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FACULDADE DE ARQUITETURA
UNIVERSIDADE DE LISBOA

CICERO

Creative Interface for Constructing Earthbag Resource Objects

Doutoramento em Arquitetura
Especialidade em desenho e computação

DEBORAH MACÊDO DOS SANTOS
Orientador: Professor Doutor José Nuno Beirão

Tese especialmente elaborada para a obtenção do grau de doutor
Documento definitivo
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Julho, 2020

Dedicatória

Aos que acreditam.

Epigraph

"In the beginning, God created

heaven and ***earth****." Genesis 1, 1*

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Resumo Geral

Ao longo do tempo os arquitetos fizeram uso de métodos gráficos e estudos volumétricos para planejar, projetar e representar os projetos arquitetônicos. Experimentam as possibilidades desde o início do processo criativo até a elaboração do projeto arquitetônico. Atualmente os recursos informáticos permitem estender as capacidades de representação dos projetos para além do universo da mera representação geométrica, associando dados técnicos, quantitativos e descritivos às referidas representações facilitando sua execução e a comunicação das suas complexidades técnicas, onde se destaca o paradigma de representação BIM (*building information modelling*). O *SuperAdobe*, também conhecido como "adobe ensacado", "saco contínuo de terra estabilizada", "*earthbag building*", "*Earth-filled bags*" ou "domo em adobe", consiste na técnica construtiva onde as paredes são construídas essencialmente por sacos preenchidos com areia e empilhados, sendo estabilizados com arame farpado entre os sacos. São construções duráveis, fortes, climaticamente eficientes, formalmente flexíveis e são compostas por recursos renováveis e reaproveitáveis favorecendo o desenvolvimento sustentável. Esta investigação responde à questão de como a modelação paramétrica, inserida em ambiente BIM, pode auxiliar na concepção específica de projetos em SuperAdobe. A técnica de construção em SuperAdobe é mais vantajosa do que as demais com terra, pois não é necessário o uso de fôrmas de madeira ou outro material semelhante, é mais resistente às ações sísmicas, exige menos manutenção e tempo de construção, e pode ser autoportante para tipologias de até dois pavimentos. Apesar de a construção em terra ser uma solução reconhecida de baixo impacto ambiental, as ferramentas informáticas existentes ainda são fatores limitantes neste tipo específico de projetos. A tese tem por objetivo, a criação de alternativas informáticas para auxiliar a concepção de projetos em SuperAdobe. Objetivamente na fase de criação de modelos virtuais em 3D com dados técnicos associados.

Com relação às metodologias, trata-se de uma pesquisa de cunho experimental dividida em duas fases, modelação paramétrica e estudos em ambiente BIM. Os experimentos foram validados por aplicação de inquéritos (baseado nas dez heurísticas de Nielsen) e simulação em computador respectivamente. A principal contribuição dessa investigação é a introdução da tecnologia de construção com sacos de terra/SuperAdobe no ambiente BIM. A principal contribuição dessa investigação é a introdução da tecnologia de construção com sacos de terra/superAdobe no ambiente BIM. Os resultados mostram que, com o uso destas ferramentas, é possível modelar domos e absides em menos de 5 minutos e depois associá-los a qualquer outra tecnologia construtiva em ambiente BIM com geração automática de dados técnicos.

Palavras-chave: arquitetura da terra; BIM; desenho gerativo; linguagem de programação visual; modelagem tridimensional; SuperAdobe.

General Abstract

Architects have been using graphic methods of representation, together with volumetric studies, for architectural design since the beginning of the creative process. Nowadays the technology available expands the projects' representation capabilities beyond the geometric representation, presenting associated technical, quantitative, and descriptive data. The building information modelling (BIM) paradigm facilitates building execution and the communication of technical complexities. The SuperAdobe (also known as earthbag, bagged earth, or earth-filled bags) is a construction technique where the walls are made with interspersed layers of bagged inorganic soil and barbed wire. These constructions are durable, strong, energy efficient, capable of producing organic forms, and composed by renewable and reusable materials, supporting sustainable development. The aim of this research is answering the question: How can generative design, together with BIM, help to improve the design of earthbag building projects? Earthbag building techniques are more advantageous than other earth-building techniques because they don't require formwork, they are more resistant in earthquake-prone zones, they benefit from both lower maintenance and construction time, and they are self-supporting up to double storey typologies. Although earth construction is recognized as a low environmental impact solution, existing software tools continue to be limiting factors in this specific type of project. This thesis aims to present design computational tools that are suitable for earthbag construction technology, with a focus on generating 3D models with associated technical data. The research methodology is an experiment involving two phases: (1) parametric modelling and (2) studies in BIM environment. The validation of this research encompasses surveys (based on the ten heuristics of Nielsen) and a computational simulation. The main contribution of this research is the implementation of earthbag/superAdobe technology in the BIM environment. The proposed tool allows modelling earthbag/superAdobe domes and clusters in less than five minutes, associating the generated model with any other standard constructive technologies and other variations of earthbag/Superadobe shape walls, generating the technical data automatically.

Keywords: 3D model; building information modelling (BIM); earth architecture; earthbag building; generative design; visual programming language (VPL).

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List of Abbreviations and Acronyms

ACADIA – Association for Computer Aided Design in Architecture

ASA – International Conference Architectural-Science-Association

BIM – building information modelling

CAADRIA – Computer-Aided Architectural Design Research in Asia

CAD – Computer aided design

CAH – Conference on Conservation of Architectural Heritage

CESB – Conference on Central Europe Towards Sustainable Building

CIAUD – Research Centre for Architecture, Urbanism and Design

CICERO – Creative Interface for Constructing Earthbag Resource Objects

CIM – City Information Model

CNPQ – Brazilian National Council for Scientific and Technological Development

CT – Computational thinking

EAEA – Envisioning Architecture: Design, Evaluation, Communication

eCAADe – International Conference on Education and Research in Computer Aided Architectural Design in Europe

FDM – Fused deposition modelling

GRAIL – Graphical input language

ICBO - International Council of Building Officials

IFC – Industry Foundation Classes

ISPRS – International Society for Photogrammetry and Remote Sensing Congress

IT – Information Technology

NASA – National Aeronautics and Space Administration

PLA – Polylactic acid or polylactide

PVC – Polyvinyl chloride

TPL – Textual programming language

VPL – Visual programming language

WCED – World Commission on Environment and Development

WMCAUS – World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium

WoS – Web of Science

Chapter 1. General Introduction

This chapter presents the overall thesis structure, the aims of the thesis, and the object of study, named as “the research for informatics tools in aid of earthbag designs”. Once the object of study is defined, the chapter presents the motivations for the choice of theme, the justification for its purpose. Ultimately, it presents a discussion on the need for further investigation on the research theme.

1.1 Object of study

On the opposite way of social and environmental degradation, groups of ecologists, bioconstructors, and permacultors are using natural materials to build more environment-friendly constructions. These groups aim to cause less damage to the environment, while trying to find alternatives to avoid the perpetuation of the current society supported by high energy consumption, pollution, and consumerism. They look for answers to their problems while working with nature and not against it.

The building sector can make a difference in this sense, using materials that are natural, recyclable, easy to find on site (minimum transport required), produces less waste, durable (long life-cycle), etc. (Bica, Rosiu, & Radoslav, 2016; Minke, 2006; Morel, Mesbah, Oggero, & Walker, 2001; Zhao, Lu, & Jiang, 2015). There is no consensus in how to call this specific architecture. The terms found the most are: green buildings, eco design, ecological architecture, environmentally sustainable design, resilient design, all of them often used to describe construction that presents a minimal environmental impact, not just during constructive time, but also during the hole building life cycle.

When using natural materials for construction the disposals are easily reused while the use of chemical additives and synthetical materials are reduced. With adequate architectural design, the building can present energetic efficiency in terms of temperature, natural light, and ventilation.

Based on the idea of resorting to natural materials, the object of this research is **the architectural design of earthbag buildings**. The choice of earthbag construction stems from both its unique plastic appeal, and the existence of an easy construction system, which is faster and cleaner to build up than other earth-construction techniques.

> "The method offers more structural integrity than adobe, more plasticity than rammed earth, and more speed in construction than cob." (Hunter & Kiffmeyer, 2004, p. XI)

Some authors disagree on how to name the construction technique that uses plastic or textile bags filled with soil and sometimes sand or gravel, assembled in tamped layers. At first it was called 'earthbag' or 'sandbag' and these systems have historically been used as a fast-assembly method for erosion control, flood control, military bunkers, and retaining walls (Calkins, 2009). The term earth-filled bags, was used during the seventies in Germany, when the building research laboratory (BRL) tested building walls with sand or earth inside bags of polyester fabric or hoses, (Minke, 2006). In the eighties, an Iranian architect named Nader Khalili, in collaboration with NASA studies, further developed this constructive technique to respond to the earthquake code tests in California, attending also global safety requirements. His system of building domes and vaults with earth, bags and barber-wire, was patented and named as SuperAdobe (Khalili, 1986; Minke, 2006).

Even though SuperAdobe is the name of the patented technology developed by Nader Khalili and earthbag simply refers to using sandbags to build, and it is quite common to find both terms to define any of these cases in literature. It happened also during the literature review phases, that will be presented in this thesis.

The tool developed and presented in this thesis conclusion, follows Khalili's rules for dome and vaults, but not exclude other ways of assembling earthbags in linear structures.

The earthbag construction system allows linear, curvy, or dome walls, with different wall lengths, textures, and colors. Those variations have some specific constructive design rules developed (as disseminated by Khalili).

The earthbag dome geometry design, uses antigravitational, heavy compressive systems (Campos 2013). In other words, the geometry curvature works against the gravity action, where the heavy earthbag layers, assembled into an upward dome curve maintains its shape and stability though the mutual pressure of a load and the separate pieces.

According to Campos, 2013, this constructive geometry is more sustainable regarding energy/time requirements; in his work, he does a comparison between compression and tensile architectures (conventional architecture structural system that squeezes the material together, holding up a certain amount of tension), and affirms that the compression architecture presents lower energy applied and longer durability, resulting in a bigger building life cycle (Campos, 2013).

In architectural offices it is quite common the use of new technologies, namely information technologies (IT) during the design process, such as CAD (Computer aided design) software, BIM (building information modelling), and other analysis tools that are available since the initial phases of the design process. However, data on the influence of these tools over the development of earth architectural designs is scarce, specifically on how those tools could contribute to improve and incentive the design of earthbag buildings.

This research is based on the use of traditional materials together with informatic tools, to adjust the existent technology for designing with earthbag as a construction material.

> "There are many opportunities to create systems that work from the elements and technologies that exist. Perhaps we should do nothing else for the next century but apply our knowledge. We already know how to build, maintain, and inhabit sustainable systems." (Molisson & Slay, 1997, p. 2)

The object of study in this research is located in the intersection of two fields of knowledge: computer-aided design and ecological architecture (Figure 1). Because of this compound knowledge format, it can be characterized as an interdisciplinary research.

