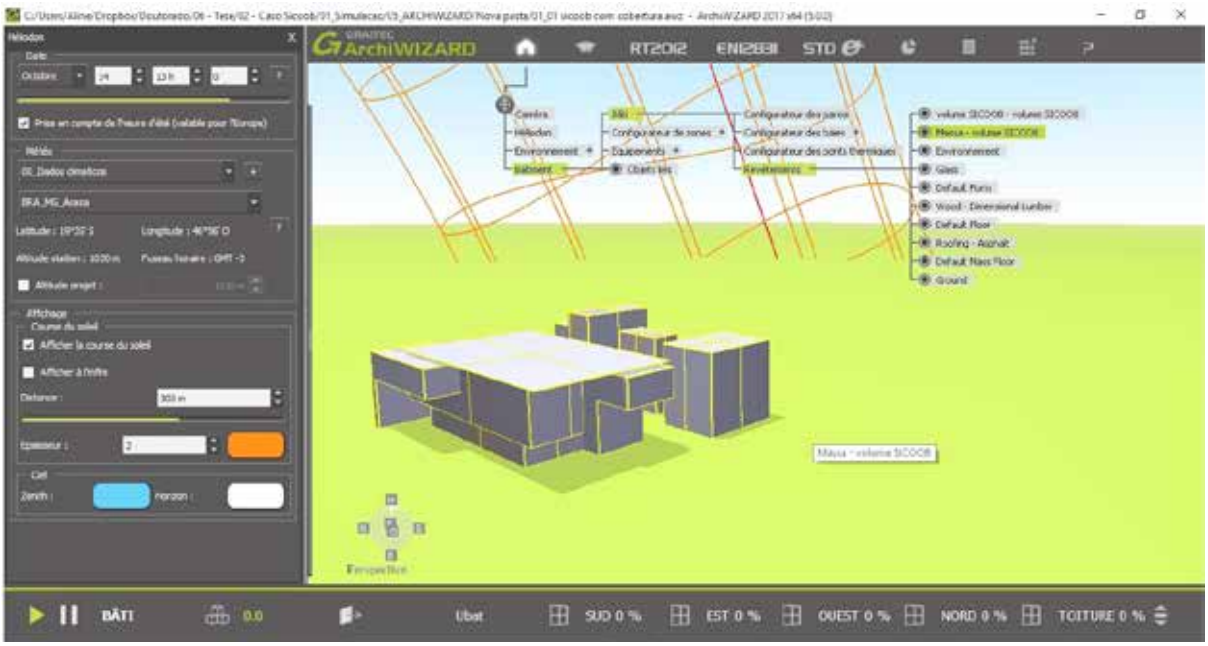

Figure 114 - Conceptual mass – AWZ platform.
Source: Authors.

Even if the model is imported from BIM software such as Revit or Archicad, where there may be information already added to geometry, it is better to import bulk geometry, without information, to avoid in-compatibilities. The interoperability between technical information is not efficient as the geometric one, which can even be updated. It demands checking and reworking. It is therefore recommended to import the geometry and to insert spans, windows and building features directly into the AWZ platform. Each group of surfaces can have their composition defined with greatest accuracy. The database of building elements is systematized and standardized, containing editable technical features to meet the demand and objectives of the simulations that can focus on one or more environments and even on the entire building (figure 115).

Figure 115 - Study area: AWZ platform.
Source: Authors.

The comparison between different simulated scenarios enriches the decision-making process inherent in the design process. This software encourages collaborative work between architects and thermal engineers, dedicated to work with the digital model (CELNIK; LEBÈGUE, 2015). It offers the opportunity for these professionals to work under an integrated way from the preliminary stages of the design process.

One of the major benefits of using this software model is its applicability in preliminary design steps. Nonetheless, as well as other digital simulation software, they only simulate, which does not guarantee the efficiency of the building in practice. That is, during the useful life of the building there are several unstable variables that are difficult to include in digital simulation. For example, there is the action of the user, which can only be estimated by contexts defined over specific periods for simulation data. Hence, conscious and responsible actions when considering the environment is as important as each action of the designer throughout the other stages of the analysis.

CONSIDERATIONS ABOUT THE APPLICABILITY OF ARCHIWIZARD SOFTWARE IN BRAZIL

The use of this software, specifically in humid climates, is restricted to simulation of insolation or comparative studies, since the humidity of air interferes directly in the investigation of thermal control and energy efficiency of the building. Such complex calculations are not yet covered by the system. Nevertheless, the simulation does not have specific algorithms for the isolated calculation for natural ventilation, considering the permeability of the building through indices and standards pre-established by norms in force in the French context.

Given information reported so far, how could *Archiwizard* soft-ware be applicable? As for *Archiwizard*, the restrictions are similar to other international software regulations which do not apply to our weather characteristics. Buildings with high permeability, indoor natural ventilation and humidity interference in thermal conditions are, ac-cording to Bernard Lecussan, characteristics that increase the complexity of the calculations needed for simpler simulation software (CELNIK, O.; LEBÈGUE, 2015).

Despite its limitations, there are no restrictions to consider *Archiwizard* software as a potential analysis tool. Among others, the challenges of integration with the BIM system and of interoperability; the opportunity for integration between different professionals; the systematized database of building elements; the possibilities of use for simulation of insolation and all other comparative tools allow the thorough reflection of the criteria and parameters considered. Being aware of the tool's efficiency for low-permeability environments and considering heating energy costs –an item that should be deactivated for calculations in most of Brazil – we can consider it as efficient for study purposes. Presumably, it is inadequate for validation of energy efficiency indices, as it does not use domestic laws or standards as a basis for calculation.

The platform provided by AWZ also alerts us to the existence of a consistent database and a systematization and standardization of the physical characteristics of the materials used in the Brazilian civil construction. The environmental analysis depends directly on the database linked to the design, be it the climatic database or the physical and mechanical properties of materials. Even with the limitations and problems described, software with this profile are configured as important tools to study the alternatives for the design process.

FINAL CONSIDERATIONS

If we reflect about the dynamics and challenges proposed by the architectural design practice, is possible to identify an opportunity to investigate and better understand the multidisciplinary relations established during a design process, as Mitchell (2008) states: parameterization aspects, three-dimensional modelling associated with information and interoperability, when associated with and applied to the project. Favour the creation of *"new design worlds"*, paraphrasing Mitchell (2008).

The technology offered through the BIM system is *"particularly valuable for sustainable design"*, since it enables the creation of a virtual three-dimensional model of construction and all its systems (KUBBA, 2012). Prepared in a format that can be shared among the design team, it facilitates integration and information sharing. This change must happen frequently throughout the design process, be-tween the actors or between the tools involved.

As standards and certifications are advancing, software, considered as design tools, are also developing at great strides. Digital analysis tools are increasingly being incorporated into the design tools, most of which directed to management, costs, heat analysis, thermal and energy performance. BIM accepts plug-ins that can perform thermal, light and other simulations, as well as provides a platform for the data required by certification bodies (KIBERT, 2013).

By adopting the three-dimensional model as a catalyst for information on the design, there will be the benefit of a faster and more dynamic process. This will allow the integration and collaboration of the different actors in the process. We consider this scenario as an opportunity to strengthen the links between aesthetic and technical criteria, to cooperate in the development of projects related to high performance and committed to sustainability.

Some issues still prevent this set of proposals from working properly. Interoperability is one of the oldest issues and the solution adopted by the software management companies, the plug-in, is here to bring up new questions. The use of plug-ins as a partnership strategy be-tween software make the designer's access easier to the analysis tool. Until some years ago, plug-ins were almost exclusively used by experts in the field. With user-friendly interfaces and simplified data processing, in a few steps, with correct information, you can see, for example, the solar building incidence and the thermal load obtained for the envelope. The thermal and light simulations are incorporated into the BIM system. However, more complex simulations such as natural ventilation, performed using CFD (Computer Fluid Dynamics), are not frequent.

Summarizing, the BIM system is understood as an environment that associates the physical space (actors and decision territories) with the digital space (parameterizable 3D model). It is believed that the potential of the BIM environment lies in the exchange ability it offers, either among the actors, between actors and tools or among the tools. Hence, we highlight that all this potential of articulation depends directly on the decision-making of one or more actors in a context of a broad set of physical and digital information considered together.

CHAPTER 11

A DIGITAL FABRICATION EXPERIMENT: FURNITURE PARAMETERIZATION, PROTOTYPING AND MANUFACTURING

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A DIGITAL FABRICATION EXPERIMENT: FURNITURE PARAMETERIZATION, PROTOTYPING AND MANUFACTURING

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LETÍCIA MENDES

ABSTRACT

The techniques of digital fabrication and rapid prototyping are already consistent technologies and increasingly present in the fields of design and construction. The increasingly significant presence of Computer Aided Design and Computer Aided Manufacturing systems in designing the most varied artifacts has been a subject of much discussion in the various fields of the creative industry. Parallel to this discussion, the introduction of the parametric design approach has great importance in obtaining new perspectives and innovation in design. Thus, in order to associate the potential of rapid prototyping and digital fabrication tools and a generative design system, this paper describes the development of a furniture design - an exhibition panel and tool organizer - through the detailed documentation of the processes and procedures carried out for its completion. Unfolding as well, about the paradigm shift in the design process, consistent with the potential of the digital resources.

INTRODUCTION

Geometric representation through digital files is already a usual procedure in the design process. CAD / CAM (Computer Aided Drawing) has been the leading industrial design and engineering technique for over 50 years (IWAMOTO, 2013). The CAD was essentially a transfer of the traditional drawing techniques to the digital medium, which allowed greater precision and control of the compositions, through layering and defining properties referring to each 'trace'. In a digital environment, a precise shape registration made it possible to fabricate objects with accuracy, from parts of the building to a whole, using automated machines (Computer Numerically Controlled, or CNC).

In contrast to the repetition paradigm imposed by mass production, the use of rapid prototyping (RP) and digital fabrication technologies (DF) enabled us to produce much more quickly and discuss the concept of mass customization[1]. From a parametric design approach, it becomes possible to develop the precise design of the elements that make up each piece, as well as change easily characteristics of these elements. Within this paradigm of conception and representation, the present experience made it possible to highlight two problems: the limitations of editing imposed by the software used in the design process, and the need for such changes to be continuously appeased to the conventions and consistencies of the designer.

In order to reduce and streamline these repetitive tasks within complex compositions and expand the possibilities of editing within the digital medium, new forms of interaction with these platforms were created, incorporating programming within the design process. The design began to be planned and linked to parameters and operations with algorithm logic - the parametric design. An algorithm is a procedure used to return a solution to an issue - or to perform a given task - through a finite list of basic and well-defined instructions (TEDESCHI, 2014). Linked to properly structured procedures, this design strategy also consists of defining topological relationships between the parts of elements, the definition of precise measures being a subsequent phase of the project. In general, these dimensions can be selected from a desirable range, with minimum and maximum values, always multiples of the measures of the constructive components, resulting in greater flexibility and variety (Figure 116).

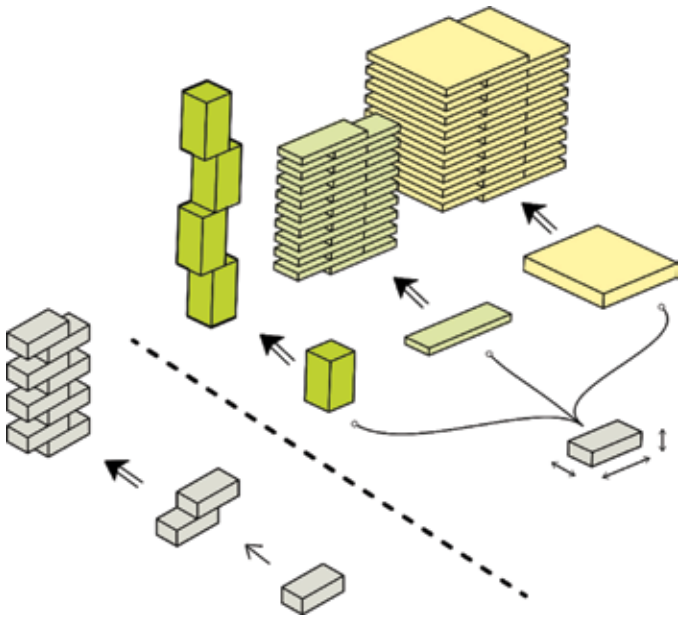

Figure 116 - Example application of the parametric design approach in a rule based design.
Source: Authors.

[1] The concept of mass customization was defined by authors such as Stan Davis (1996), Tseng and Jiao (2001), Pine (1993), and Kaplan and Haenlein (2006). In architecture it was notably used by José Pinto Duarte in his doctoral thesis entitled "Customizing Mass Housing: A discursive grammar for Siza's houses at Malagueira" (2001), which proposes a discussion about the profound implications of mass customization in architecture and the construction industry (MENDES, 2014).

Parameterization incorporates associative relationships between elements of a design, viewing these relationships as processes rather than static results. This allows properties (both quantitative and qualitative) to be bound to the parameters. Such parameters are interactive in a defined and planned manner by the designer, and allow the rapid change in complex compositions, generating diverse results with precision and agility.

With regard to the manufacture of these artifacts designed and registered in digital media, several technologies are already quite popular in the market. This machinery (CNC) is able to interpret the numerical data (recorded through software input) in processes that perfectly materialize the shapes in the materials used. The most common processes are subtractive, additive and formative. In his thesis, Pupo (2009) adopts the terms prototyping and digital fabrication, referring to methods that allow the transition from the digital model to the physical in an automated way.

The first term, DIGITAL PROTOTYPING, includes all the techniques of rapid prototyping (layer overlapping), laser cutting, milling and cutting with vinyl, for the production of small scale models and prototypes in a 1: 1 scale. The second term, DIGITAL FABRICATION, includes techniques for the production of buildings or parts of them (file-to-factory[2], metal and tube bending). These, in turn, are destined to the production of forms or final pieces of buildings, with CNC equipment (PUPO, 2009).