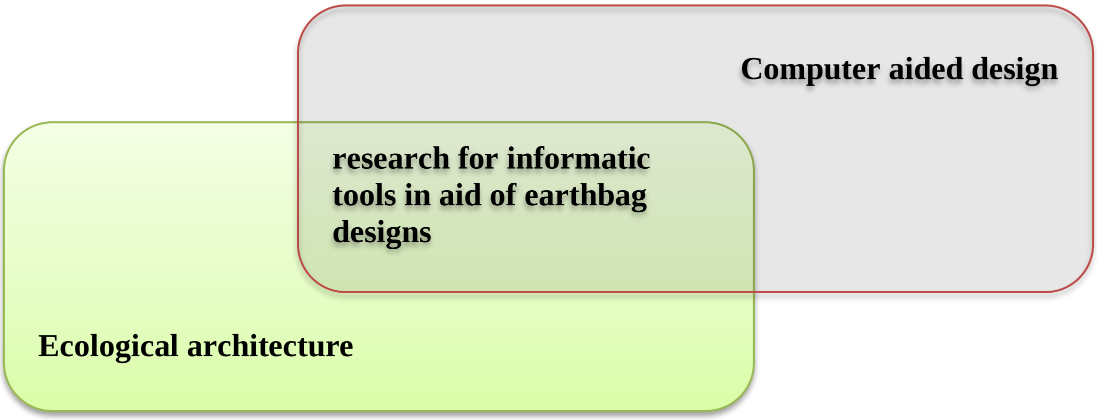

Figure 1. Diagram of object of study.

1.2 Research Motivation

The motivation of this research focus on the inexistence of informatic tools specific for designing earthbag buildings, even though it is known that earthbags are low environmental impact solutions. Furthermore, it seems that architects are reluctant to use BIM tools when designing with earthbag techniques because they create difficulties in the modelling process not only due to their specific geometries, and in particular the dome structures, but also because such wall types do not exist in the BIM's material libraries.

The extreme consumption of natural resources in contemporary societies has led to an alarming degradation of the environment (Assadourian, 2010; Brundtland, 1987). Therefore, it is desirable to enforce new sustainable architectural practices resorting to building techniques that have less environmental impact (Kumar, Sachdeva, & Kaushik, 2007; Morel et al., 2001; Sargentis, Kapsalis, & Symeonidis, 2009). This research has the ambition to contribute to the production of architectural strategies for sustainable development in particular through the possibility of incrementing and improving the use of earthbag techniques as part of such strategies.

In addition to the architectural practice contribution, this research also intends to contribute to the enlargement of earthbag architecture theory, which is still very low in scientific resources.

On May 2016, the author of this research participated in a Portuguese meeting named “Práticas de Arquitetura: Construções em Terra” (Architectural practices: earth constructions, Genin, 2016), where there was the opportunity to interact with many reference researchers of earth architecture in Portugal. None of them had researched or worked with earthbags before. As a matter of fact, some of them had never really heard about it. The earthbag technique is therefore scarcely disclosed even among earth architecture specialists in Portugal.

There is a lack of studies about earthbag/SuperAdobe, confirmed by a bibliographic search on websites and books of international earth centers, such as CRAterre (France), ABCTerra Association (Brazil), Associação Centro da Terra (Centre of the Earth Association, Portugal), LNEC (Portugal), and FCT/UNL (Portugal). Additionally, CRAterre have designed and published in many different languages a schematic circular diagram with 18 kinds of earth construction (*Figure 2*) where earthbag/SuperAdobe is not included.

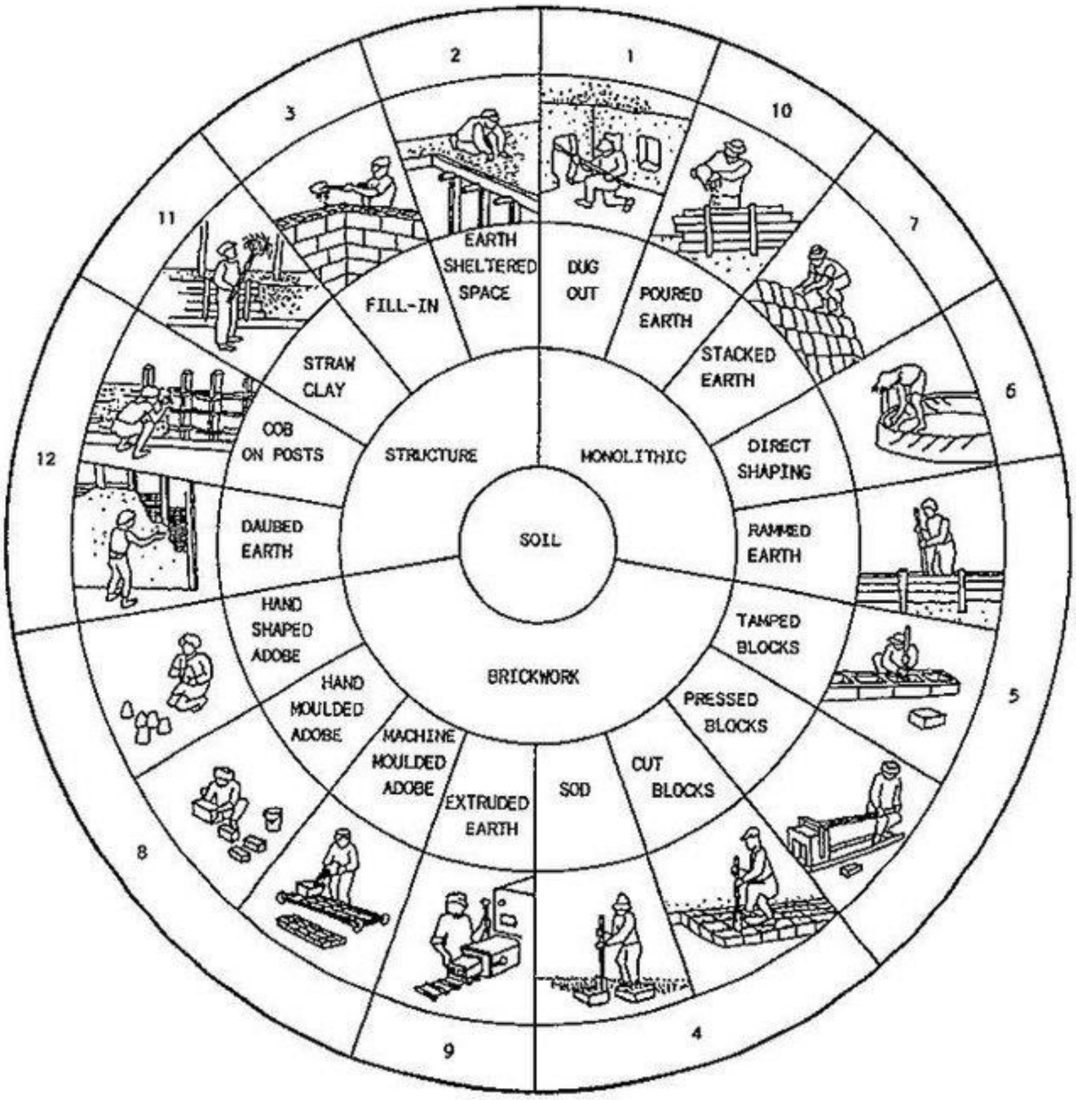

Figure 2. Schematic diagram created by CRATerre listing 18 types of earth architecture. Source: Giuffrida, Caponetto, & Cuomo (2019).

Regarding scientific publications, a search on 123 references databases using the keywords “SuperAdobe” and “earthbag”. Only two indexed papers were found with double blind review process (Santos & Beirão, 2016a).

The lack of theoretical resources became an extra research motivation in order to produce knowledge in this field and enlarge the number of publications on the subject. By formatting this thesis as a collection of papers, we offer to the community new scientific papers related to the field, expanding and disseminating the literature.

Another important contribution of this research is to promote the adoption of sustainable architectural development as a way of obtaining balanced, fair, accessible, and better quality of life for future urban societies.

1.3 Research problem

The research problem of this research is: **the lack of informatic tools for the design of earthbag buildings**, linked with the challenge of associating innovative and accessible technologies to support earthbag construction design.

> "we have to change the lifestyle and the way we build if we want to preserve the planet for future generations. Although more and more people are starting to make such changes, I am concerned that the current trend about high-tech solutions for sustainability, many of which are so expensive that they are only affordable to one third of the world population." (Hertzberger, Heringer, & Vassal, 2013, p. 15)

Regarding virtual modeling in CAD tools, when an architect wants to model earthbag domes, the usual available processes are arduous, since such processes require the need to do several calculations by hand before starting to model. After modelling, it is necessary to describe all the technical construction requirements.

With the advent of BIM, architects are becoming more demanding about accurate technical answers, than in the past, forcing the use of BIM to foster a better control over the design, costs, and management. With BIM tools, the tasks of designing and planning may happen together, as the design models are representations of real-world items (object-based design). These items have identity and quantitative constructive data associated, which is generated automatically while modelling (Eastman, Teicholz, Sacks, & Liston, 2011; Kensek, 2014; Turk, 2016). However, earthbag is not part of the set of standard materials in BIM platforms. Consequently, these platforms are not enabling the generation of the specific quantitative data for that construction system, such as the necessary description for construction materials supply. Thereat, it becomes arduous, if not pointless, for architects to use BIM tools to work with this technology. The main purpose of this research is to eliminate this flaw.

Physical scaled models are essential to understand the planned earthbag building before the construction starts, especially regarding the spatial complexity of domes and their intersecting points (Hunter & Kiffmeyer, 2004). Earthbag projects have a plastic appeal, commonly provided by the curvilinear or dome shapes, which comprises a different appearance from the conventional constructions.

The geometry of such domes and their intersection areas are not easy to understand using traditional bidimensional representations of plans, sections, and elevations. These shapes are easier to understand with the use of higher precision techniques, such as 3D modelling, whether resorting to CAD or BIM. Calculating the quantities of materials for such complex shapes is also a non-trivial task which could be easily performed by BIM software. Physical models are also essential to communicate such complexity to clients or even just for architects to test their ideas.

> “Since domes are three-dimensional, it is easier to comprehend their design in a three-dimensional medium, like sculpture.” (Hunter & Kiffmeyer, 2004, p. 148)

When using 3D printing to produce scaled models, the architect would benefit to be able to the interweave of digital and non-digital approach to present the project (Song, Ha, Goo, & Cho, 2019), presenting a touchable resource beyond the screen-based model. The 3D printing process is an efficient way to generate such physical models, as long as the 3D models are accurate. By resorting to 3D modelling the architect can get rid of hand modelling and gain time, acquire modelling precision while producing the base virtual model for printing the physical model (Groat & Wang, 2013). Other advantage of having a 3D digital model is to create the architectural scaled model by 3D printing, reducing the time and human effort required to do it.

The use of BIM software can improve the design process of earthbag buildings in two main ways: by (1) addressing the design specification issues by calculating shape and construction materials and resources, and by (2) providing a 3D digital model, which facilitates the prototyping phase of design.

1.4 Research Question

This research answers the question: **Can digital tools be developed to support earthbag building designs in BIM environment?**

1.5 Hypothesis

The hypothesis of this research is: **it is possible to develop a digital modelling tool in a BIM environment to help the design phase of earthbag constructions, with quick simulation capacity, while informing the necessary constructive specifications, and also enabling the rapid prototyping of accurate physical scaled models.**

Since the existing software tools are still limiting factors in this type of project, with the creation of specific tools for earthbag design it will be possible to design faster, with higher quality, and better precision.

1.6 Objectives

The main thesis objective is **to create a set of alternative tools to support earthbag architectural design, using BIM technology.**

From the main objective, five specific objectives are defined and addressed, each one originating five thematic papers. These five specific objectives are also related with five methodological steps, better described in the next topic. The specific objectives are:

1. To characterize and categorize earthbag buildings – a systematic characterization of earthbag building types;
2. To test parametric modelling versus textual programing languages to find out which one of them could be more suitable to create the tool;
3. To develop a parametric tool to design earthbag domes (including the generation of quantitative material descriptions);
4. To identify previous research regarding the use of BIM for designing with earth construction techniques; and
5. To connect the parametric tool to design earthbag domes in a BIM environment inserting the expected BIM functionalities such as parametric constructive data.

1.7 Research design and methodology

The research was strategically divided into five steps, organized as illustrated in the diagram of *Figure 3*. Each of them producing as an output a paper that corresponds with the specific objectives of this research and therefore present their own methodology.

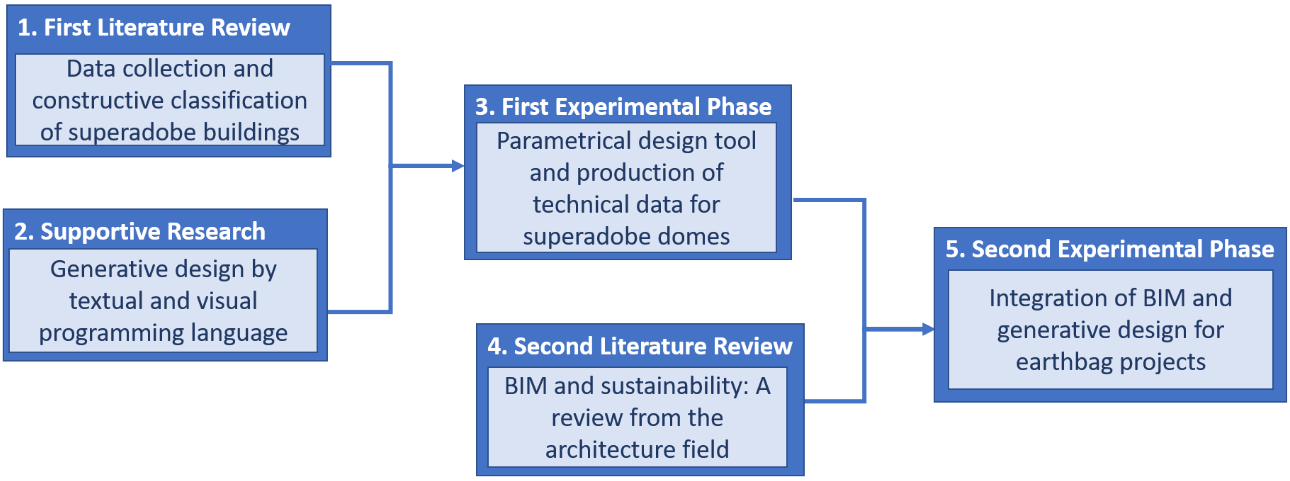

Figure 3. Schematic diagram of the research design.

The general research methodology resorted to experimental methods of development, defined as a *systematic effort, based on existing knowledge from research or practical experience, directed toward creating novel or improved products or processes* (OECD, 2015). The experiments were conducted in informatic laboratories and comprised the development of tools to support earthbag architectural design.

This experimental part encompasses two phases presented in two different steps summarized in two published papers: (1) the development of a parametrical tool for earthbag domes design and (2) the insertion of this tool into a BIM environment including data and construction procedures management. The development of the tools needed some supportive research to understand which programming language would suit better the tool development (one paper) and literature review to support the experimental phases, one regarding the earthbag construction technique and its typological variants, and another to trace the main research topic regarding BIM and sustainability (two papers). The papers methods and their outputs in the thesis context are separately presented in the following paragraphs.

Step 1: Literature Review.

The first step is to understand the earthbag construction technique and its typological variants. This is an important step as it compiles the necessary information to create the design tools. For this retrospective study, the methodology is based on a qualitative analysis of a collection of documents (Marconi & Lakatos, 2006), with a survey on 123 scientific online databases, publications, and documents. The result is a compendium of information from journals, books, and webpages dedicated to earth architecture, engineering, and sustainability fields. The search on additional publications and documents covered the information about earthbag typological variations that the scientific databases did not cover.

The output of this step is a paper that presents a typological classification of earthbag construction types:

Santos, D. M., & Beirão, J. N. D. C. (2016a). Data collection and constructive classification of SuperAdobe buildings. *Revista Ciência e Sustentabilidade*. ISSN 2447-4606, v.2, number 2, pages 208-226. doi 10.33809/2447-4606.222016208-226

Step 2: Supportive Research.

Following the literature review, the second step of this research is the experimental phase. This phase encompasses two methodological parts. The first one aims to develop a parametric tool to model earthbag domes. The second part aims to link this tool to a BIM environment, proving the tool's capability for designing complex projects involving mixed construction technologies (in this case, earthbag walls and domes mixed with other construction technologies). This leads to the development of a totally flexible design tool for designing complex earthbag buildings comprising multiple construction techniques. To start these experiments, it was necessary to understand which programming language would be the best for the tool development. In order to do so, a previous experiment was developed to compare two types of algorithmic aided design procedures: (1) using a textual programming language (TPL) (python and khepri) or (2) using a visual programming language (VPL) (Grasshopper). To understand the constraints and possibilities of both languages the comparison addresses scripting practical parametric examples with different levels of challenge, according to each computational thinking approach (Lee et al, 2011; Papert, 1980; Wing, 2008).

The output of this step is a paper that shows the comparison between TPL and VPL. It provides the information that conducted to the selection of the programming language used to develop the CICERO tool: the VPL with Grasshopper. This one was chosen because of its easy interaction with BIM environment through specific ad-ons, and because of the possibility to share online through the ShapeDiver platform (www.ShapeDiver.com):

Santos, D. M., Pontes, T. B., & Leitão, A. M. (2019). Generative Design in textual and visual programming languages. In F. T. de A. Lima, M. M. Borges, & C. F. R. Costa (Eds.), *Digital Techniques Applied to Design Process* (pp. 72–95). ISBN: 978-85-93128-35-6.

Step 3. First Experimental Phase

The third step was to program the parametric tool. Both TPL and VPL were able to provide the necessary functions and results that were expected to program the desired tool. However, the VPL (Grasshopper) presents two preferable features that could be useful for the tool development. First, in order to share and use the tool online there was already available the ‘ShapeDiver’ platform (www.ShapeDiver.com) to provide such type of interface. Second, there are also already developed tools connecting Grasshopper codes with BIM platforms easily (such as VisualARQ and ArchiCAD), by resorting to user friendly ad-ons that extend

Grasshopper's functionalities. After deciding between TPL and VPL the first part of the experiment started. The first challenge is to identify the experiment variables (Gil, 2002): the variants and constructive rules of earthbag domes.

Using the computational thinking approach, which is an analytical way of thinking that can solve any (solvable) problem (Lee et al., 2011; Papert, 1980; Wing, 2008), we performed three additional procedures: 1- *abstraction*: to discard unnecessary information, 2- *automation*: to develop the code to parametrically generate solutions and related construction specifications, and 3 – *analysis*: to analyze the program to check if it works as expected. Those three procedures were repeated until the results were found satisfactory. Then, the tool was submitted to experts on earthbag construction for research validation purposes.

To validate this first experimental phase of the thesis, the tool was posted online and with free access. The subjects of the experiment are from an international community (Brazil, United States, Guatemala, Turkey, Portugal, and Italy) and they were responsible for testing and evaluating the tool, through an inquiry. The first questions refer to user characterization to capture information on the type of interested public. To measure the user interaction, the following 10 questions of the inquiry adopted the ten Nielsen heuristics (Nielsen, 1995). To answer the survey, the subjects had to reproduce three known dome projects using the tool. The inquiry ends with an open space for comments and suggestions.

The output of this step is an paper that presents is a parametric tool for earthbag dome models. This parametric tool provides the basis for CICERO tool:

Santos, D. M. dos, & Beirão, J. N. (2019). Parametrical design tool and the production of technical data for SuperAdobe domes. *Gestão & Tecnologia de Projetos,* 14 (1). ISSN: 1981-1543

Step 4. Second Literature Review.

Step four is a second literature review about the relation between BIM and Sustainability. Before starting the second phase of the experiment, it was necessary to expand the literature review to understand the relationship of BIM and earth constructions in the field. To address this objective, the paper includes a survey for the combination of descriptors "BIM" plus "earth", "BIM" plus "sustainable", and "BIM" plus "sustainability". To trace the main previous research regarding these topics, the adopted methodology is a quantitative method of bibliometric analysis, where the researcher analyzes the bibliographic information, of a selected database, for a whole range of specific measurement of published papers (Okubo, 1997).

The output of this step is a paper that presents the research gap, identifying that the relationship between BIM and earth construction is underexplored in literature in searched databases, evidencing the innovative character of this PhD study. It also provides basic technical information for the development of the BIM experiment, identifying the bibliographic resources:

Santos, D. M., & Beirão, J. N. D. C. (2019). BIM and sustainability: A review from the architecture field. *Modern Environmental Science and Engineering*, 5 (5). ISSN: 2333-2581

Step 5. Second Experimental Phase

Step five is the second experimental phase, with the implementation of the Integration of generative earthbag design tool in a BIM environment that supports the earthbag design. It involves the insertion of a new material (earthbag) in the BIM library, and the improvement of CICERO code to generate earthbag domes within a BIM environment. In this new version of the code the earthbag construction system can be associated with other construction and structural elements, producing the required technical data to inform construction, including technical specifications, materials, and task quantification. VisualARQ is a BIM software that supports the integration with Grasshopper in Rhinoceros and therefore was the most suitable software for the second experiment.

CICERO code was improved using the VisualARQ add-on in Grasshopper. VisualARQ provided the user-friendly platform to insert a new variable data in the BIM database, in this case the new construction material.

BIM software normally allows import and export the building projects and its semantic contents into the IFC (Industry Foundation Classes) standard. The IFC data format is “the framework of semantic content of all objects and the hierarchical organization between them (geometrical, temporal, material, etc.)” (Markova, Dieckmann, & Russell, 2013).

As a BIM tool, VisualARQ can export this new earthbag data in IFC format, which makes the information interoperable as it can be accessed on different software.

The methodological procedures for tool validation involve *simulation research*, using an *analogue model* (Groat & Wang, 2013; Mitchell, 1975). Mitchell (1975) categorizes representational models for design problems in *analogue, iconic* and *symbolic*. Models on the *analogue* category present one or a set of properties from the real object. The tool validation procedures were: (1) chose an existing building (2) simulating the design, (3) printing a 3D scaled model, and (4) compare the model with the actual building.