The additive ways of producing prototyped objects, that is, those built layer by layer, are the most popular (PUPO, 2009) (Figure 117). All additive manufacturing technologies share the principle that the solid model is sliced into two-dimensional layers. The computer that controls the machine processes each layer of information, overlapping layer upon layer, gradually generating the product (JACOBS, 1992 *apud.* KOLAREVIC, 2001). Using this manufacturing process, several different technologies compete in the market, using various types of material and curing processes, based on exposure to light, heat or chemicals. Stereolithography (SLA) is based on liquid polymers that solidify when exposed to light. In Selective Laser Sintering (SLS) a laser beam melts layer by layer of metallic powder to create solid objects. There is also the 3DP, where layers of ceramic powder are glued together forming objects, the LOM (Laminated Objects Manufacturing), where sheets of material (paper, plastic, wood) are glued and cut. In the most widespread method, the Fused Deposition Modeling (FDM, widely known as 3D printing), each cross section is produced by melting and depositing plastic filament that solidifies to cooling. The overlapping of these sections creates three-dimensional solids.

[2] File-to-factory, which means "from the archive to the factory", deals with the production of digitally produced projects through digital fabrication. Pupo (2009) characterizes the process as "when the 3D digital model communicates directly with programmable cutting machines".

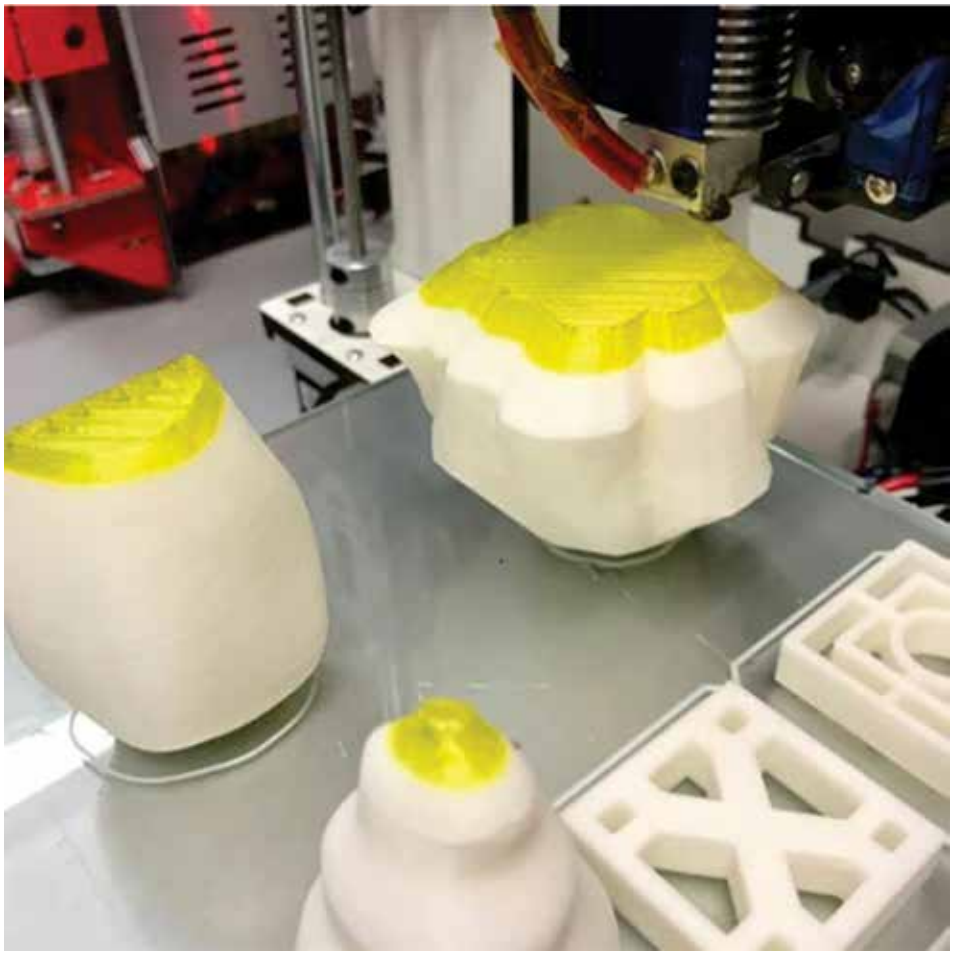

Figure 117 - Additive production process in the GREA3D laboratory, through the 3D printing process with two different types of filaments.
Source: Authors.

In the formative process of manufacture, mechanical forces, restrictive forms, heat or steam are applied in a material to mold it into the desired shape, through reforming or deformation, which can be restricted to an axis or surface (KOLAREVIC, 2001). With little use in the context of prototyping, this process is more applied in the digital fabrication in folding and mechanical deformation of metal parts and tubes (Metal Bending and Tube Bending).

The subtractive process involves the removal of certain volumes of the solid's material, using for example three-dimensional milling. In CNC milling, a dedicated computer system controls the functions and movements of a tool using a set of coded instructions (MCMAHON, BROWNE, 1998 *apud.* KOLAREVIC, 2001). These instructions precisely guide the computer to the location and depth of cuts and scratches applied to the material, subtracting part of its volume and resulting in the desired three-dimensional artifact.

One of the subtractive procedures, two-dimensional cutting of materials is the most common manufacturing technique. Several technologies such as plasma arc, laser beam, or water jet, involve the relative movement in two axes, of the sheet of material in relation to the tip that performs the

cut (KOLAREVIC, 2001). In plasma arc cutting, an electric arc is passed through a compressed gas at the cutting tip, heating the gas to the plasma form with a high temperature (14,000 ° C), which converts to gas again when transferring its heat to the cut material. In CNC waterjet machines, a high-pressure water jet is mixed with abrasive particles and forced through a narrow outlet, in a precise flow, causing the rapid erosion of the material in its path, but making very clean and precise cuts. In the present work, laser cutting technology was used, whose high-intensity infrared ray in combination with a jet of highly compressed gas (gas or carbon dioxide) makes it possible to melt or burn the material to be cut (KOLAREVIC, 2001). The choice of the most suitable type for each application depends on the material used, since each technology has specific thickness and material capacities (PUPO, 2009). While water jets can cut virtually any material with high thicknesses, laser cutters are limited to materials that can absorb light energy and only effectively cut small thicknesses.

The combination of this new conception paradigm, which quickly idealizes continuous changes and improvements in the production of artifacts, and the popularization of digital fabrication technologies, has massified the practice of production of intermediate models, either for the documentation of the design process, or for empirical verification of design decisions. This nimble digital fabrication of prototypes, of intermediate test models, has been termed rapid prototyping. As the set of technologies known as rapid prototyping emerges and is absorbed in practice, it has been recognized as an advance of potential design significance (SASS, 2006). For this method, small scale models are made quickly, using rapid prototyping machines that transform virtual data into physical models with high precision (IWAMOTO, 2013). The distinction between the objectives of the manufactured product determines the digital process terminology applied, according to Pupo (2011), prototyping methods are intended for the production of prototypes or evaluation models and used during the design of the project and assist in the evaluation of the alternatives generated. When these products (or constructive elements) are used directly in construction, they refer to the fabrication system or manufacturing. (PUPO *et al.*, 2011).

Facing this new horizon, opened by the increasing popularization of digital manufacturing techniques, several international and national universities have presented a growing number of experiments aiming the discussion of the transformations that occurred in the design process from the introduction of digital technologies, such as systems generative models, parametric modeling and RP and DF techniques (Figure 118).

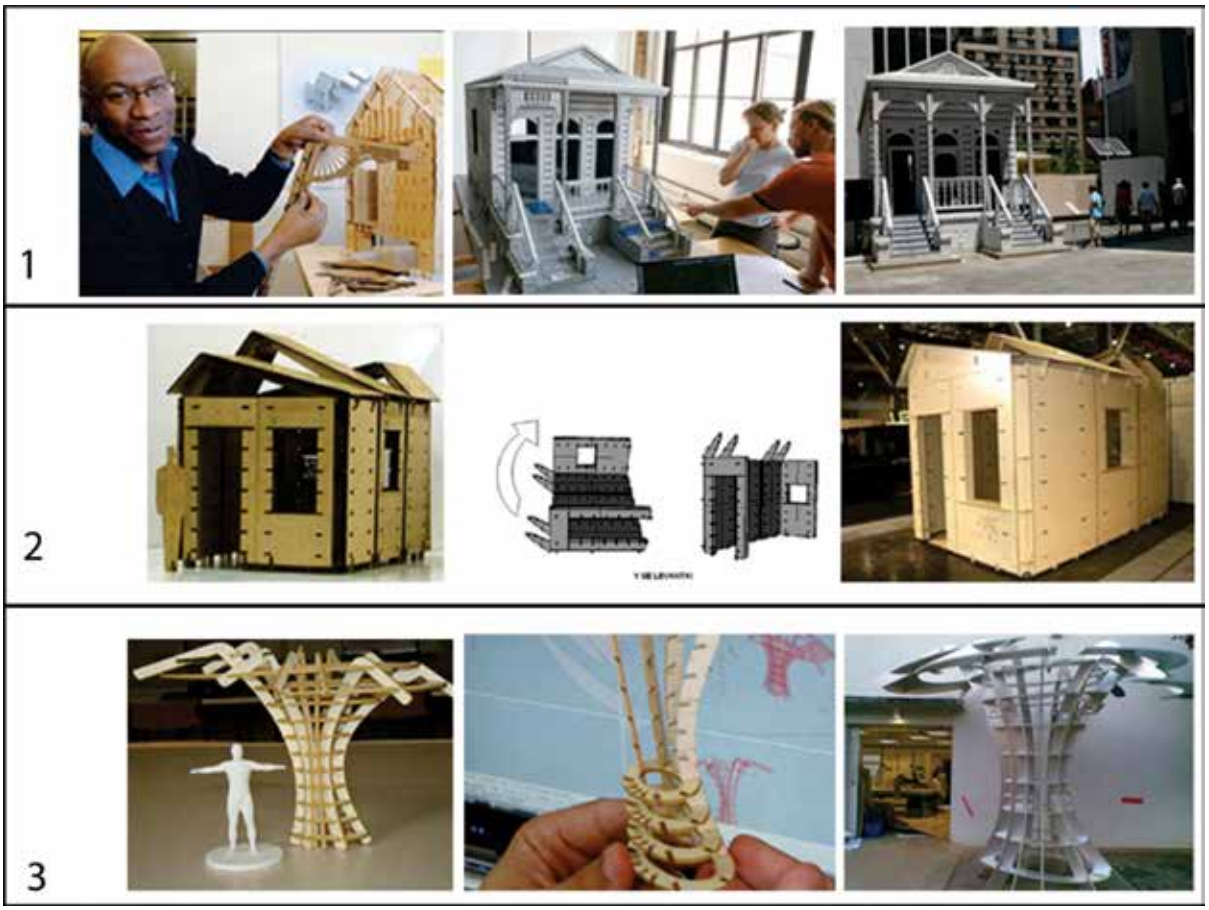

Figure 118 - Examples of experiments developed at international and national universities: (1) Instant House - a project developed at the Massachusetts Institute of Technology (MIT), coordinated by professor Dr. Larry Sass (SASS, 2008); (2) Casa Generativa (Casa G), a project developed at the Federal University of Rio Grande do Sul - UFRGS, coordinated by professors Dr. Benamy Turckienicz and Dr. Rodrigo Garcia Alvarado (CASA G., 2010); (3) Structure developed at the State University of Campinas (UNICAMP), coordinated by the teachers Dr. Gabriela Celani and Dr. Regiane Pupo (PUPO et al, 2011).

Source: Authors.

Within this context, in 2017, a laboratory was inaugurated within the Department of Graphic Expression of the Federal University of Pernambuco - the 3D Artifacts Experimentation Group, or GREA3D. The GREA3D laboratory came from the didactic need for researches developed in disciplines and scientific projects involving topics such as prototyping and digital fabrication, generative design systems, robotics, parametric modeling, among other disciplines where the practice would be enriched with a laboratory equipped with equipment of automation applied in the design process. This initiative was made possible by resources from research institutions, among other partnerships, that equipped the lab with several 3D Printers and a Laser Cutter, which are operated by monitors, students of Graphic Expression and Architecture and Urbanism (Figure 119).

Figure 119 - The lab's CNC laser cutter fully functional.
Source: Authors.

The present work aims to describe the development of a furniture project - a panel for exhibition of objects and tool organizer - designed by a student of Architecture and Urbanism during the period of Institutional Internship. The result of the experiment would be exposed in the official inauguration of the laboratory and, later, would be used continuously by the lab. In addition, the panel should be manufactured within the laboratory, using its RP and DF equipment.

In light of all the new paradigms presented here, and considering the objectives aimed by the laboratory, the student's project choices reflected the desire to incorporate these aspects into an interesting experiment in the pedagogical sense, through the empiricism involved, and in the symbolic sense, to produce a panel consistent with current challenges and practices. Thus, the design party was defined: unite the potential of rapid prototyping technologies, opened by the availability of the equipment present in the laboratory, with the relevance of parametric design, agility of adjustments and design improvements.

In the following section, the design and manufacturing process of the parametric panel for the GREA3D laboratory —a product of the combination of the parametrization approach and digital fabrication technologies — will be presented from its design to its cutting and assembly process.

DEVELOPMENT, PROTOTYPING AND MANUFACTURING METHODOLOGY

The panel should be 2.10m x 1.10m in size, be wall-mounted and serve as a tool panel for the laboratory's daily routine. Among the established requirements, it would be necessary to ensure that it would be distant enough from the wall, due to the apparent piping of the split system air conditioner installed in the room (Figure 120).

Figure 120 - The wall where the panel was placed, being painted.
Source: Authors.

The source of inspiration for the design was the visual identity of the laboratory, chosen by tender in the previous year (2016). The developed two-dimensional logo suggests a three-dimensional shape with the addition of contrasting colors (Figure 121). Thus, the design concept aimed to materialize the logo as a three-dimensional figure, later using its forms for the purposes of exhibition and tool support.

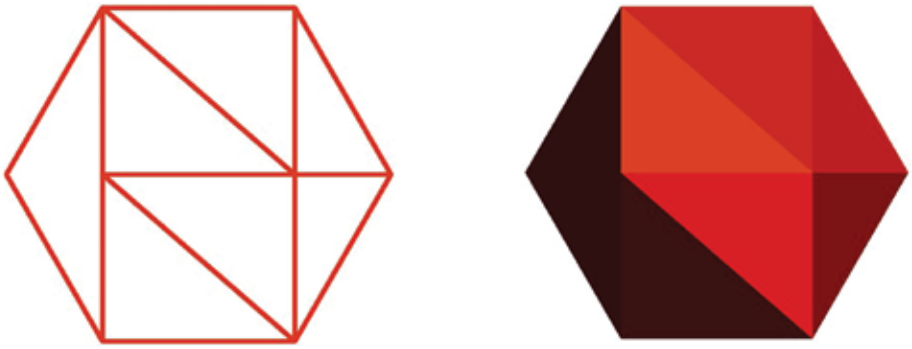

Figure 121 - The Laboratory logo, drew in lines on the left, and colored on the right.
Source: Authors.

CODE AND MODELLING

The artifact coding and modeling was performed through the 3D modeling software Rhinoceros 5 and the Grasshopper plugin. Grasshopper is a graphical algorithm editor, completely integrated with Rhinoceros modeling tools. Without the need for in-depth knowledge of the programming languages involved, this plugin allows designers to build form generators, from the simplest to the most complex (GRASSHOPPER, 2017). With the use of these tools it was possible to generate the three-dimensional form of the panel, by means of the parameters defined within the project to fit it perfectly to its point of implantation.

The conceptual design established as the starting point a three-dimensional artifact whose frontal view projection referred to the original logo, so it was clear that it needed to contain the triangular elements already present in the logo. To account for the long useful area, these elements were separated into three fundamental groups departed from each other. In the remaining spaces of the surface, curvilinear shelves were arranged, with parameterized variations of depth. These shelves, because they are horizontal and flat elements, would not interfere with the intuitive front view of the logo and would give unity to the composition. Due to the elongated dimension available to the panel, the logo needed to be centralized later, at the suggestion of the teachers themselves, something that was done quickly, by parameter adjustments.

Because the defined fabrication was a two-dimensional cutting process, all the objects that composed the artifact demanded to be decomposed in planar curves to be able to be produced. For this reason, the primary concern in the parameterization was to create the surfaces that generated the panel volumes. The other details, such as the fittings between these pieces, would be implemented later, with reference to these already defined surfaces.

The first starting parameter defined was the panel area itself, a flat, orthogonal surface, and was a reference for various procedures within the design. This area was divided respecting the proportions of the logo and maintaining the identity of the symbol. The resulting surfaces of the division were then subdivided into the triangles of the logo and rotated out of the plane. The

rotation was in such a way that the figure projected onto the surface of the wall exactly traced back to the original symbol (Figure 122). These surfaces were then used as reference to generate their "closures" - other surfaces (perpendicular to the working area) that would connect their vertices and displaced edges to the original plane, giving a unit volume for each group of triangular pieces.

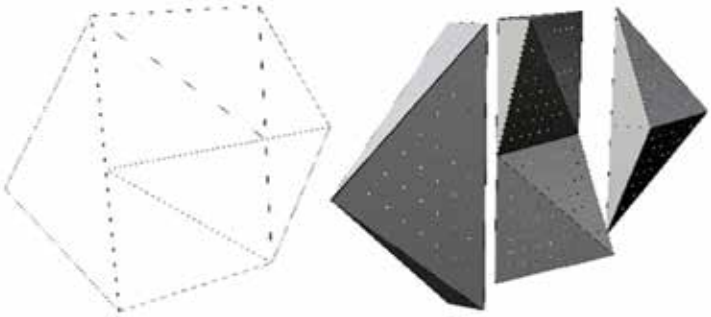

Figure 122 - On the left the edges of the logo that originated the volumes (on the right) present in the panel.
Source: Authors.

The shelves were generated from 4 basic parameters: a minimum depth, a maximum depth, the distance between them (maximum height of the placed objects) and a curve entry. These input curves have a modeling function on the shelf set, generating variation in their depth according to the distance to these drawn curves (Figure 123). After that, the final design of the shelves was then adjusted to match the edges of the logo volumes, matching the points of intersection between the plane of each shelf and the volumes of the logo.

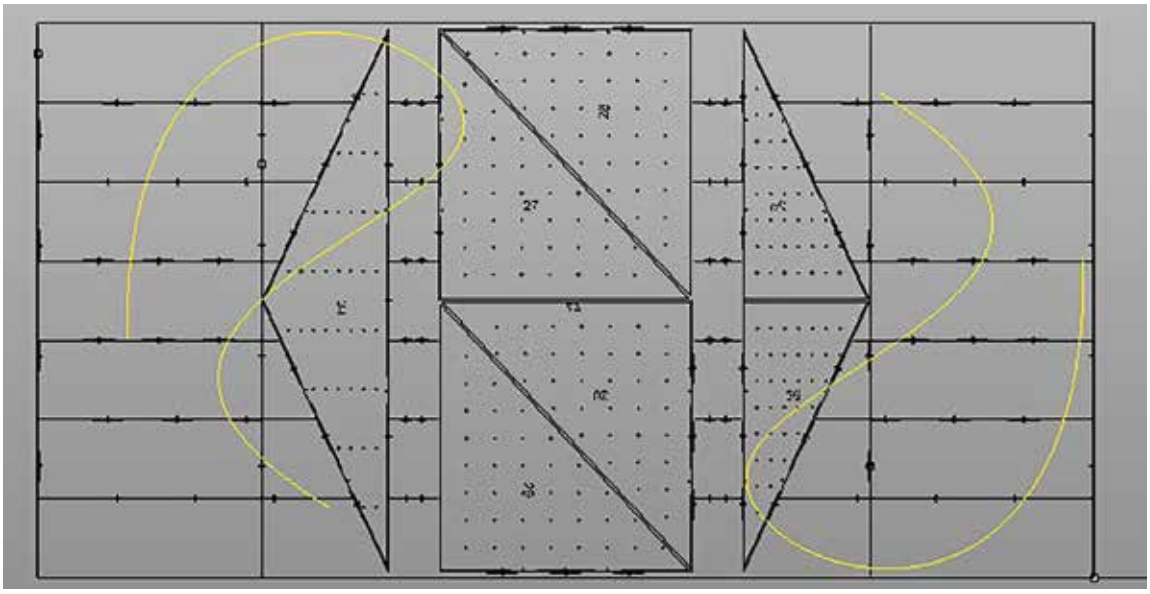

Figure 123 - In Yellow, the curves used to generate the shape of the shelves on the panel.
Source: Authors.

The logo was thought beyond sculptural element to have the purpose of tool support. For this, another function performs the drilling of the plates, in a grid of circular holes similar to those found in Eucatex metal panels, which are often used for storing tools.

Only one type of joint was used in every artifact, and its implementation was one of the most interesting in this experiment, since it has great potential to be repeated (and improved) in later designs. Within this project the inserts were implanted from a function that receives the pieces to be inserted, size and number of inserts between them, and draws the details of these inserts automatically. The recess consists of the rectangular extension of sections of the plates, which begin to penetrate the others through rectangular holes also drawn. On each side of these extensions and orifices are two other holes, made for the passage of nylon clamps, which permanently fix the nested parts. This was a very practical and low cost solution for the execution of the project, for generating a manual assembly process, without the need for tools.

The agility of parametric modeling allowed the design of several preliminary designs (Figure 124), each of which was submitted to the judgment of the laboratory users. This allowed the integration of the most relevant qualities to the final product.

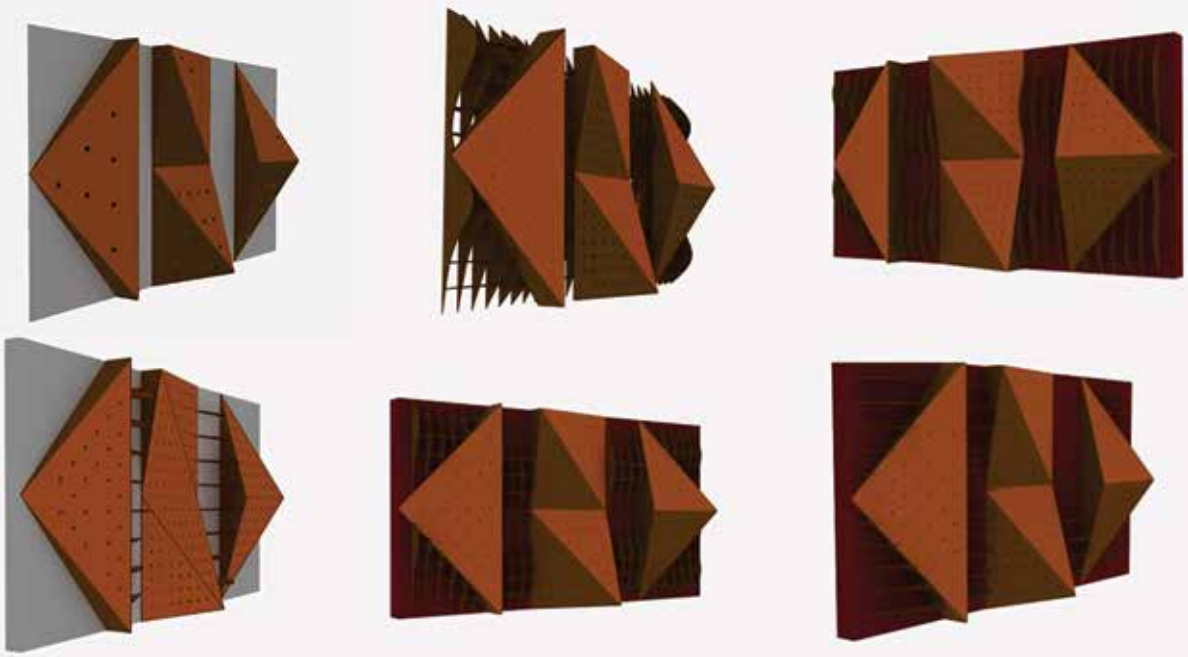

Figure 124 - Several preliminary designs elaborated and judged by laboratory users.
Source: Authors.

After approval of the final design, it was necessary to transfer the implemented geometry inside the Grasshopper (Figures 125 and 126) to the Rhinoceros, to then manufacture the first prototypes, for testing the material consistency and the panel volume. Thus, through rapid prototyping, it would be possible to verify the efficiency of the joint system, in addition to exploring the possible ergonomics of the final product.

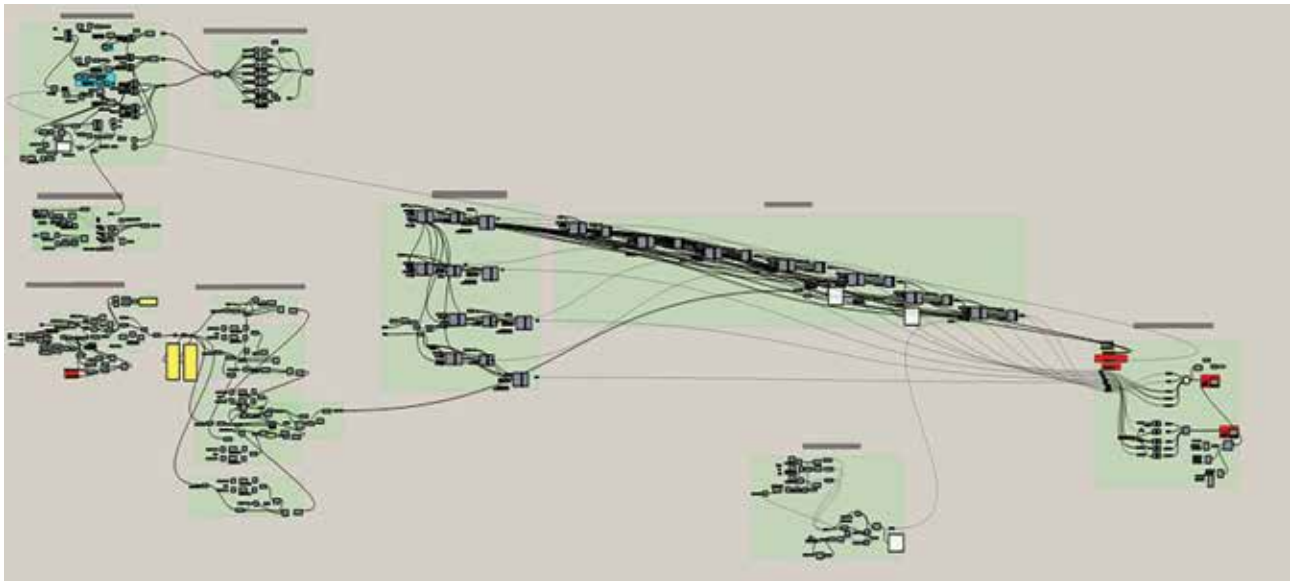

Figure 125 - The structure of the coded algorithm inside Grasshopper interface.
Source: Authors.