To test CICERO’s capabilities, an existent awarded building was chosen as a reference project; that the project involves domes, straight and curvy walls, and presents also different constructive techniques such as one internal brick wall, flat roofing, wooden beams and conventional doors and windows.

The output of this step is an paper showing the CICERO tool set that runs in BIM environment capable of generating parametric earthbag domes as BIM objects (Walls), with associated materials' data, that allows the production and integration with other morphological types than domes, involving also several construction techniques. The produced BIM model can be exported and shared in a standard format (IFC), providing software interoperability:

Santos, D. M. Beirão, J. N. D. C. (2020). Integration of BIM and generative design for earthbag projects. In: Almeida, H. Vasco, J. *Progress on Digital and Physical Manufacturing*. Leiria, Portugal: Elsevier Scopus.

1.8 Thesis organization

This thesis is defined by a collection of the papers above-mentioned in the research design as methodological steps outputs. All of them are already published in journals, international conferences, and edited books. These papers define a thematic chapter inside the thesis, which are delimited by this general introduction and a general ending discussion/conclusion chapter. A small introductory section is presented before each chapter. The overall structure of the thesis is organized as presented in Table I.

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Table I

Thesis Organization.

Title	Papers
Chapter 1. General Introduction	
Chapter 2. Data Collection and Constructive Classification of SuperAdobe Buildings	Data collection and constructive classification of SuperAdobe buildings (output of step 1).
Chapter 3. Generative Design by Textual and Visual Programming Language	Generative design by textual and visual programming language (output of step 2).
Chapter 4. Parametrical Design Tool and Production of Technical Data for SuperAdobe Domes	Parametrical design tool and production of technical data for SuperAdobe domes (output of step 3).
Chapter 5. BIM and Sustainability: A Review from the Architecture Field	BIM and sustainability: A review from the architecture field (output of step 4).
Chapter 6. Integration of BIM and Generative Design for Earthbag Projects	Integration of BIM and generative design for earthbag projects (output of step 5).
Chapter 7. Conclusion	
General References	
Appendix 1: Additional research paper 1	Generative tool to support architectural design decision of earthbag building domes.
Appendix 2: CICERO additional images	
Appendix 3: CICERO additional Information and validation	

There are four *research* papers (including the one in the appendices which is the short version of paper 3, *Parametrical design tool and production of technical data for SuperAdobe domes*) presenting the experimental research, and two *literature review* papers presenting the theoretical background for the experiments (*Figure 3*, p. 46). In order to maintain an operational and contextual cohesion between the methodology of each experiment and their specific underlying theoretical models, the literature review of the thesis is divided in two chapters (two and five), with their related experimental chapters in sequence.

Chapter 1: General Introduction presents the objectives of the research, the general object of study, the research delimitation and motivation, and a general description of its structure and methodology. It also presents a brief explanation of the main thesis title.

Chapter 2. Data Collection and Constructive Classification of SuperAdobe Buildings presents the first published paper with the same title (Santos & Beirão, 2016) and addresses the main knowledge fields of this thesis: the earthbag construction, characterizing the construction system, its environmental advantages and providing a typological classification of its construction possibilities.

Chapter 3: Generative Design by Textual and Visual Programming Language is a book chapter and it is a collaboration with professor António Menezes Leitão and professor Thiago Bessa Pontes (Santos, Pontes, & Leitão, 2019). This chapter presents a set of experiments comparing TPL and VPL. The importance of this chapter on the broader research context is the process of learning and understanding the programming logic behind both languages, their advantages, and constraints. This paper helped to identify the existent interfaces that can work together with both programming language. The paper also helped to choose the more adequate programming language and the interfaces for the following experimental phases.

Chapter 4: Parametrical Design Tool and Production of Technical Data for SuperAdobe Domes presents a paper about the first experimental phase of this thesis, the development of a parametric tool to design earthbag domes with constructive data associated. This paper was previous published, in a compact form, in Blucher Design proceedings, as presented at the SiGraDi conference (Santos & Beirão, 2017). After the conference the authors were invited to submit an expanded version to a special issue of the journal *Gestão & Tecnologia de Projetos* (Design & Management Technologies) (Santos & Beirão, 2019b).

This special issue presents a selection of the best conference papers, after a new peer review process.

Chapter 5: BIM and Sustainability: A Review from Architecture Field presents a paper of literature review on building information modelling (BIM) that highlights the relevant literature and gaps in science in this field that supports next chapter experiment. This paper is published on Modern Environmental Science and Engineering Journal (Santos & Beirão, 2019a).

Chapter 6: Integration of BIM and Generative Design for Earthbag Projects presents the second phase of the experiment. This is the output of this research and presents an improved version of the paper *Progress on Digital and Physical Manufacturing*, published as a book chapter by Springer under the book series "Lecture Notes in Mechanical Engineering" (Santos & Beirão, 2019c). This paper presents the insertion of the results of chapter four (the parametric tool for dome design) in a BIM environment and the creation of earthbag material in a BIM library, which allows the development of new architectural designs with mixed materials, including earthbag walls and domes working together with other BIM standard materials.

Chapter 7: Discussion and Conclusions presents the final general discussions and conclusions.

References presents the extended supporting bibliography.

The **Appendices** presents, as an appendix 1, the paper is published in Blucher Design Proceedings (Santos & Beirão, 2017). It refers to the compact version of the paper presented in chapter four. The appendix 2 presents additional images of CCICERO tool. The appendix 3 presents additional data regarding CICERO tool first phase validation.

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Chapter 2. Data Collection and Constructive Classification of SuperAdobe Buildings

The paper presented in this chapter[1] addresses the literature review of the main knowledge field from this thesis: Earthbag architecture. The paper has as goal to provide a systematic characterization of earthbag building types.

The chapter presents the result of a systematic survey in specialized databases, books, publications, and documents. The output of this paper is a typological classification of earthbag construction types, which is summarized in a table as final result.

[1] This chapter is a slightly modified version of "Santos, D. M., & Beirão, J. N. D. C. (2016). Data collection and constructive classification of SuperAdobe buildings. *Revista Ciência e Sustentabilidade*. ISSN 2447-4606, v.2, number 2, pages 208-226. doi 10.33809/2447-4606.222016208-226" and has been reproduced here with the permission of the copyright holder.

Data collection and constructive classification of SuperAdobe buildings.

(Levantamento e classificação tipológica construtiva das construções em SuperAdobe)

Resumo

As construções em terra são soluções reconhecidas de baixo impacto ambiental. São construções duráveis, fortes, climaticamente eficientes, formalmente flexíveis e são compostas por recursos renováveis e reaproveitáveis favorecendo o desenvolvimento sustentável. Também conhecido como “adobe ensacado”, “saco contínuo de terra estabilizada”, “*earthbag building*” ou “*Earth-filled bags*”, o SuperAdobe consiste na técnica construtiva onde as paredes são construídas basicamente por sacos preenchidos com terra e areia empilhados, e travados com arame farpado entre eles. A técnica foi desenvolvida como possível solução de construção na lua, depois foi aplicada pare resolver a problemática de habitação popular. Atualmente é possível encontrar construções em SuperAdobe robustas, com diferentes usos e com associações de outras técnicas construtivas. Este artigo tem por objetivo fazer um apanhado geral sobre a literatura dedicada as construções em SuperAdobe e oferecer uma alternativa para sua classificação tipológica com base nas construções já executadas, a fim de auxiliar pesquisas futuras no reconhecimento e superação dos limites e variações da técnica construtiva. O método é descritivo qualitativo, com investigação de cunho exploratório interdisciplinar, por meio de levantamento em revistas científicas, livros e páginas eletrônicas dedicadas aos temas de arquitetura, engenharia e sustentabilidade.

Palavras-Chave: SuperAdobe, sustentabilidade, arquitetura, construção em terra.

Abstract

Earth constructions are recognized as low environmental impact solutions. They are durable constructions, strong, climatically efficient, formally flexible and the resources are renewable and reusable, promoting sustainable development. Also known as "bagged adobe", "continuous bag stabilized earth", "earthbag building" or "Earth-filled bags", the SuperAdobe is a construction technique where the walls are basically built by bags filled with earth, stacked and reinforced, with barbed wire between them. The technique was developed as a possible solution for building on the moon, then applied for housing construction, and it is now possible to find buildings in robust SuperAdobe with different uses and with other constructive technical associations. This paper aims make an overview of literature dedicated to SuperAdobe construction and offer an alternative for their topologic classification supported by already implemented constructions, in order to assist future research on recognizing and overcoming the limits and variations of the construction technique. The method is qualitative research with an exploratory nature through survey in magazines, books and webpages dedicates to architecture, engineering and sustainability fields.

Keywords: SuperAdobe, sustainability, architecture, earth construction.

2.1 Introduction

Groups of ecologists, bio-constructors, and permaculturists that fight against social and environmental degradation, are returning to use natural materials in constructions in order to avoid harm to nature, landscape, ecosystems, and human health. They aim to create alternative solutions to the existing life system that is supported by high energy consumption, pollution, and consumerism. As a main strategy, they try to work with nature, not against it.

By using natural materials, the disposal of construction is easily reusable; there is a reduction of chemical additions and synthetic materials. With correct strategies of design, it is possible to guarantee an efficient building with good conditions in terms of natural ventilation and lighting.

Based on this reasoning, the object of this paper is to make an overview of the earth architecture project, with an emphasis on the SuperAdobe technique highlighting its particular qualities and advantages. Compared with the other types of earth construction, the SuperAdobe, or earthbag needs less maintenance, can have a plastic appeal, has a lower construction time, and has no necessity of formwork or additional structure (Hunter & Kiffmeyer, 2004).

Another important motivation is that there is not much scientific research about SuperAdobe. To start this research, an inquiry was made on the list of periodicals from “Capes” (http://www.periodicos.capes.gov.br/), a virtual Brazilian library that contains 123 reference bases. The keywords searched were “SuperAdobe” and “earthbag”. Only two indexed papers were found with double blind review process. In both of these papers, it was not possible to identify the variants of SuperAdobe construction. They were focused on testing the qualities of the material itself.

In order to help filling this gap in science, this paper aims at classifying all the existing types of SuperAdobe constructions. Furthermore, a systematic classification of the technique may provide objective studies regarding the development of best practice recommendations as well as tools to support “SuperAdobe” design. The final aim of the research is the development of BIM and parametric design tools for “SuperAdobe” construction. The classification presented in this paper defines a rigorous starting point for the development of such tools.

The paper is divided as follows: State of art, disadvantages and advantages, methodology, different SuperAdobe applications, conclusion, final considerations, acknowledgements and references.

2.2 State of the Art

The SuperAdobe technique was created by the architect Nader Khalili in 1985. It was a contribution with NASA researchers and it aimed to finding out a way to build houses on the moon, associating high tech with the use of local materials (Khalili, 1989). After this work he thought to apply this new technique to address the lack of housing (Minke, 2013; Hunter & Kiffmeyer, 2004).