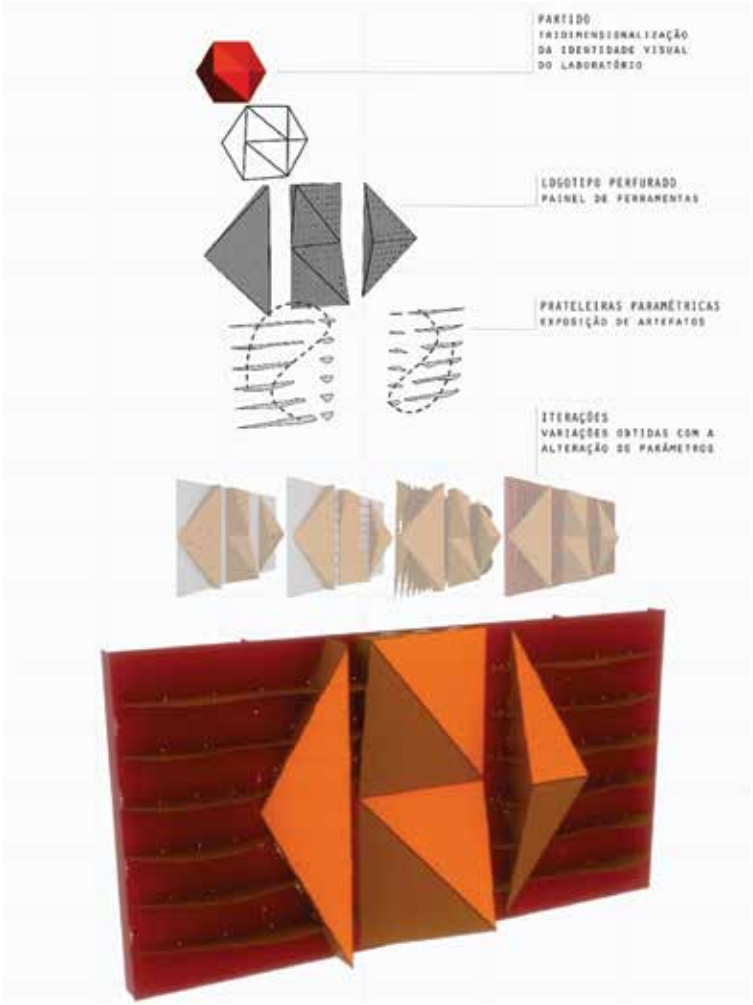

Figure 126 - The conceptual process leading to the final design.
Source: Authors.

PROTOTYPING

The material used for panel prototyping was the same material used in the final product. The rapid prototyping process of the panel used MDF sheets, 1 and 3 millimeters thick, cut with laser cutter CNC. The laboratory machine has the maximum cutting capacity of a sheet of 0.90 m x 1.20 m, and MDF cutting of up to 5 mm thickness has been tested. It was necessary to perform some tests to verify the best power and cutting speed for the 3mm MDF before proceeding to the first prototype.

The most adjusted parameters in this phase - those that justified the parametric implementation of the project - were the material thickness, the laser clearance and the length of the joints. As the model created through programming was relative to the thickness of the material, this allowed the immediate adjustment of the design to any thickness of material, allowing any of the materials available in the laboratory stock to be used for prototyping. And because the machine's laser performs cuttings by burning the material, these cuts directly influence the final area of the subtracted surfaces from the sheets. It was by the fine adjustment of the laser clearance parameter, which verified empirically the thickness in millimeters of the cut made by the machine, that it was possible to adjust the dimensions of the cuts to consider this aspect. Finally, as the prototype tests were made on smaller scales so as not to waste material, the length of the joint was also regulated for each case.

The first prototype produced was a scaled-down part (1:10) of the panel, in 1mm MDF sheet, containing one of the parts of the logo and its support surface. This prototype proved to be insufficient to be assembled successfully, due to the exaggerated scale. But it served to understand the best laser slack for that thickness.

The second prototype produced was a slightly larger (1: 7) scale version of the same parts of the panel, this time using the thickness 3 mm (present in the final product), containing the same parts of the panel. In this prototype, there was one more problem in the design: the pieces failed to take into account the way the thickness of the cut plates influenced the fit between them. In this prototype, the cut elements were slightly larger than the space available for their joining, because the design still counted them as planar elements, without thickness. After the material thickness parameter was implemented, a real-scale cut of the same parts of the panel was performed. However, it was necessary to adjust this parameter in the final cut. The first prototype cut in real scale still presented problems of fit (Figure 119), although it managed to be properly mounted.

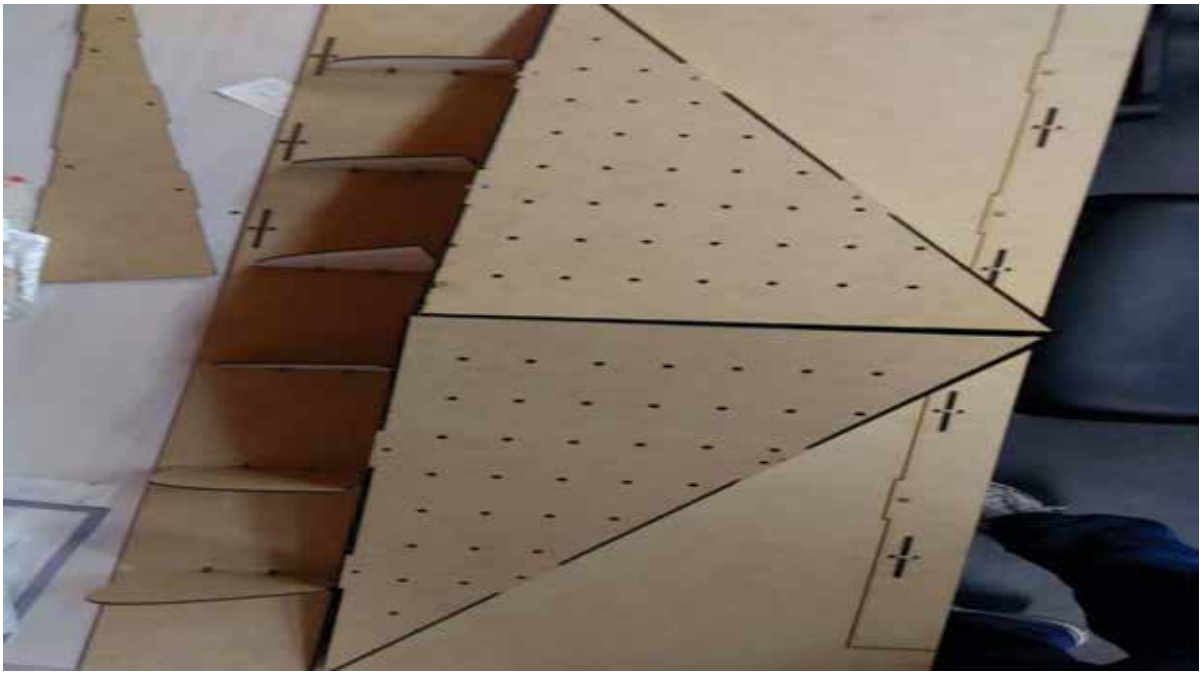

Figure 127 - First real-scale prototype, with joint problems.
Source: Authors.

The execution of these preliminary tests gradually gave confidence and feasibility to the project. After the production of these prototypes, there was discernment in relation to unforeseen problems, but that could be solved before the next step: manufacturing.

DIGITAL FABRICATION

In this stage, the final activities of artifact production were performed: the cutting and assembly of its elements.

At the first moment, prior to cutting, it was necessary to optimize the position of the pieces to minimize material expenses, a procedure called nesting (Figure 128). A plugin called RhinoNest was used to perform this task in an automated way, taking into account the size of the sheets purchased for manufacturing (0.90m x 1.20m). Only then was the the files produced by the Rhinoceros software were converted to the software-readable format used on the computer controlling the CNC machine (STL format).

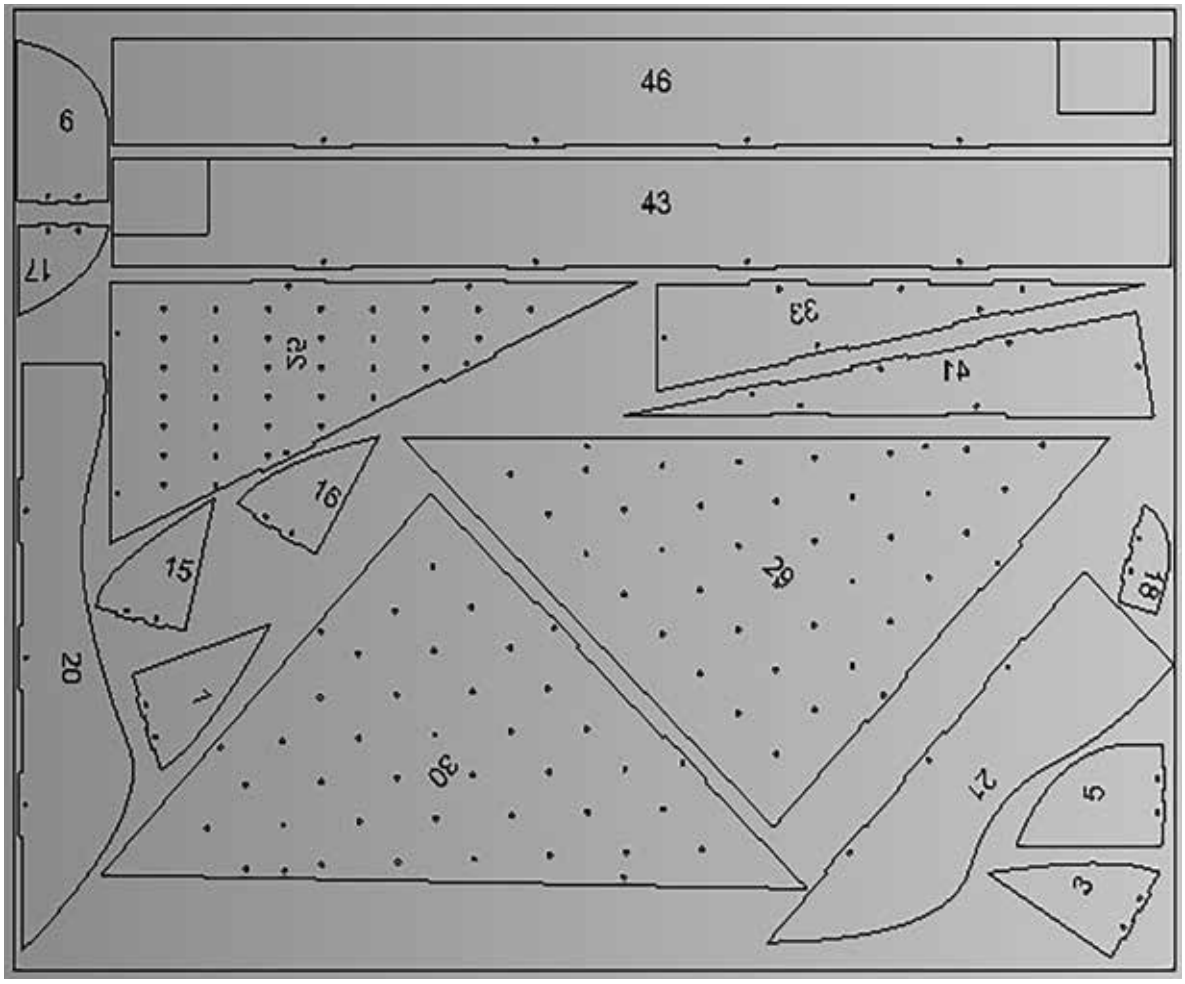

Figure 128 - Nesting of parts on one of the sheets.
Source: The Authors.

However, some issues have undergone unforeseen changes, which were only confronted at the time of manufacture. For reasons of economy and practicality, a large plate with the exact size of the panel (1.10m x 2.10m) and already with a factory red finish, was bought. This plate was even thicker than the others (5 mm thick), to give more stability to the panel. Because it was thicker, it took much longer to be cut, and because it was longer it needed to be cut in 3 parts to be able to receive the joint holes. Behind these boards, metal profiles were then attached to firmly hold them, and serve as supports of the panel on the wall. In addition, the purchased MDF boards had different treatments on each of their faces. One face was raw MDF, and the other had a white plastic finish. As the cut pieces were painted with orange paint, these elements had differentiated adhesion of the paint, having slightly different colorations on each face. The design did not take into account an orientation towards the faces of the material, which generated some chromatic and directional discrepancies in the final product. Despite these unanticipated facts, the panel was assembled (Figure 129) and presented satisfactorily.

Figure 129 - The panel during the assembly process.
Source: The Authors.

FINAL PRODUCT

In the final product, artifacts already produced in the laboratory by laser cutting and 3D printing were exhibited (Figures 130, 131). The panel shelves ended up serving this purpose of exhibition, but have very limited load capacity: because of the contrast between the depth much greater than the thickness of the shelves, these were slightly unstable and free when exposed to considerable loads. In spite of this, they are able to withstand the generally light works produced in the laboratory and serve the purpose of exhibition.

Figure 130 - The finished panel.
Source: Authors.

Figure 131 - Front view of the finished panel.
Source: Authors.

DEVELOPMENT, PROTOTYPING AND MANUFACTURING METHODOLOGY

The development of this exercise provided the discussion of aspects of the project that justify the use of the new applied technologies, explaining the influence of parameterization and prototyping in the fabrication of the executed panel.

Considering the experience of the project author, this work was an opportunity to explore the combined use of parametric modeling and the application of rapid prototyping in the design process. The agility inherent in parametric modeling and the design of a process rather than a product allowed the design of several preliminary artifacts that could have their judged qualities prior to manufacture. The varied design features were incorporated in an associative way, which generated a much more integral design experience. In it, each choice of project was necessarily analyzed among the other relations existing between the elements of the composition. In addition, these relationships had to encompass the physical viability of the artifact, requiring constant concern with the manufacturing aspects, precisely because of the direct control and involvement of the designer in this process. This is one of the great possibilities open by digital fabrication technologies, clearly involved in this approach, as cited by Kolarevic (2010):

Knowing the production capabilities and availability of particular digitally driven fabrication equipment enables designers to design specifically for the capabilities of those machines. The consequence is that designers are becoming much more directly involved in the fabrication processes, as they create the information to be translated by fabricators directly into control data that drives the digital fabrication equipment (KOLAREVIC, 2013).

Although it was more used in the final stages of the design of the artifact, rapid prototyping, through the production of intermediate models, was fundamental for understanding the material aspects, adjustments and materialization of the project. The combination of this empirical finding with the possibility of rapid correction of errors in a digital process, by changing defined parameters, corroborates with the statement that this computerized process simplifies production, effectively mixing design and detail processes that are typically compartmentalized, and frequency between intermediate design and final product (IWAMOTO, 2013). This mixture of design and fabrication in Sass's vision allows for "simultaneous conceptual manipulation of the spatial configuration, physical and material behavior, and fabrication aspects of the project" which "seems to present a truly unique potential for an integrated design" (SASS, 2006). Potential reflected precisely in the pedagogical benefit of the clearer involvement of the designer with the manufacturing process, which reestablishes materiality to the design conceived in the virtual environment.

CHAPTER 12

MODERNIST DWELLINGS IN LISBON, PORTUGAL

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MODERNIST DWELLINGS IN LISBON, PORTUGAL

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ABSTRACT

This research work addresses the relationship between public household units built in the early 60's with underprivileged resident's lifestyles of the late 70's. The study focuses on the differences between initial household designs and the 'new' layouts, a product of accommodation needs of occupant families as result of their distinct lifestyles. This analysis allows for the determination of dwelling tendencies. The intent is also to understand the extent to which some of society's attributes contributed to redefine families' social behavioral patterns, particularly their way of life and use of housing spaces, so to determine their impact in apartments layout. Examples of public housing in Lisbon, and their respective layout adjustments were analyzed, based both on the original designs and on the renovations carried out by users in the late 70's. The results of the research are supported by syntactic measures (integration and depth), to better understand how the renovations made by the families to their households best served their lifestyles. Apartment layouts were analyzed by recurring to justified graphs and visual graph analysis, both used as a comparative assessment in the validation of attained results. It is argued that the original dwellings were not adequate to disadvantaged families' household necessities and lifestyles and that in most of the analyzed households the renovations performed by the residents were seemingly well-adjusted to their daily living requirements.

INTRODUCTION

The scope of this research is the comparison between household design in initial architectural layout and the transformed dwelling, a product of a family's needs, lifestyle and requirements.

In order to conduct the proposed analysis case studies belonging to Olivais Sul housing development, within the city of Lisbon, were selected. This urban development is paramount and exemplary in Portuguese architecture portfolio, since it was the first large scale social housing plan developed according to the Athens Charter 'hygienist' principles, and designed by an assortment of renowned Portuguese architects.

The buildings that support the case studies are a part of Olivais Sul housing development, an important urban plan in Portuguese architecture, being the first formal application of modernist principles expressed by the Athens Charter in housing design. It is also important by the array of architects attracted to design new buildings for the plan, the most significant at the time. Developed by public funding, this urban plan was designed to accommodate social housing and is considered to be *(…) the biggest social housing ensemble (…), 'neighborhood' to house almost 50000 people in Lisbon (…), and a real collective domestic design school to many professionals (…)*[1] (ALMEIDA; FERNANDES, 1993, p. 153).

Intended to serve different households (in both economical and sociological aspects), the plan proposed a total of 6.458 units, to house 31.000 inhabitants. The selected units were analyzed in the *Inquérito à Habitação Urbana* carried out a decade later by Valente Pereira and Corrêa Gago. This document illustrates plans of the units and plans that show users modifications and, more importantly, attests for user satisfaction towards the lived-in dwelling. The selection of these previously analyzed case-studies allowed for the knowledge of inhabitants' uses and opinions regarding the dwellings, thus providing for a more substantiated and supported analysis. Space syntax was elected as the preferred methodology.

METHODOLOGY

As already stated, the main goal of the research is the comparison of a household's initial layout with two transformations carried out by dwellers, to comprehend their differences but also to determine which layout is more conducive to better living conditions and flow.

The research paper will likewise focus on the assessment of the results attained in *Inquérito à Habitação Urbana*, aiming at understanding if different methodologies allow for similar readings and conclusions. Additionally, the case studies will be analyzed according to housing requirements that were affirmed at the time of Valente Pereira and Corrêa Gago's investigation, as asserted by Portas in *Funções e Exigências das Áreas da Habitação*, also published by LNEC, in 1979.

Control and visibility of interior spaces and privacy vs sociability are the primary concepts that the study aims at analyzing.

CASE-STUDY SELECTION AND SPACE SYNTAX METHODS

The key departure of the study was the selection of the case studies that were deemed relevant and richer. The four chosen typologies consist of two-bedroom units, which is probably the most common and sought-after typology in Portuguese housing. Each unit was analyzed in initial

[1] Free translation from the original research work '(...) o maior conjunto de habitação social (...), para alojamento de quase 50000 pessoas em Lisboa (...), e verdadeira escola do projeto doméstico coletivo que foi para muitos profissionais (...)' (ALMEIDA; FERNANDES, 1993, p. 153).

design layout and two alternative designs, as altered by the dwellers and as described by Valente Pereira and Corrêa Gago in the *Inquérito à Habitação Urbana (Vol. I and Vol. II)*. The identification (ID) of the case studies remains the same as in the reference study to allow for a more direct correlation between the apartments initial and renovated layouts, thus enabling the reading and assessment of the results. To assess such results, the authors recurred to Space Syntax Theory as the selected methodology, which can be defined as *"(…) a set of techniques for the representation, quantification, and interpretation of spatial configuration in buildings and settlements (…)"* (HILLIER; HANSON; GRAHAM, 1986, p. 363).

Hanson (1998), refers that the first studies in housing using this theory support the notion that there is a correlation between spatial configuration and space use, stating that because of its complexity, Space Syntax methodology is determinant in household layout analysis. Considering the study's intent, justified graphs and Visual Graph Analysis (VGA), as well as output calculations regarding qualitative features of *depth*[2], *integration*[3] and *choice*[4] proved to be the most relevant spatial measures.

For the research, two different software's were used – *Depth map*[5] for VGA and *AGRAPH*[6] for justified graphs. The graphic elements used in the analysis are simplified design plans, convex break-down, VGA representation and justified graphs. The latter are considered determinant since they provide for a clearer reading and better validation of the results. When building the justified graphs, and bearing in mind the concepts that the paper aims to discuss – control and visibility – it was considered relevant the presentation of graphs considering relations of visibility and not only accessibility or physical links, as proposed by Griz and Amorim (2015).

According to space syntax methodology it is possible to obtain two different layouts, *tree-like* layout and '*ringy*' layout. According to Hanson (1998), *tree-like* layout is the most common in several cultures' dwellings and it is the one that enables a greater control of inner movement and movement in relation with the exterior, making them more predictable. Apart from that, '(…) *tree-like* domestic space arrangements produce strongly programmed forms of domestic space arrangements (…)' (Hanson, 1998, p. 278). Unlike the *tree-like*, a '*ringy*' layout allows for choice or *route choice*. The spaces where the rings intersect usually highlight the households' most significant areas and residents preferred locations (Hanson, 1998).

When drawing the graphs, considering that some options could influence the results, it was decided that the household main entrance should be identified as an outer space (IN) as root of the graph. As per Amorim (1997), transition spaces are relevant as mediators, also characterized

2 *'Depth', among a set of spaces always expresses how directly the functions of those spaces are integrated with or separated from each other.* (HILLIER; HANSON; GRAHAM, 1986, p. 365)

3 *(…) the distribution of integration gives a rather good account of the relative organization of the plan.* (Hanson, 1998, p.43)

4 *(…) the existence or otherwise of alternative routes from one space to another.* (HILLIER; HANSON; GRAHAM, 1986, p. 364)

5 *DepthmapX is a multi-platform software used to perform a set of spatial network analyses designed to understand social processes within the built environment.* Available at https://varoudis.github.io/depthmapX/

6 *Software for Drawing and Calculating Space Syntax "Node-Graphs" and Space Syntax "Axial-Maps".* Available at http://www.ntnu.no/ad/spacesyntax

by Hanson (1998), and, Hillier, Hanson and Graham (1986) as such: *Transitions have the effect of insulating spaces from one another (…). (…) Strong arguments have been adduced that link the use of transitions in houses with the intent to assure that social separations within the home are strictly maintained* (HANSON, 1998, p.285). *The transition space type works by more uniformly segregating interior functions through a central transition space which controls both interior relations and relations with the outside* (Hillier., Hanson and Graham, 1986, p. 385).

In accordance, Amorim (1996, p.18.11), states the following: *It seems that mediator units were introduced to compose different configurations, assuring one or another requirement, as segregating sectors (…) or integrating systems (…). As a joker in some card games, mediation spaces assumed different roles, according to the interest of the player, but under the general rules of the game.*

In addition to unit layout, this study presents *integration* (absolute and relative[7]) and *depth* graphs of rooms and functional areas.

'INQUÉRITO À HABITAÇÃO URBANA' – ANALYSIS AND RESULTS

Being an exemplary and ground-breaking study, the *Inquérito à Habitação Urbana* was able to assemble countless information and present important conclusions, analyzing various housing facets and dwellers satisfaction, also intending to correctly social characterize the latter. In the instructions given to the interviewers some objectives are made clear: *(…) characterize and interpret the different modes of inhabiting a dwelling through the knowledge of who are the people (…), how they inhabit the dwelling (descriptions and interpretation of the unit's use) and which unit they inhabit (project design characteristics) (…)* (VALENTE PEREIRA; CORRÊA GAGO, 1984, p. 245).

This research work focuses in a few of those information and conclusions that are relevant to the proposed analysis. Thus, it is paramount to reference the aspects that cause dislike and that the inhabitants most stated as not satisfactory. Firstly, *compartment distribution* (18%), being also important the mention to the *entry of the dwelling* (12%), *living room crossing* (5%) and *violation of the living room in relation to the interior* (4%) (VALENTE PEREIRA; CORRÊA GAGO, 1984, p.110)[8]. It is essential to highlight that the primary complaint is compartment distribution, result supported by space syntax analysis namely in type 25 in which the original layout plan unit does not present

[7] *When applying "Colour by RA" for comparing different graphs, the "Colouring by RA, absolute" is useful. If analyzing only one graph the "RA-relative" is better as this gives a larger range of colour and thereby a more differentiated information.* (MANUM, 2009, p. 3). Relative integration can also be denominated *Relative Asymmetry: The Relative Asymmetry (RA) describes the integration of a node by a value between (or equal to) 0 and 1, where a low value describes high integration. RA is calculated by the formula RA=2*(MD-1)/(k-2).* (MANUM, 2009, p. 2). *The RA-value is defined to be zero when a node is as integrated as possible. (…) Contrary, RA is defined to be 1 when a node is as segregated as possible.* (MANUM, 2009, p. 6). In AGRAPH, warmer colors (reds) equate to values of more integration (RA near or equal to 0) and colder colors (blues) to those of less integration (equal to or near 1). Absolute integration (i) is said to be the opposite of RA, the highest the value, the more integrated. *This is the integration value of RA. Integration might be defined as the inverse of other asymmetry parameters than the RA. The most usual is to invert the RRA, the Real Relative Asymmetry, as described by Hillier and Hanson, 1984, p.111-113.* (MANUM, 2009, p. 6).

[8] Of all these answers, only *compartment distribution* and *dwelling entry* were given as choices, the rest were referred freely by the inhabitants (*vide* question 64 of the inquest that, combined with question 63, reflects the *Opinion of the Dwelling. Important to infer judgement on the dwelling* (VALENTE PEREIRA; CORRÊA GAGO, 1984, p.253)).

the best functional layout. Living room crossing and its violation with relation to the rest of the dwelling were also pointed out in type 25 and partly in type 28B, where the living area is treated as a transition space to one of the bedrooms. Another question relates to modifications having been registered a percentage of 42% of modifications to the initial design (VALENTE PEREIRA; CORRÊA GAGO, 1984, p. 112). Of these 38% corresponds to the creation of new compartments (as seen in Type 25 – Use 01, the creation of a new transition space by reducing and enclosing one bedroom). One of the appointed motives for altering the initial layout was *poor plan distribution* (10%), also being stated, though less representatively, *isolation and privacy* (4%)[9] (VALENTE PEREIRA; CORRÊA GAGO, 1984, p. 112). Poor layout plan distribution is also substantiated by space syntax analysis, especially in types 25 and 28B. The need for isolation and privacy was largely studied and integration graphs being noticeable that type 25 and in some degree type 28B are the units that present greater problems with regards to bedroom privacy, specifically original layout plan unit 25.

It is important to consider these findings when conducting and reading the space syntax analysis that follows, so to better compare the two methodologies and their scopes and potential.

HOUSING STANDARDS AND DESIGN REQUIREMENTS

Contemporarily to the development of Valente Pereira and Corrêa Gago's investigation, Portas devoted part of his research to the examination of housing standards and design requirements suited to a new way of life[10] in the 1970's, redacting *Funções e Exigências de Áreas da Habitação*[11], also published by LNEC. In this work Portas reflects upon *(…) the minimum area standards and other project requirements (…)* and proposes an *(…) analysis of the functions and activities that take place in the dwelling* (PORTAS, 1979, p. 3), defining 16 activities that a dwelling and its rooms can contain. For each activity different requirements are established: general, area and articulation requirements.