This technique consists in a constructive system that uses polypropylene, raffia or other bags, barbed wire, and earth. These bags are acquired in rows, which can variate from thirty to sixty centimeters of length. They are filled with inorganic earth to create walls, domes, and arches. The bags can be cut by the desired size and filled with a funnel using earth with 20% of humidity.

As soon as these bags are filled, they are stacked in layers with barbed wire between them, to improve security and stability, until the entire wall is complete. The length of the walls varies according to the length of the bags, and is only limited by load restrictions.

Sometimes chicken wires are applied over the walls and underside the building openings windows to provide extra texture and develop a grippy surface, helping for the application of a plaster finish later on.

Many variations of soil can be used in this technique because of bags retention capacities (Calkins, 2009), however it is suggested the mixture of approximately thirty percent of loamy soil and seventy percent of sandy soil. This mixture was adopted by most of the old buildings of rammed earth in the world that can still be seen nowadays (Hunter & Kiffmeyer, 2004).

2.2.1 Disadvantages and Advantages

Because of the natural material advantages, this technique was proposed to build small constructions to address the problem of lack of housing. Just after was tried to apply in buildings of different sizes and uses, such as ecovilles, hotels, exhibition pavilions, and others.

The known disadvantages to use this material are just a few, and most of these are related to the unfamiliarity of the technique by the population. Table II summarizes these advantages and disadvantages, as the next paragraphs will talk more about what the literature has written about this theme.

Table II

Resume of advantages and disadvantages to the use of SuperAdobe.

Advantages	**Disadvantages**
Flexible Form	Unknowledge (architects, engineers, constructors, etc.)
Speed of construction	Legal issues
Thermal comfort	Social acceptance
Energy efficiency	Technical limitations
Low cost	Fragility of site construction
Structural strength	Specific Tools of Computer aided design
Self-supporting for up to 2 floors	
Low maintenance	
Recyclable and reusable resources	

2.2.2 Disadvantages

Unknowledge: In general, neither architects nor engineers have received adequate knowledge during their academic backgrounds to create SuperAdobe designs. To solve this problem, it is recommended to make a short workshop qualification before starting to build a SuperAdobe dome on large scale (Hunter & Kiffmeyer, 2004).

Legal issues: There are few countries that include earth in their building codes. Even those that have included earth, do not specify the SuperAdobe technique (Hunter & Kiffmeyer, 2004). Moreover, the natural loam (mixture of clay, sand and aggregates) is not a standardized material; these characteristics may differ depending on the place from which it was extracted (Minke, 2013). This lack of accuracy in composition may prevent its industrialization process and hence hinder the quality control.

Social acceptance: Earth architecture has faced many allegations, dominated by psychological factors that are based on unrealistic concerns, such as that they are not durable, they have always a primitive design, or they are buildings for poor people (Sameh, 2014).

Technical limitations: The self-supporting dome is best employed on constructions up to 6 meters of internal diameter. To create projects with bigger internal areas, other project strategies are needed. For example, connecting small domes, or using other structural support in association with the bags, or trying other designs with perpendicular walls (Hunter & Kiffmeyer, 2004). Another question is that the material is not water resistant, then it is important to protect and make walls and foundations waterproof (Minke, 2013).

Low resistance of site construction: As the material is not resistant to water, the site construction must be protected from rain because there is the risk of collapsing rows before applying the cover application or closing the dome.

Specific tools of computer aided design missing: The material "SuperAdobe" is not available in libraries of computer aided design software, nor of BIM (building information modelling) systems.

2.2.3 Advantages

Flexible form: The material plasticity allows creating freeform walls in horizontal projection. In vertical projection, orthogonal walls, arches or domes can be easily executed (Calkins, 2009; Hunter & Kiffmeyer, 2004).

Speed of construction: it was made an experiment with the "Honey house" that was built in 19 days by a team of five persons that spent 5 hours per day at work (Hunter & Kiffmeyer, 2004). This duration happens because the bags are placed in the layers while they are still wet, differently from alternative earth constructions where there is the need to wait for the earth to dry before continuing to build (Calkins, 2009).

Thermal comfort: earth walls are natural thermal isolators; they create more comfortable internal microclimate especially for hot and dry climate zones. They are also natural regulators of internal moisture, allowing the absorption of its excess letting it escape to the external environment. However, for dry climates, these walls are able to do the reverse process and release moist in the air, regulating the internal space. (Hunter & Kiffmeyer, 2004).

Energy efficiency: the earthbag thickness combined with an exterior insulation creates a kind of air buffer of resistance to extreme external temperature change. Other suggestion to get benefit of passive solar design creating a wraparound porch, which provides shadow to the walls during summer, and receive the solar rays during winter (Hunter & Kiffmeyer, 2004).

Low cost: in 2011, a SuperAdobe Project earned the third place in the competition named “The $300 Houses Challenge”. The objective was creating a low cost sustainable project, that could be built in community (eliminating the cost of labor), by applying low technology. The calculation memory of this project, according to the architect Rogério Almeida and the engineer Gustavo Thron, started that 14 SuperAdobe terraced houses, would cost $283,33 each (Jovoto, 2011).

Structural resistance: Nader Kalili has tested SuperAdobe foundations to simulate earthquake movement, according to ICBO[2] standarts for an earthquake zone 4, no deflection was observed during the tests (Khalili & Vittore, 1998; Hunter & Kiffmeyer, 2004; Wojciechowska, 2001). In 2013, the researchers Ross, Willis, Datin, and Scott did a laboratory experiment with a SuperAdobe wall to test the effects of wind pressure. They subjected a SuperAdobe wall to out-of-plane pressure up to 3.16Kpa. It did not collapse during loading (Ross *et al.*, 2013). In 2009, the researchers Daigle, Hall, and MacDougall did another structural experiment with SuperAdobe, this time exploring vertical compressive

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[2] In 2000, the International Council of Building Officials (ICBO) merged together with the Building Officials and Code Administrators International (BOCA) and the Southern Building Code Congress International (SBCCI). They became the new International Building Code (IBC), published by the International Code Council (ICC) - https://www.iccsafe.org/.

loading. The method was based on submit earthbag specimen with loading plates on top and bottom (*Figure 4*). They concluded the adequacy of earthbag technology for use in housing applications from a compressive strength perspective (Daigle *et al.*, 2011).

Figure 4. Earthbag specimen with loading plates on top and bottom.
Source: Daigle, 2011.

Self-supporting for up to duplex: It was not found in the consulted literature a limitation to the height of these kind of buildings. However, some cases were found of self-supporting dome working as a duplex. In this case, the second floor is made of timber, which just sit on the walls between the earthbags, with no need of columns. Two of these examples are: the earth house domes of Solscape in New Zeeland (*Figure 5*) and the “Majestic dome” in Panamá designed by the engineer Knott (*Figure 6*).

Figure 5. House dome of Solscape, New Zeeland.

Source: http://www.theshelterblog.com/the-beautiful-tiny-earth-domes-of-solscape/

Figure 6. Construction of 2nd floor of Majestic Dome, Panamá.

Source: Landtrees, nd.

Low maintenance: As the walls must be finished and waterproofed, their surface have the maintenance reduced. Waterproofing finishes can be natural or synthetic such as plasters and stucco, that provide a wearing layer that is affected first in case of erosion. Other finishes are able to waterproof the building such as tile, stone, asphalt and others (Calkins, 2009).

Recyclable and reusable resources: The biggest amount of employed materials in this constructive technique, as it was shown, is the earth, which is completely natural. The other materials (bags and wire), although not natural, are easily recyclable or reusable, supporting the sustainable development.

2.3 Methodology

The adopted methodology is based on a qualitative analysis of documents. The documental research aims at a retrospective study starting with information on documented events that already happened.

> "A característica da pesquisa documental é que a fonte de coleta de dados está restrita a documentos, escritos ou não, constituindo o que se denomina de fontes primárias. Estas podem ser feitas no momento em que o fato ou fenômeno ocorre, ou depois.
> (The characteristic of documental research is that the source of data collection it is restricted to documents, written or not, constituting what is named as primary sources. These can be made at the time the event or phenomenon occurs, or after.)" (Lakatos & Marconi, 2006, p. 176)

From the beginning, a research was made in specialized books, then in scientific journals, and at the end in specialized websites. The papers of scientific journals were inefficient in this paper, because they did not contain information on the variations of SuperAdobe technique. These were just the studies about material resistance presented in this paper.

2.4 Different SuperAdobe Applications

In order to tabulate and classify SuperAdobe variants, variations of roofing, foundations, structural variants and formal compositions were systematically approached.

2.4.1 Roofing

Earthbags can make roofs just in case of domes and small vaults. In both cases, the earthbag roof will receive a layer of a waterproof material (for example: clay plasters, lime plasters, waterproof membrane, or other), then a natural or artificial covering such as grass, papercrete, bamboo wrapped around grass overlapping, loam, stones, tiles, or other (Wojciechowska, 2001).

For the other SuperAdobe structures, most of all existing styles of roof that already exist in other constructive types can be adapted to use in SuperAdobe (Hart, 2015).

There are different ways to attach the beams and trusses to the walls. The easiest way is to apply them directly between SuperAdobe layers, creating a tension ring with halos of barbed wire in between rafters (Hunter & Kiffmeyer, 2004).

To improve the resistance of tension between SuperAdobe walls and beams and trusses, some details were created with Velcro plates (*Figure 7*).

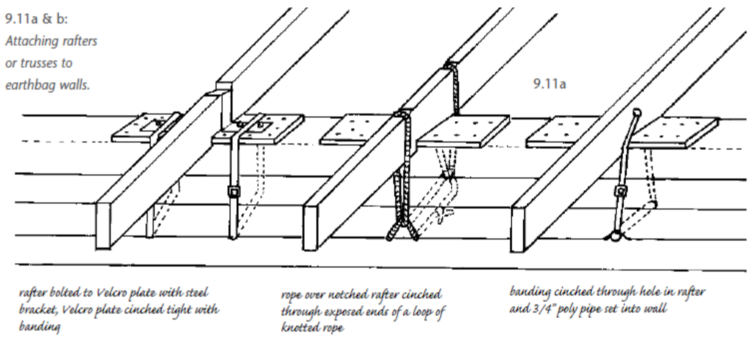

Figure 7. Details to improve attachment of roof into the walls.

Source: (Hunter & Kiffmeyer, 2004, p. 55).

Other option is to create a wood or concrete roof frame over the SuperAdobe wall to attach the ceiling structure.

2.4.2 Foundations

Many foundation systems can be applied to the SuperAdobe building. Most of them start digging a hole until an undisturbed ground is found. The most challenging situation for superadobe building is where the temperature gets too low, in particular with negative temperatures. Even for these places it is possible build a stable foundation. In this case the depth aims to find a level that is below the frost heave level to bedrock or compressed subsoil.

To fill the hole, depending on the climate issues of the place, there are some different kinds of foundation that can be choose such as concrete, "shallow, frost-protected" (this one recommended for cold places, because the expansion of the water when freezing can crack the structure), "earthbag rubble trench" and the earthbag foundation by itself.