Of all the proposed functions and activities, seven should be analyzed, the ones considered the most relevant for the paper and the case studies at hand, numbered as by Portas:

1. Sleep/Personal Rest
2. Food/Preparation
3. 4. Food/Regular Meals and Food/Formal Meals
4. 6. Living/Entertaining
13. Personal Hygiene

9 Also mentioned by the inhabitants, not given as possible answer (*vide* question 20; along with question 19 explains *the reasons for alterations that have been made to dwelling project and that are to be registered in plan* (VALENTE PEREIRA; CORRÊA GAGO, 1984, p. 251).

10 Social evolution related to the role of women at home and the workplace, mechanization (home appliances) and new leisure activities taking place at home are just some of the facets of the new way of life Portas refers to.

11 *Family Needs and Space Requirements in Dwellings*

- Sleep/Personal Rest (1)

General Requirements:

a) (…) safeguard 'intimate area conditions' either by location in plan or by isolation from common and work areas flow, safeguard violation from the outside. (…)

b) *(…) 'visual contact' with exterior (…).* (PORTAS, 1979, p.24)

Articulation Requirements:

a) Grouping and independent access.

Due to privacy and isolation requirements he group of bedrooms should constitute a conjoined area and link itself to hygiene facilities through spaces that separate them from the common area or safeguard transition spaces from outsiders' gaze. (…)

b) Possible use of one bedroom for a different activity.

Altering needs in households with more than two children makes it desirable to have a room that could be partially or exclusively used with other activities (3)(4) Meals, (5) Living, (6) Entertaining, (9) Work; (…) possibility of link with living or dining room; possible independent access from the entrance. (PORTAS, 1979, p.27)

- **Food/Preparation (2)**

Articulation Requirements:

a) Including or adjoining other functions – (3) and (4). *(…) As design proposal the kitchen should always predict such overlay or open itself (…) to a nook specifically designed for this end.* (PORTAS, 1979, p.33)

b) Communication with other areas

With dining spaces – (3) and (4) – *(…) the distance between (2) preparation and the primary meals table (4) should be short and obstacle free; on the other hand, it should be possible to separate both areas because of smells, noises, cleanliness, look, etc. (…)*

With family common areas – (5) and (6) – *(…) participation of housewife in family activities when working in the kitchen. (…).*

With dwelling entrance and outside life (5) – *(…) tending to caterers, arrival of family members or visitors, relations with neighbors, etc. (…) placing of kitchen near the entrance (…).* (PORTAS, 1979, p.34-35)

- **Food/Regular Meals and Food/Formal Meals (3) (4)**

Meals (3) and (4) do not occur in characteristic autonomous rooms, being volatile to family life preferences and ways. (…) (PORTAS, 1979, p.37)

a) The typical dining room is found especially for daily and exclusive use in upper and middle class, presupposing an abundance of space that allows for this specialization. However, it is also found in popular classes, used more seldomly and serving also as a place for (6) Entertaining (…).

b) *The traditional kitchen is in fact the place of (3) informal meals for obvious proximity reasons.* (PORTAS, 1979, p.38)

Articulation Requirements:

Portas (1979, p.43) states the need for adjacency with the kitchen and in continuity of the living area.

- **Living/Entertaining (5) (6)**

Both activities tend to take place in the common living area or in the visitors living room. In terms of relation with other rooms, adjacency to dining areas is desirable as well as with outdoor spaces, however these activities are not compatible with *(…) functions that require silence such as (1) sleeping, (8) study, (9) work; with whichever implies the loss of privacy of common and informal family life (as being the dwelling entrance, which is often found in more economical solutions).* (PORTAS, 1979, p.46)

Articulation Requirements:

There should be a connection with dining areas and the kitchen. It is also advocated that: *It is obvious that (…) the living area should have direct access from the entrance hall without being disturbed, which equates to denying the living room as entrance to the dwelling; it is likewise censured that the access to the living room is done through the kitchen, with no other alternative, and on the other hand that it functions as a passageway and distribution from the outside to interior spaces (bedrooms and hygiene facilities).* (PORTAS, 1979, p.52)

- **Personal Hygiene (13)**

Articulation Requirements:

a) *(…) access to the bathroom from the bedrooms should always be secured by a vestibule or hallway and in any case demand the crossing (without alternative) of the living area or other bedroom.* (PORTAS, 1979, p.70)

ANALYSIS AND RESULTS

Four apartment units, from the *Inquérito à Habitação Urbana (Vol.II)* (VALENTE PEREIRA; CORRÊA GAGO; LOPES, 1984), were selected and analyzed as case-studies – Type 19, Type 25, Type 28a and Type 28b – having also been selected two different user modifications per each type, except for Type 28 where only one transformed layout per sub-type was analyzed. The graphic representation of these units is presented in both simplified plans (Figure 132) and convex maps (Figure 133), depicting the changes from the project unit to the two uses. These alterations can be either spatial or functional, or in some cases, both.

In Type 19 the noticeable modifications in Use 01 are spatial – the asserted adjoining of the two living areas – and functional – the specialization of these living areas, dividing them functionally into living room and dining room; in Use 02 the alteration is carried out in the opposite direction – the once part of living area is closed off and created a bedroom and one existing bedroom is transformed into a living area.

Type 25 modifications occurred only in the spatial sense and regarding the bedroom near the entrance – Use 01 encloses the bedroom but allows for the existence of a circulation and transition space, whereas Use 02 enlarges the same bedroom by enclosing it near the entrance transition space.

The last cases, Type 28a and 28b, in Use 01 of 28a the alteration refers to the removal of the connection between the living area and the kitchen support area; Use 01 of 28b preserves this link but ends the one between the living area and the circulation and transition space near the dwelling's entrance.

Figure 132 - Simplified plans of all dwellings types.

Figure 133 - Convex break-up of all dwellings types.

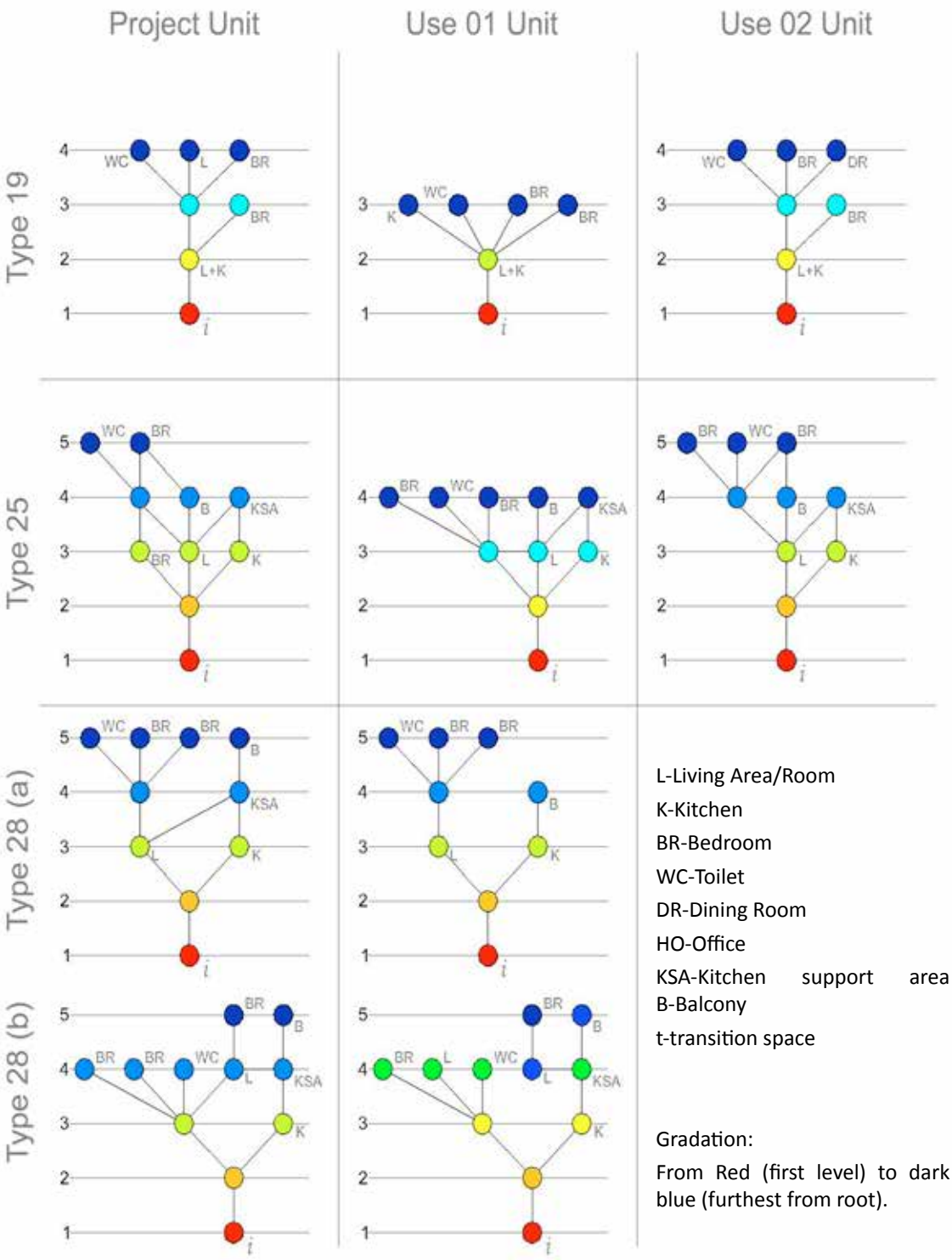

Figure 134 - Depth justified graphs by dwelling rooms.

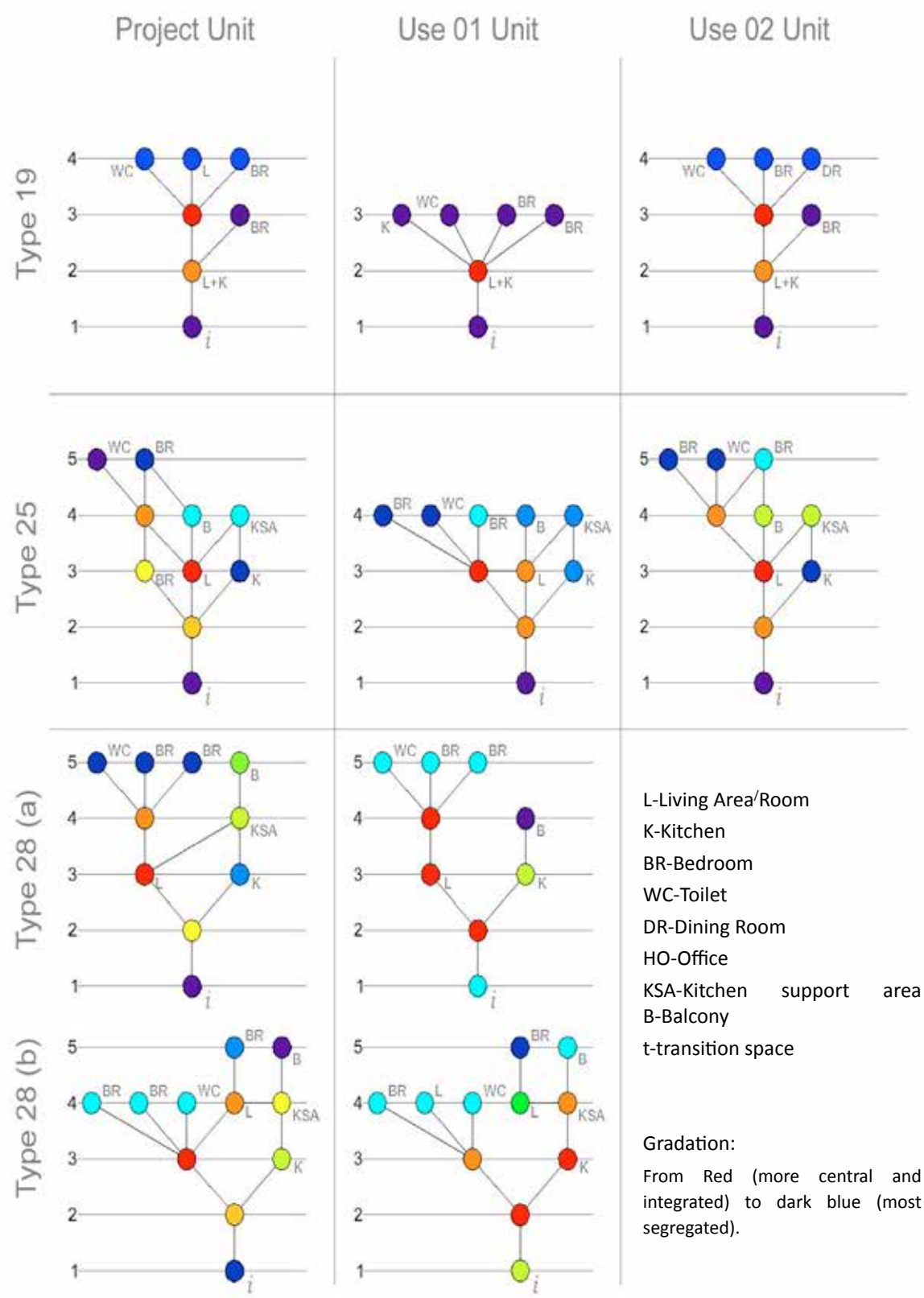

Figure 135 - RA justified graphs by dwelling rooms.

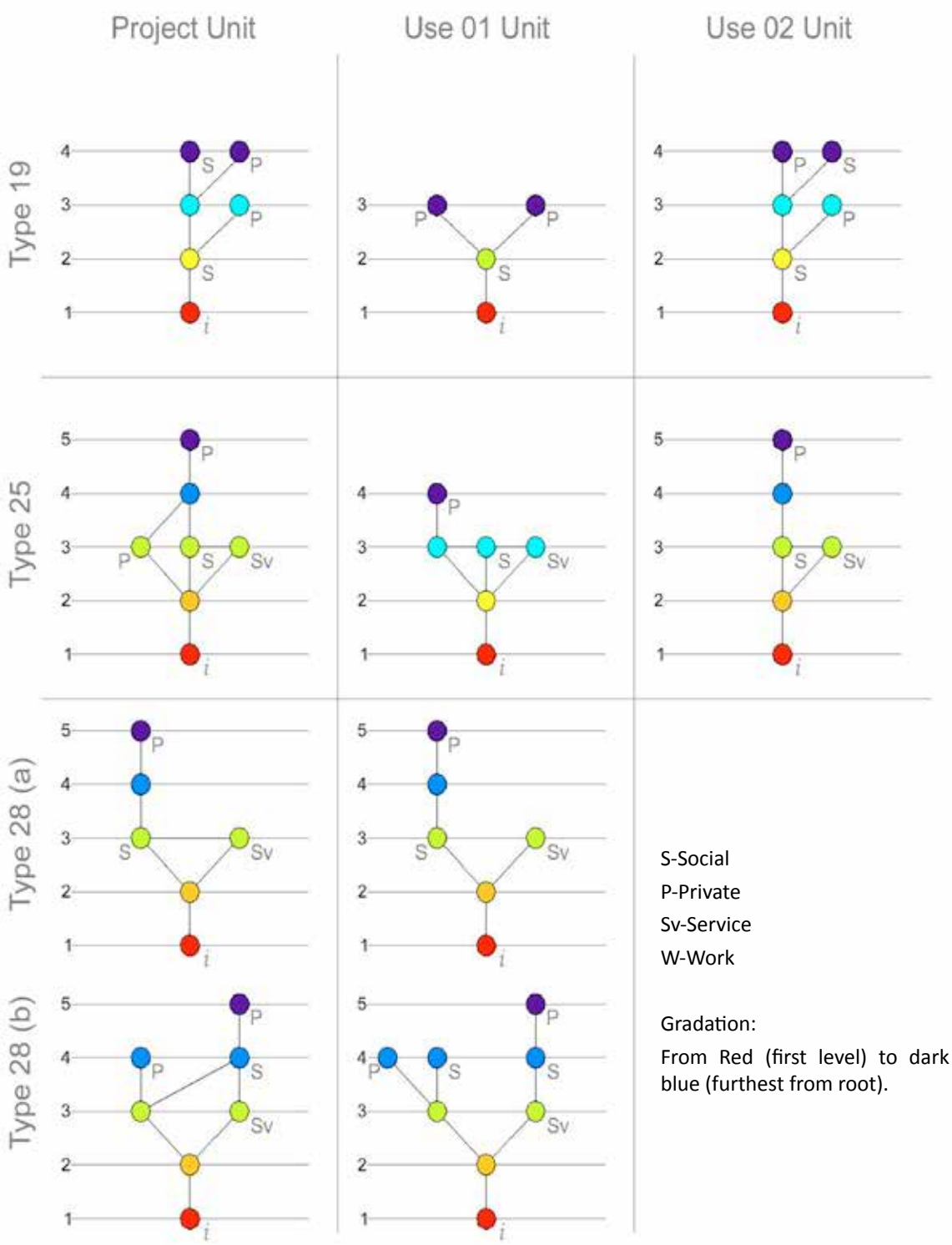

Figure 136 - Depth justified graphs by functional zone (social, private, service and work).

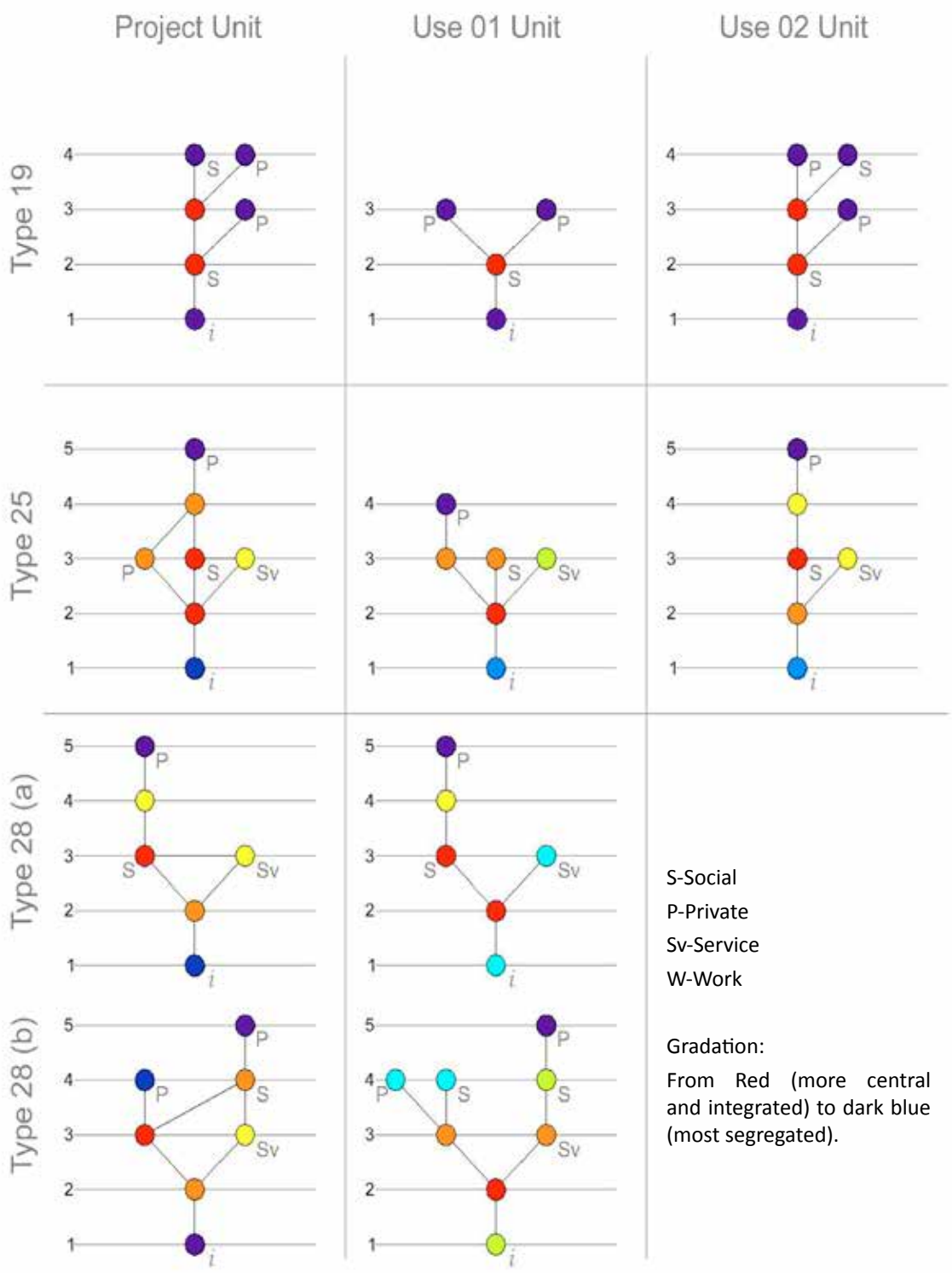

Figure 137 - RA justified graphs by functional zone (social, private, service and work).

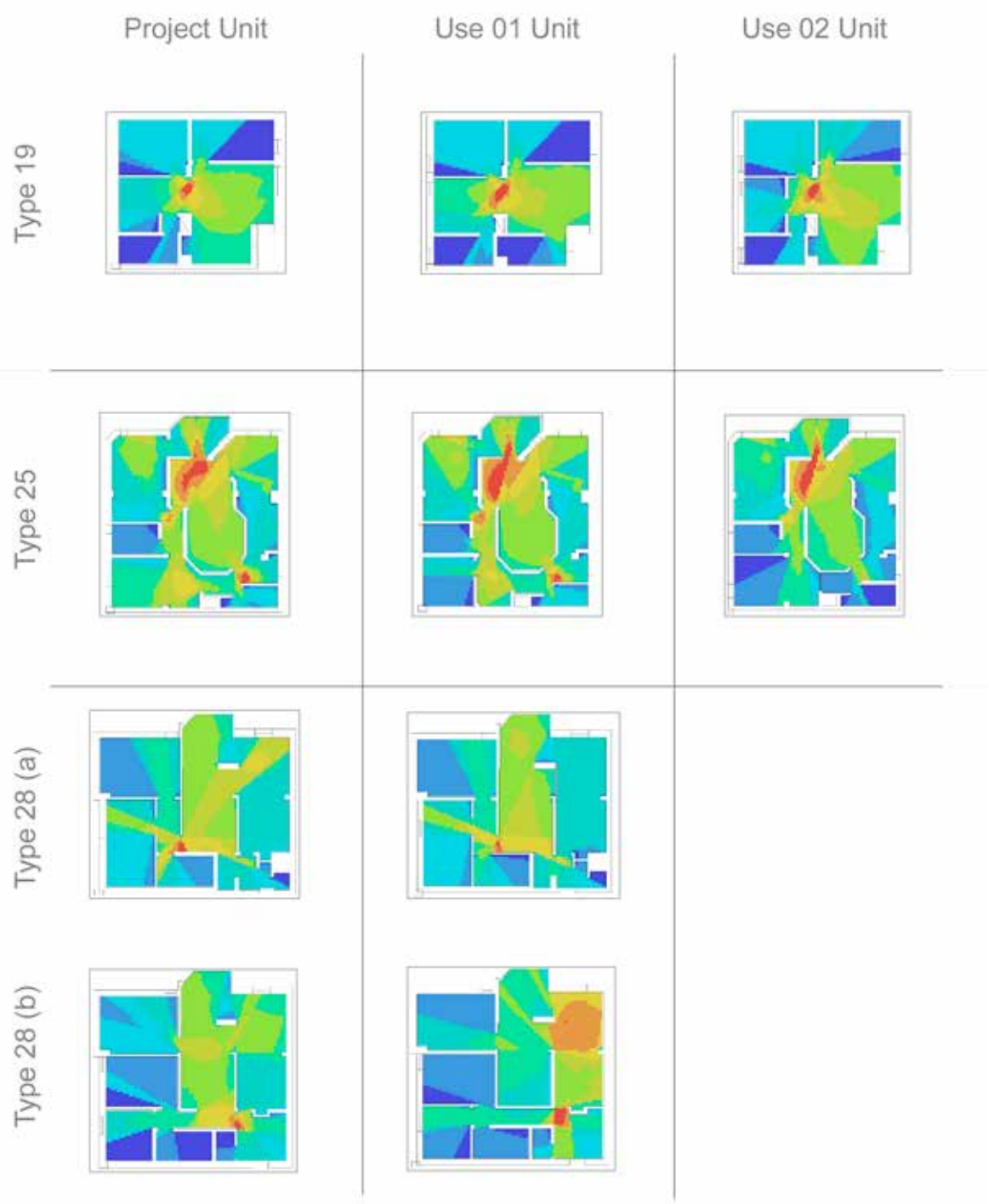

Figure 138 - Visual Graph Analysis (VGA) using DeathmapX software.

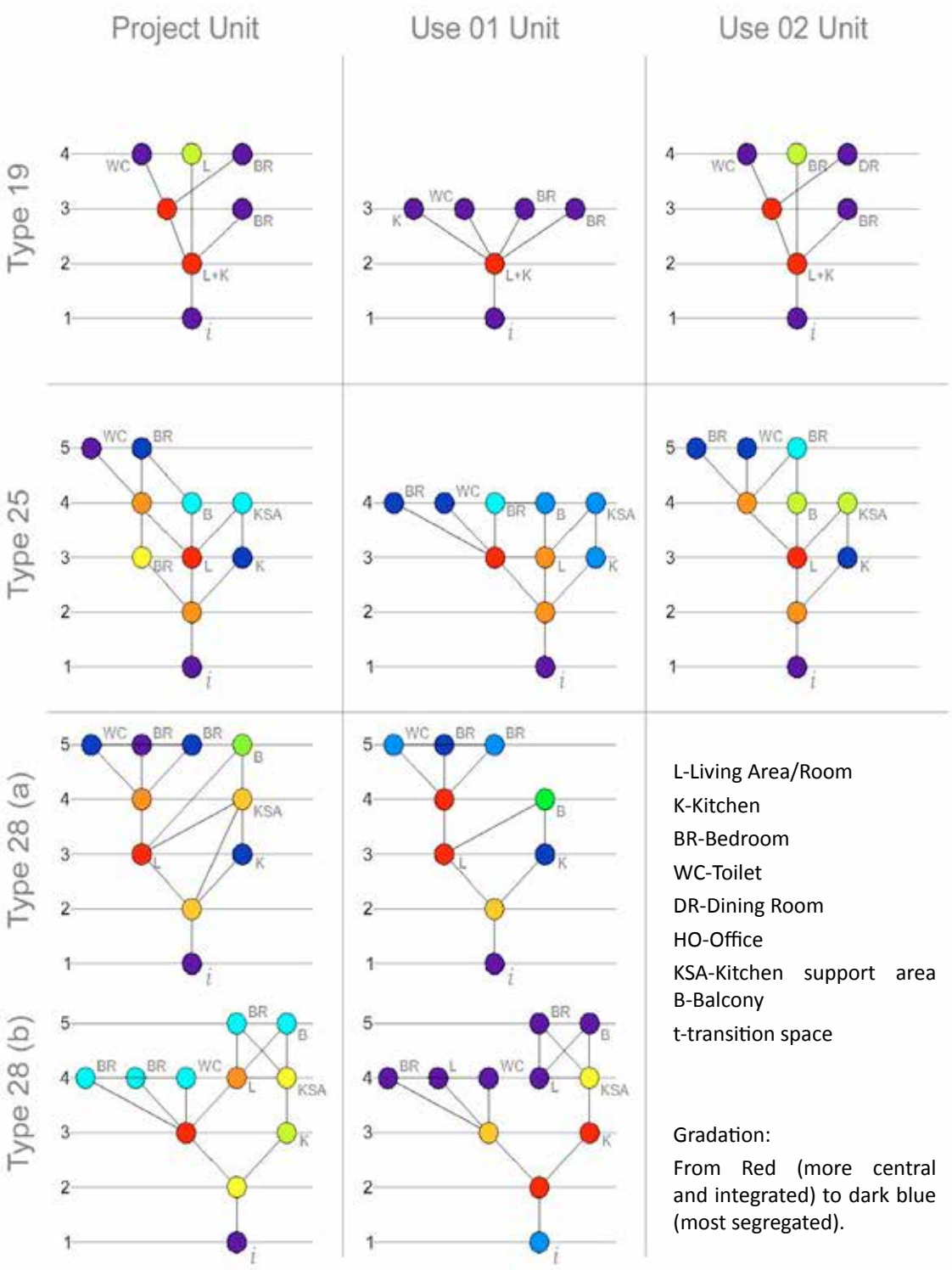

Figure 139 - Visibility justified graphs (RA). It is interesting to notice that in Type 25 apartments the accessibility graph is the same as the visibility graph, indicating less complex interiors.