In a *concrete foundation* system, one applies a concrete "footer" wider than the width of the SuperAdobe compacted wall. In this case, it is recommended to build the first layers with gravel-filled bags, or place a waterproof barrier on top of the foundation wall, to avoid concrete sending humidity to the wall (Hunter & Kiffmeyer, 2004; Hart, 2015).

In *shallow, frost-protected foundation* system (*Figure 8*) it is applied a vertical and horizontal rigid form insulation on exterior of the stemwall to protect the structure to frost penetration. This protection also helps to reduce heating costs. (Hunter & Kiffmeyer, 2004)

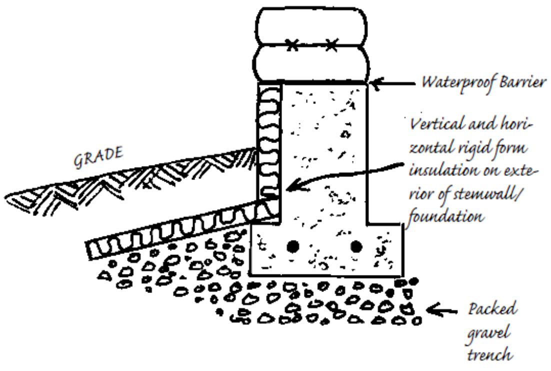

Figure 8. Scheme of shallow, frost-protected foundation.

Source: (Hunter & Kiffmeyer, 2004, 55).

Otherwise, earthbags themselves make good foundation and their application can variate according to type of soil and climate characteristics (*Figure 9*). The "*Earthbag rubble trench foundation*" systems are based on the low-cost technique developed by Frank Lloyd Wright for foundations in frozen areas. After digging the hole, one applies packed gravel and rubble stone. This provides spaces between the stones to drain the humidity. The top of the hole may be recessed below, with the first layer of gravel-filled bags (Hart, 2015; Wojciechowska, 2001).

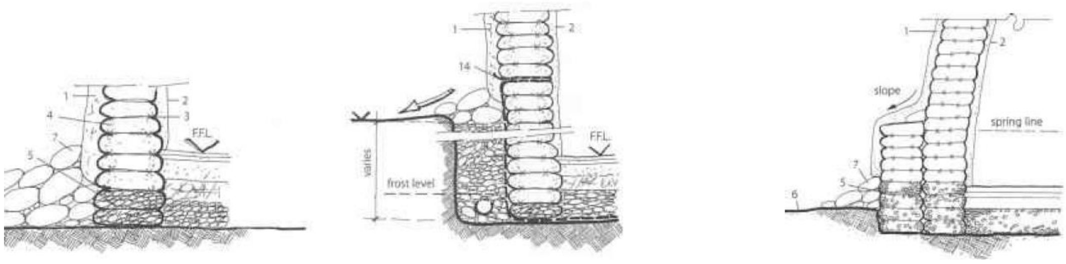

Figure 9. Details of earthbag foundation variants.

Source: (Wojciechowska, 2001, p. 36).

2.4.4 Self-Supporting

SuperAdobe Dome

There is the possibility of building an entire construction almost exclusively with SuperAdobe, applying the dome design. The SuperAdobe domes are simple and more resistant than domes made with bricks (Hunter & Kiffmeyer, 2004).

The cover of SuperAdobe domes can be impermeabilized in different ways, such as: applying layers of quality clay plaster, multiple layers of lime plaster, or pally cement, and others.

Some authors suggest that six meters of diameter is the maximum for self-supporting domes. They say that it is better to build small domes connecting each other instead of building a large one, because they can work as a buttress of each other, providing even more strength to the overall structure (*Figure 10*) (Hunter & Kiffmeyer, 2004).

Figure 10. constructions of self-supporting SuperAdobe domes.
Source: http://images.arq.com.mx/eyecatcher/590590/20809-1.jpg

SuperAdobe Arch

The arch shape provides structural integrity to any building by stacking units such as bricks, stones and SuperAdobe as well.

There are two types of arches building made with SuperAdobe: The gothic and the roman arches. In most of the seen examples, applications of both kind of arches were found, routinely to support doors, windows or small corridors (*Figure 11*).

Figure 11. SuperAdobe gothic arch as a small entrance corridor.

Source: https://maggimck.files.wordpress.com/2014/03/blog-16_12.jpg

To build these structures it is necessary to use a temporary arch form, normally made of wood. The bags are stacked along the arch form using barbed wire between the layers. After complete, the form can be removed and the structure will support by itself.

SuperAdobe with linear design

There is also the possibility to build orthogonal self-supporting walls with SuperAdobe (*Figure 12*). Empirical research suggests in this case, no more than three meters height for the walls. More than that, it will need extra structural resources. (Hunter & Kiffmeyer, 2004)

Figure 12. Construction of self-supporting orthogonal earthbag building.

Source: http://sitioamarelo.blogspot.pt/2010_04_01_archive.html

2.4.5 Mixed Structure

Wood

There are two ways of building SuperAdobe walls with wood structure. The first one is made with solid timber, driven into the ground and after filled the spaces between them with the earthbags (*Figure 13*).

Figure 13. SuperAdobe construction with timber structure in Ceará, Brazil.

Source: Courtesy of the owner of the house.

In the second way, the structure is made with a piece containing wood and metal. It was created for the engineer Mike Temeer, membership of a South African company in Cape

Town. They also created geo-textiles to make special bags that are able to contain any kind of earth, including just sand. The sandbags are staked between the EcoBeams and revolved with wire. (*Figure 14*) (Stemmett, s.d.)

Figure 14. Before and after of a sandbag construction with Ecobeam construction

Source: http://www.ecobeam.co.za/

In sequence, we show two examples of constructions that have adopted this constructive technology.

10x10 low cost housing project (Figure 15)

Designed by Luyanda Mpahlwa of “MMA Arquitects” office, it was built in September of 2008. Ten houses were made with the same shape at Cape Town in South Africa. This project won the international prize “Curry Stone Design Prize”.

Figure 15. Housing buildings with one block under construction and other already done.

Source: http://www.designindaba.com/projects/10x10-low-cost-housing-project

Sand bag pavilion Pavilion –AZA 2010 (Picture 13)

Project built in Joannesburg, at Mary Fitzgerald Square. Designed by the architects Sara Callburn and Dustin Tusnevios. It won the third place in the international prize "URBANIFORM".

Figure 16. Sandbag pavilion.

Source: http://dustintusnovics.blogspot.pt/2011/01/aza-pavillon-was-realised-on-mary.html

Concrete

Precast concrete structure

These structures consist in columns and beams made with blocks of precast concrete. The SuperAdobe is used in the spaces between columns. For example, there is a construction made in Utah (*Figure 17*), where the local built code did not allow SuperAdobe for structural buildings. The adopted solution was to use SuperAdobe mixed with precast concrete structure.

Figure 17. SuperAdobe construction made with precast concrete in Moab, Utah.
Source: (HUNTER and KIFFMEYER 2004, 74)

Confined earthbag constructions in reinforced concrete (Figure 18)

This kind of construction is made with columns and beams of reinforced concrete and the earthbags confined between them. In this case the columns are launched in the place after the lifting of the walls (Rodriguez, 2010).

Figure 18. Detail of a confined earthbag construction with reinforced concrete.

Source: http://www.naturalbuildingblog.com/confined-earthbag-construction/

2.5 Conclusion

This paper was focused on an extensive survey of existing examples of buildings built out of SuperAdobe/Earthbag, In order to classify the different types of SuperAdobe construction. We created Table III synthetizing the construction type variants exposed during the paper.

Table III

Variants of SuperAdobe applications.

Structural variant	Formal composition		Foundations	Roofing
Self-supporting	Dome		- Concrete	Natural and artificial covering
	Arches		- Shallow, frost-protected	
	Linear design		- Earthbag rubble trench”	
Mixed structure	Wood	Solid		Conventional roofs
		Ecobeam		
	Concrete	Reinforced	- Concrete	
		Precast	- Shallow, frost-protected	

2.6. Final Considerations

Few academic researchers have attempted to study SuperAdobe buildings. Only 2 papers were found in a search over a 123 different databases about this subject. In this paper we have classified several existing applications of the SuperAdobe technique in order to establish a formal classification its constructive variants.

Although there is not much scientific literature about this subject yet, we could find consistent and valid publications not inserted in the scientific field, like books with no peer review process and specialized websites. Carefully we could delimit a set of technical qualitative characteristics and organize them according to their structural differences as found in Table III. As future work we will improve the Table III with quantitative information about the application limits of each variation presented in this paper. The information about earthbag construction technologies will serve as a base to the development of a computational tool to design SuperAdobe buildings faster, easier, and more precise.

As a final objective, once we develop new tools to help designers with the particular aspects of SuperAdobe design, we hope this will promote to build with sustainable and natural resources.

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Wojciechowska, P. (2001). *Building with earth: A guide to flexible-form earthbag construction*. Chelsea Green.

Chapter 3. Generative Design by Textual and Visual Programming Language

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The paper presented in this chapter[3] addresses a comparison between Visual and Textual programming languages for 3D modelling, using Grasshopper and Python script plus Khepri.

The goal of this paper is to run a comparison between parametric modelling versus textual programing languages. This comparison shows which type of programming language is more suitable to create the tool (the choice is presented in the introduction for chapter four).

The output of this paper is the comparison between TPL and VPL. The same design was experimented in both languages and succeeded. The VPL with Grasshopper was selected for CICERO tool coding.

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[3] This chapter is a slightly modified version of "Santos, D. M., Pontes, T. B., & Leitão, A. M. (2019). Generative Design in textual and visual programming languages. In F. T. de A. Lima, M. M. Borges, & C. F. R. Costa (Eds.), *Digital Techniques Applied to Design Process* (pp. 72–95)." and has been reproduced here with the permission of the copyright holder.

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.

3.1 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 paradigms: 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 one 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 & 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 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 widely 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.

3. 2 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 19* below.

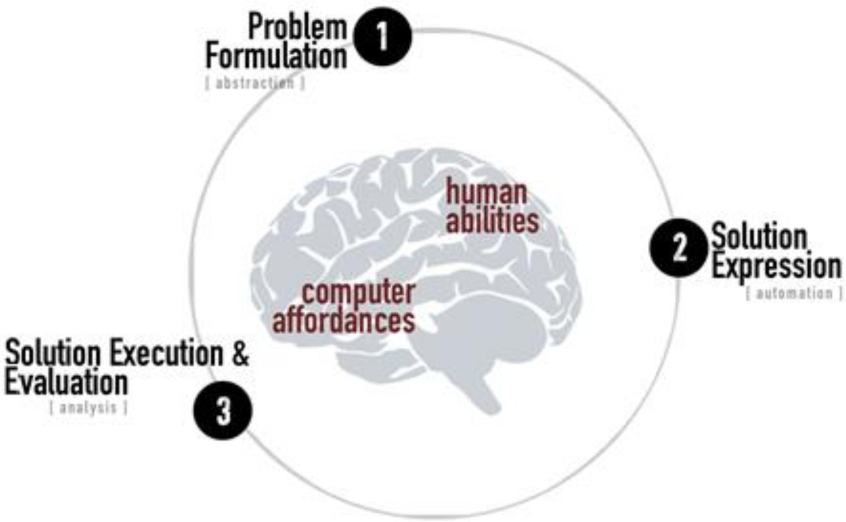


Figure 19. Procedures of Computational Thinking.