To better analyze all the units (both in initial design and uses), it is firstly important to read the justified graphs – depth and integration (relative asymmetry – RA) concerning not only dwelling spaces (Figures 134 and 135) but also functional sectors (Figures 136 and 137). In addition, aiming at examining control and visibility/privacy, it is proposed a Visual Graph Analysis, illustrating visual integration by means of isovists (Figure 138) and justified graphs considering relations of visibility and not only accessibility (Figure 139), as proposed by Griz and Amorim (2015).

When analyzing each unit type and comparing the initial design unit with the modified dwellings it is possible to understand which layout apparently better serves familiar way of living in this context and time and that best corresponds to the notions and housing requirements stated by Portas.

- **Type 19**

Comparing the three units, Use 01 seems to be the one that better organizes the dwelling spaces, by centralizing the living area and segregating the private spaces. Both the original design layout Unit and Use 02 place part of the social area in a segregated space, thus not enabling in full its social character. In these two units, part of the living area is not only segregated but also on of the deepest levels in the dwelling, which equates to visitors having to enter in these deeper and traditionally more private levels, which takes away some of the bedrooms' privacy.

In terms of visibility and control, VGA output shows us that the transition space, when it exists (Project Unit and Use 02), or the central area of the living zone (Use 01) are the most visible spaces of the units, therefore, where control of all others is bigger. In all units, by having the living room as entrance of the dwelling, the family communal space is somewhat disturbed in relation with the outside and therefore less private in this rapport. Justified visibility graphs support this reading.

- **Type 25**

In Type 25, reading layout and depth results, it is possible to infer that both Uses correspond to a better hierarchized interior, improving interior functional distribution and establishing increasing levels and degrees of privacy which signifies that a progressive infiltration inside corresponds to access to increasingly private spaces. Comparing these, the original layout plan unit places part of the intimate area in an intermediate level, which leads to it being less private, more vulnerable to the outside. Of the two uses, Use 01 is the one that better organizes interior circulation, foreseeing transition spaces between entry hall and bedrooms and living room and bedrooms, differing from Use 02 in the fact that it doesn't treat the living area as a circulation space that acts as a transition space, allowing for a better use of the living area and its furnishing. Concerning global integration, there is a difference between the units of apartment Type 25 as opposed to the previous case-studies: the transition spaces are not the most integrated in all units. In the original layout unit, the most integrated (central) spaces are a transition space and the social area; in Use 01 the transition space of the entry hall is the most central; in Use 02 the social area reappears as the most integrated

node of the graph. In all units, the private area appears as more segregated than the exterior of the dwelling, thus reinforcing its intimate character. Integration analysis supports the findings of the previous ones: inhabitant's uses are more appropriate to standard family life, allowing for greater privacy to the private areas (bedrooms) and centrality to social spaces.

When reading VGA map and the visibility graphs, it is possible to state that a fringe part of the living area is the control hub of the dwelling. In Use 02, it appears as the sole point of greater control, whereas in the Project Unit and Use 01 other foci of control emerge – in Project Unit the foci are transition spaces (especially the entrance) and part of bedroom 1 (since it is opened to the hallways); in Use 01 the smaller foci are solely transition spaces (entrance and circulation near the bedrooms). It is evident, namely in VGA map, that the transformation in Use 01 enables control where control is due (transition spaces) and privacy where it should be intended (bedrooms); in Use 02 the transformation increases privacy of the intimate spaces but eliminates some of the control of the transition spaces.

- **Type 28**

When compared, the most visible difference between the sub-types – A and B –, and an important one, is the separation of the private area into two in type B, being one of these areas accessible only through the living area (in Use 01B, it implies a first access through the kitchen), without a transition space as seen in type A. In Use 01B there is also a division of the social area, also into two areas, each one near the private areas. Integration analysis of type A units demonstrates that the social areas (common living room) is the most integrated, *i.e.*, central of the system in both cases. The ring in the original layout plan unit A has also an integrating character regarding the service area (namely the service support space). In Use 01A, the dissolution of the ring results in a lesser integration of the service area (almost at the same level as the exterior). In both units, the private sector is the most segregated, therefore, more intimate. Being more complex than type A units and having been altered spatially and functionally, type B units suggest more dissimilarities between them. The most integrated spaces are in both cases two different transition spaces: in original layout plan unit a transition space that takes part of the ring layout and connects the entry hall, the living area and the bedrooms; in Use 01B the entry hall (where the dwelling layout bisects). In original layout plan unit B the social area is the second most central, followed by the entry hall and the service areas (all of which compose the ring layout). The private areas and the exterior are the most segregated, although bedroom 3 (adjacent to the dining room) consist in the most segregated of all spaces, being the furthest from the most central space[12]. In Use 01B, without the existence of the ring, the bisection determines the integration of the different spaces: the service areas and the bedroom transition space are in level two of centrality, followed by the part of the social area. The second social space – the formal living room – lies in the third level of centrality, as does the

[12] This should indicate that this is the most private space of the dwelling when in fact this statement is fallacious when considering that the only access to it is one of the most central and integrated (more public) compartments – the common living area.

bedroom adjacent to it. The bedroom contiguous to the common living area is the most segregated of the system.

It is thus possible to state that original layout plan unit A is the one that appears to serve family life better by integrating in a ring-like layout the most social areas (entry, living and service) and segregating and therefore protecting the bedrooms as the most private compartments. The alteration in Use 01A has little impact in the system apart from a lesser integration of the service areas.

Comparing original layout plan unit, A and original layout plan unit B, the latter due to the division of the private area seems less appropriate: the bedroom adjacent to the primary living area is greatly vulnerable to social activities and thus less private and intimate, as it should. The alterations in Use 01B aggravate the dwelling's functioning: by abolishing the access to the social area through the entry, the bedroom adjacent to the living room is placed further from the other bedroom and the toilet facility, the problem of its privacy regarding the living area persisting. Furthermore, the functional alteration (the creation of a formal living room in a bedroom compartment) causes integration issues: the living area is not central in the system causing the visitors to enter deep in the dwelling to access it, which also conflicts with the need for privacy of the contiguous bedroom.

The VGA analysis is coherent with these findings, showing us that in Type 28A, the focus of control is a transition space between the social area and the private one, allowing for a great level of visibility of the living room. By enclosing the link between this space and the kitchen support area, the latter gains privacy, but since it is a service area privacy is not required.

In type B the alteration made by the inhabitants has a greater effect on overall control, visibility and privacy. In Project Unit B the focus of control is the transition space between the entrance and the social and service areas, which enables visibility of these spaces from an interior distribution space and still secures privacy in the intimate sector; in Use 01B the enclosing of the link between the entrance and the living room determines a shift of control, albeit maintaining a focus in the entrance transition space: the large focus of control becomes the kitchen support area, which is not a central space in the dwelling layout, turning the service area in the only group of spaces where visibility and control is noticeable. The alteration has also an effect on the increase of privacy of the bedrooms and the living areas (both of the living spaces become secluded and less prone to social activities).

CONCLUSION

CASE-STUDIES

The previous analysis of all dwelling types, both original layout plan units and Uses-Units, demonstrates unity between VGA and Graph output. In general terms, it is important to emphasize that the transition space (or spaces) appears to be the most integrated in the system, especially in the present case-studies that consist of smaller dwellings where a single or a couple of transition spaces are paramount in the distribution of the entire dwelling, and that in most cases the transition

spaces become the focus of control inside the dwellings. Moreover, if one disregards these transition spaces, the social area tends to be the most integrated and central in the dwelling, more so in some units than in others nonetheless. This is especially made clear by the VGA analysis that allows for a more immediate reading. Which leads us to highlight the difference between the VGA and the Graph analysis: the former by implying integration through visibility and not only a physical link allows for an enhanced centrality of some spaces, which could prove to be misleading.

In general terms the analysis also supports that the ring layout has an integrating effect on the compartments and functions that compose it, whereas the tree-like layout tends to stratify and hierarchize dwelling interiors, creating increasingly deeper and more private levels.

When comparing the original layout plan units to the Uses-Units the findings differ from one case-study to another, a general result being inexistent: original layout plan units of Type 28 appear to be the ones that better serve the needs of social activities and privacy of the family[13] in terms of compartment distribution and layout; Use-Units of Types 19 (Use 01 only) and 25 (both Use 01 and Use 02) seem more appropriate to family living. This assessment is based upon the level of segregation of the private area, *i.e.* the bedrooms, and the level of integration/centrality of the social area, i.e. the living area, being considered that the privacy needed in the bedrooms is consistent with higher levels of segregation and the social functions of the living area with higher levels of relative integration (RA). Whenever the modifications made to the dwellings or the original layout plan unit itself didn't hierarchize functions and areas according to this premise they were considered less adequate.

HOUSING REQUIREMENTS AND SPACE SYNTAX ANALYSIS

Having analyzed the four case studies, in original layout and alterations, and having the previous findings in mind, it is important to understand if the studied dwellings or the product of inhabitant modifications correspond to housing standards and requirements highlighted by Portas (1979), mentioned earlier in the paper.

1. Sleeping/Personal Rest

In this activity the need for privacy is highlighted as is the required safeguard of feelings of seclusion and protection from activities taking place in communal areas and from the outside. Type 19 Use01, Type 25 Use 01 and 02 and Type A (initial design and transformation alike) enable a greater level of privacy of the intimate sector (Figure 136, Figure 138). Of all these, only Type 19 Use 01 doesn't conform to the need of separation from the social activities, since the bedrooms' access is done directly from the living area without a transition space.

[13] A space syntax analysis' scope is the investigation of design and layout aspects, not considering dwellers' opinions and their needs satisfaction.

2. Food/Preparation

The main requirement to bear in mind is the need for a link with dining areas (safeguarding a degree of separation due to odors and other aspects), living areas and the entrance of the dwelling.

In all case studies the location of the kitchen is consistent with the placement requirements. In Type 19 Use 01, the addition of a wall separating the kitchen from the living area enables the separation that is defended; in Type 28B Use 01 the enclosing of the kitchen to the living room is contrary to the mentioned requirement.

3. (4) Food/Regular Meals and Food/Formal Meals

All analyzed units correspond to very rationalized interiors, presenting minimum areas and restricting the number and typology of spaces to the bare minimum needs, which results in the juxtaposition of activities in the same space. That is the case of formal and informal meals that, in the analyzed cases, take place in the social area – the living room.

4. (6) Living/Entertaining

As aforementioned, the observed tendency in the selected case-studies is the common living area, juxtaposing functions (3,4,5,6). The one exception, however, is Type 28B Use 01, where one bedroom is transformed into a living area, intended to be used only as a visitor (formal) entertaining space.

When describing the requirements for these activities, Portas enhances the need for separation from intimate spaces (for sleep, study or work) and also that it is desirable that the living space is not also the entrance space, with direct connection to the outside. Type 19, being an extremely small unit, breaks both rules – at least one bedroom opens into the living area (both bedrooms in Use 02) and the entry in the dwelling is done directly to the living room; Type 25 (all units) and Type 28A (both units) are consistent with the established requirements; Type 28B doesn't conform to the requirement of separation from the private sector (one of the bedrooms is accessible only via the living room).

Portas also emphasizes the fact that the living area should never be designed as a passageway between other functional spaces, as a transition space, or that the sole access to it should be through the kitchen. In Type 28B original plan the living area is somewhat treated as a passageway to a bedroom, but the alteration introduced in Use 01 also violates the requirement that states that the kitchen shouldn't be the only access to it.

Under this light, a general conclusion remains objectionable. It is possible, nonetheless, to find that only the alterations done to Type 25, both Use 01 and Use 02, are consistent with all referred requirements and housing standards defined by Portas.

COMPARISON WITH THE RESULTS OF "*INQUÉRITO À HABITAÇÃO URBANA*"

Comparing the two different methodologies and the results made possible by each it is noticeable the coherence of conclusions, as aforementioned. Although the *Inquérito à Habitação Urbana* has a broader scope in what relates to dwelling layout its analysis is confirmed by the space syntax analysis presented in this research. The later methodology allows for a more objective and analytic investigation of dwelling layout, hence permitting an ample and extensive reading of its functioning as a hole and the relation between the various compartments. The advantage of this methodology (Space Syntax) is the possibility to review and equate the adequacy of alternative solutions and designs[14] and immediately verify their validity. As a further and more extensive development it would be beneficial a Post-Occupancy Evaluation as the work developed by Sungur and Çagdas[15] (2003), that would serve as an additional investigating methodology by adding information regarding dwelling use and inefficiency in terms of user satisfaction.

[14] As stressed by Mustafa, Hassan and Baper (2010, p.157) when mentioning that data obtained by space syntax analysis should be used as project auxiliary in future processes.

[15] *Effects on Housing Morphology on User Satisfaction*

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