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).

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

3.3 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, Miranda, & Santos, 2016a). 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 20. Ring (jewelry design).

Source: https://edmarshalljewelers.com/image/cache/catalog/R15498-1000x1000.JPG

Figure 21. Step cake (cake design).

Source: https://img.elo7.com.br/product/original/F2C02A/bolo-quadrado-clean-bolo-casamento.jpg

Figure 22. Stairs inside Nordic pavilion at the 2016 Venice Biennale (architecture scale).

Source:

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

Figure 23. Retaining urban wall (Urbanism scale).

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

3.3.1 Abstraction

Abstracting the *Figure 20*, 21, 22, and 23, 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 24*).

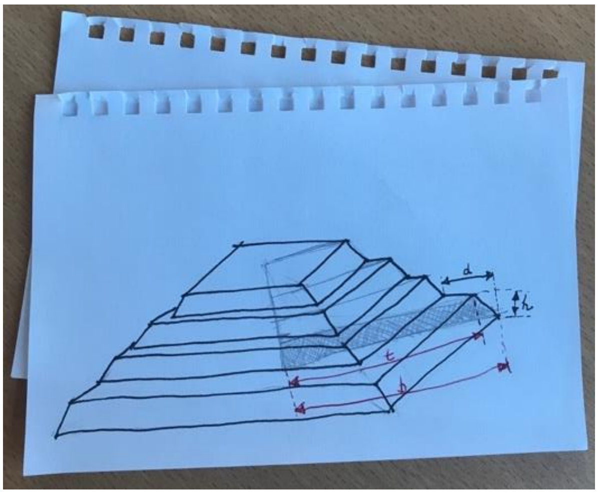


Figure 24. Drawing of a regular pyramid frustum.

During the first 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 25*):

P = center point of the base
b = bottom base radius
t = top base radius
h = height of step

s = side numbers of polygons

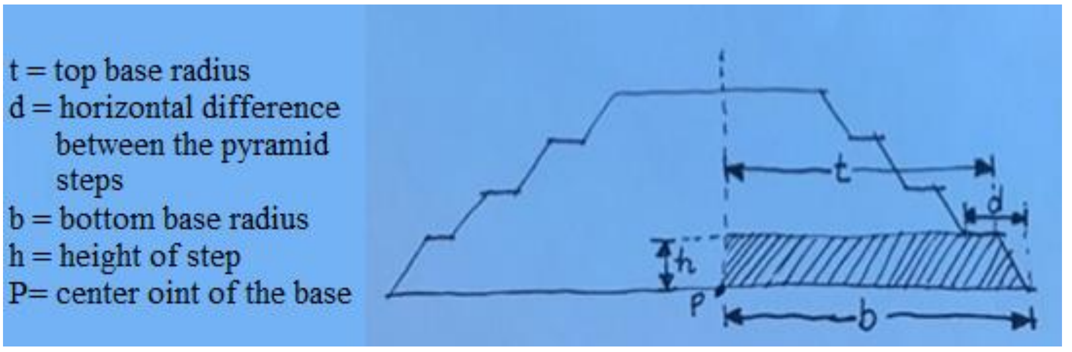


Figure 25. Drawing of a regular pyramid frustum.

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`) (n = number of steps). This new first step of the smaller pyramid entails subtracting from the polygon radius (top and base) the difference (*d*) between the pyramid steps (d = horizontal distances between steps). In that way, we need two more parameters to generate the hole pyramid.

3.3.2 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. If that is not what is intended, we just remove this line of script. See *Figure 26*.

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

Figure 26. Zero point to TPL script.

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`" (*Figure 27*and *Figure 28*).

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

```

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

Figure 27. Parameters of the step in TPL.

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

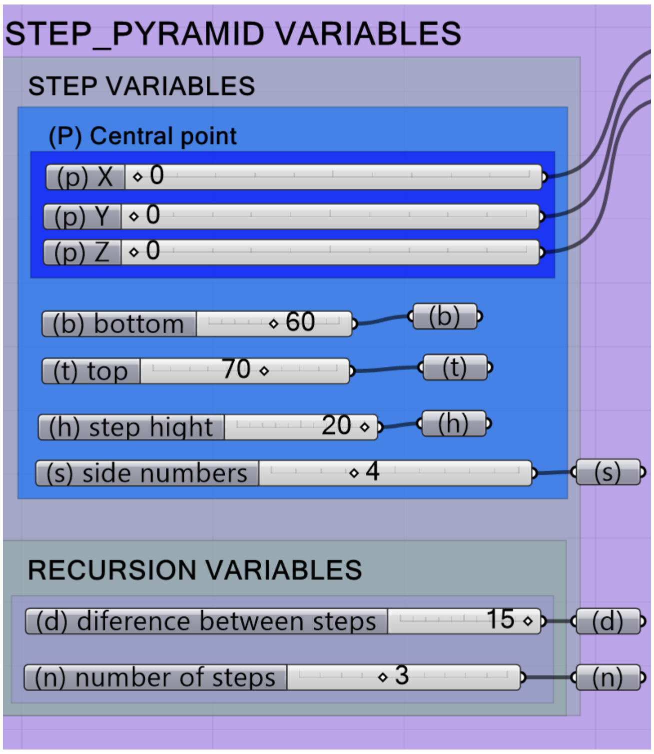


Figure 28. Parameters of the step in VPL.

Designing the first step

Second, the pyramid trunk was designed by two regular polygons in both languages (*Figure 29* and *Figure 30*). 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.

```
def step(s, p, b, h, t):
    loft([
        surface_regular_polygon(s, p, b, pi/4),
        surface_regular_polygon(s, p+vz(h), t, pi/4)
    ])

```

Figure 29. Design of first step in TPL.

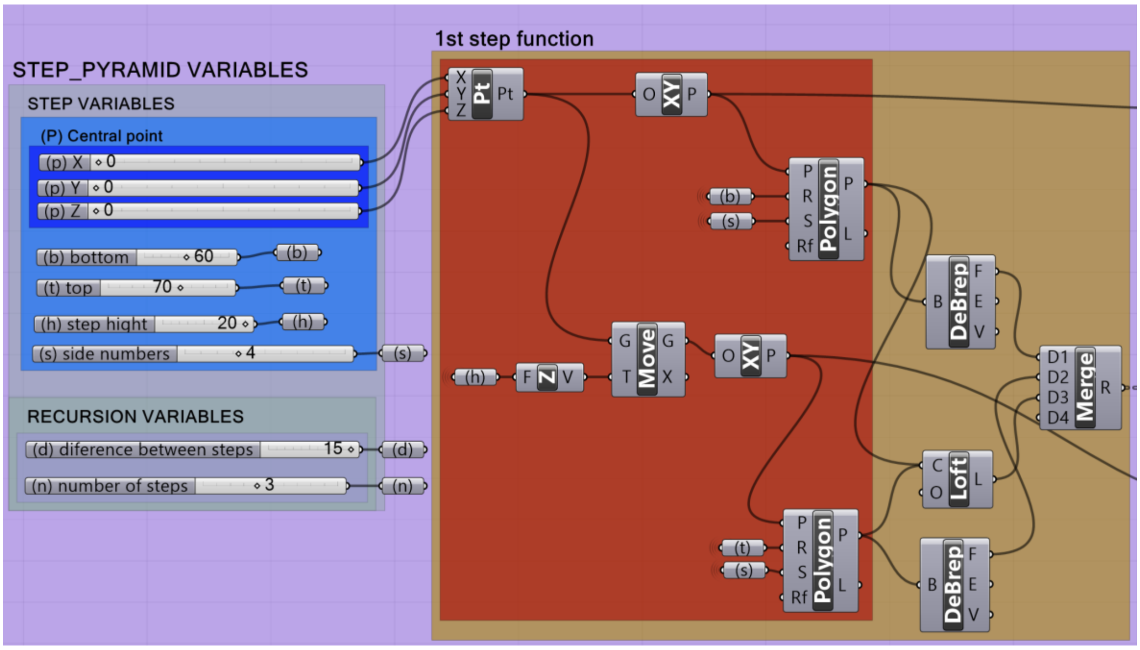


Figure 30. Design of first step in VPL.

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.

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 31*). 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.

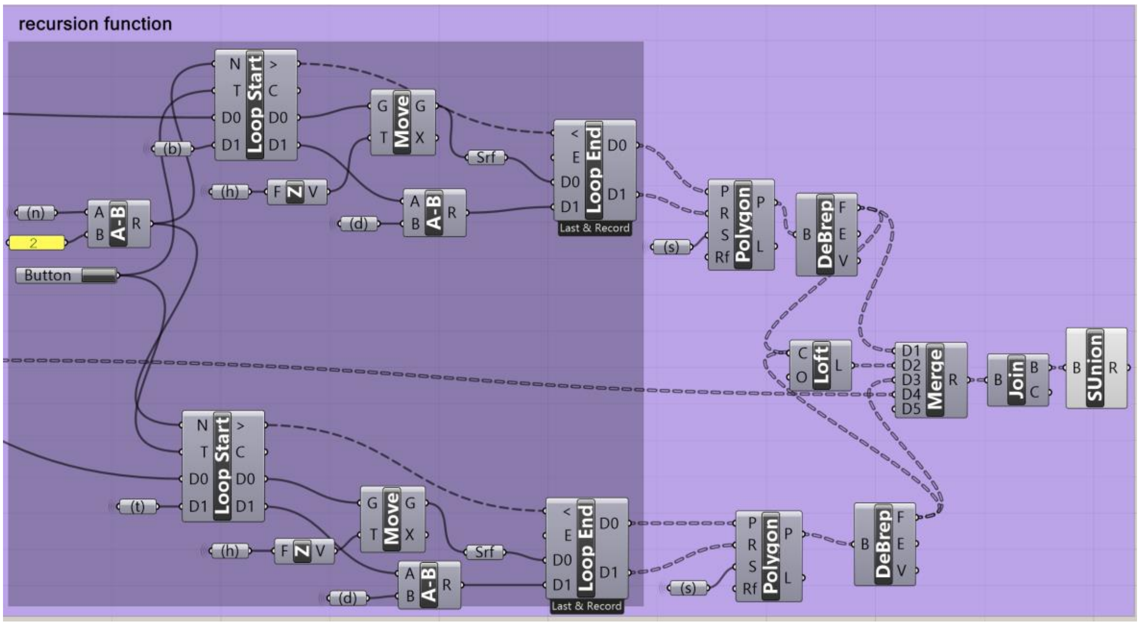


Figure 31. Loop in VPL.

In *Figure 31* and *Figure 32* and there is a recursive function in TPL and a loop in VPL designing the remaining steps of the pyramid. In figure 13 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 32. Recursion in TPL.

The same relation between the variables happens in a VPL and are presented in the workflow of *Figure 31*. 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.

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 33*) 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.

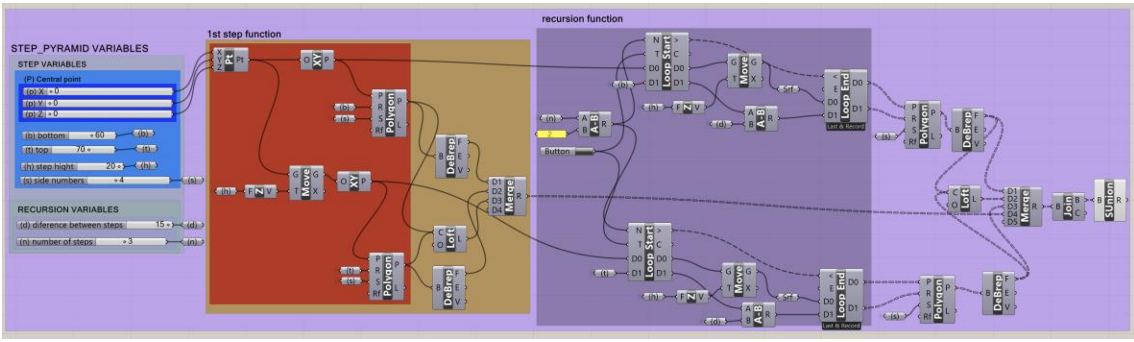


Figure 33. VPL final script.

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.

Textual final script

For a beginner in a Textual Programming Language, it might be difficult 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

```

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

Figure 34. Calling the function in TPL.

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

def step(s, p, b, h, t):
    loft([
        surface_regular_polygon(s, p, b, pi/4),
        surface_regular_polygon(s, p+vz(h), t, pi/4)
    ])

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)

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

```

Figure 35. Final script in TPL.

3.3.3 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 36*).

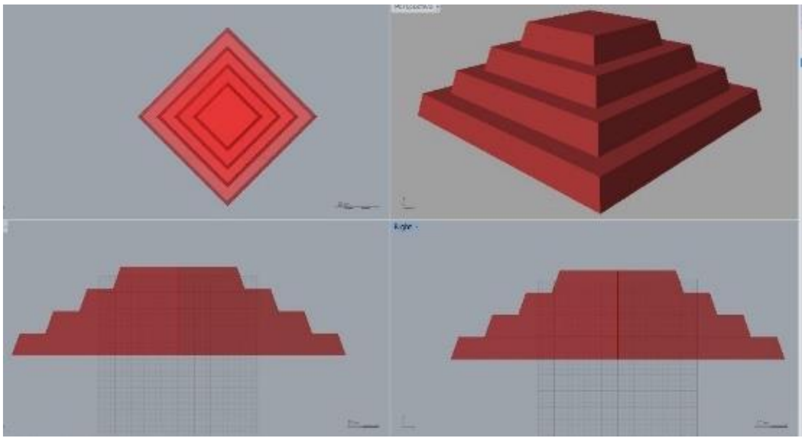
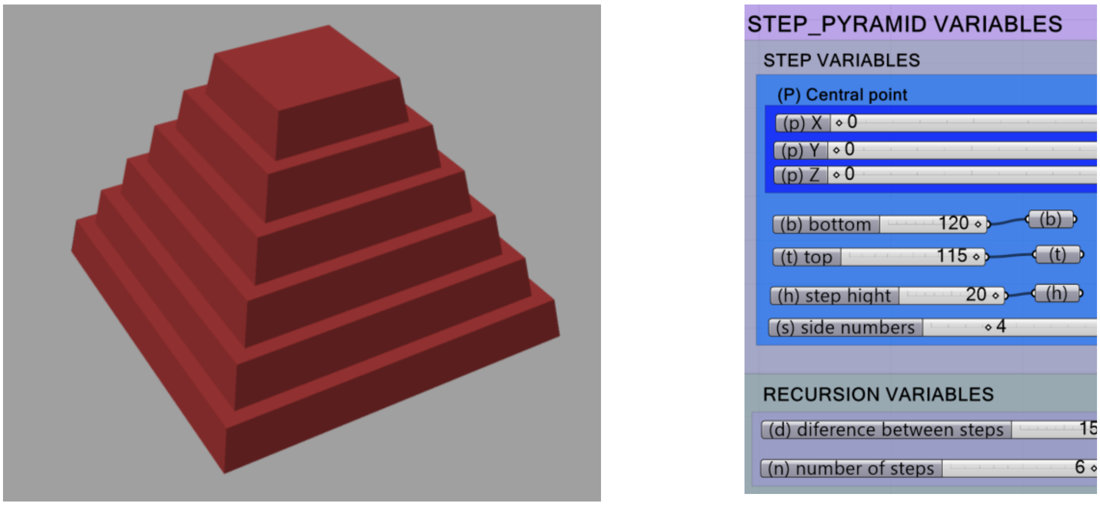
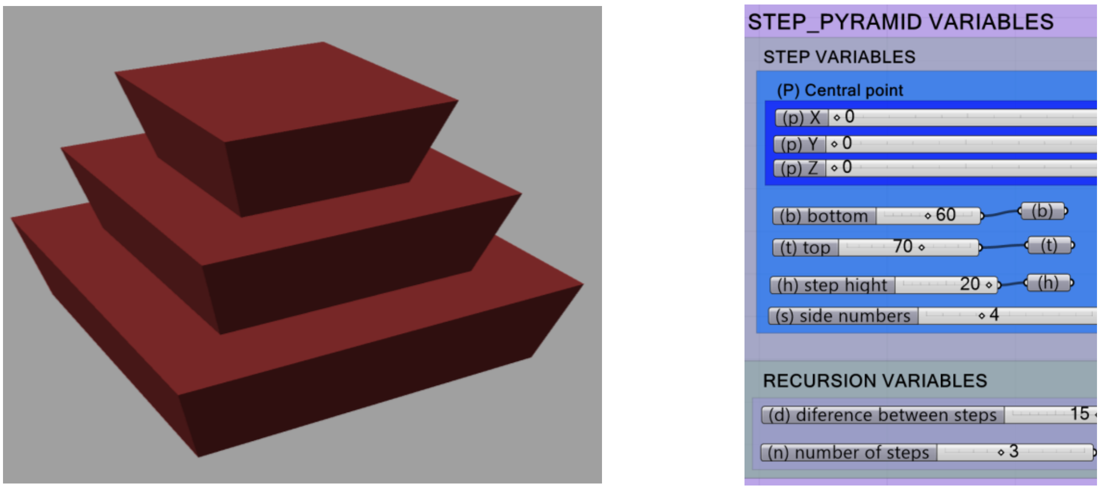


Figure 36. Final model shape.

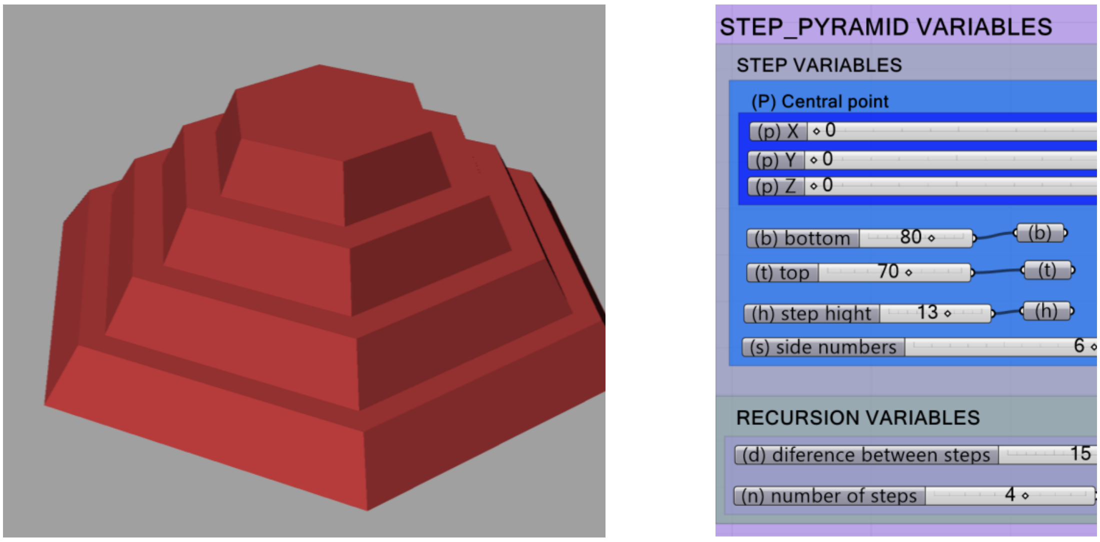
After the script was done, it was tested applications of different numbers to generate various pyramids (*Figure 37*). For TPL was a question of change the call of function and run, for VPL just change the sliders and “bake” the final component.




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




```
step_pyramid(xyz(0,0,0), 60, 70, 20, 4, 15, 3)
```




```
step_pyramid(xyz(0,0,0), 80, 70, 13, 6, 15, 4)
```

Figure 37. Variationally shape from changing numeric variables.

3.4. 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 be solved. The objective is to 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 38* shows an example of monotonous city.

Figure 38. Example of monotonous city.

Source: http://www.vitruvius.com.br/media/images/magazines/grid_9/cf00_1-sw.jpg

3.4.1. 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 39*):

P = initial point

l = block length
s = street length
h = height of the building
N = number of streets
M= buildings greed

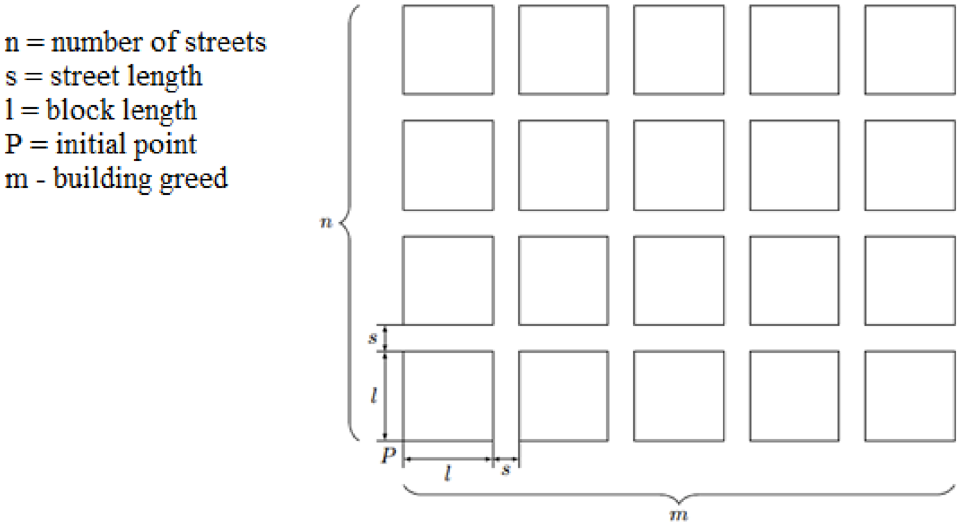


Figure 39. Sketch of abstraction process.

3.4.2. 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" (*Figure 40* and *Figure 41*).

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.

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

Figure 40. 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.

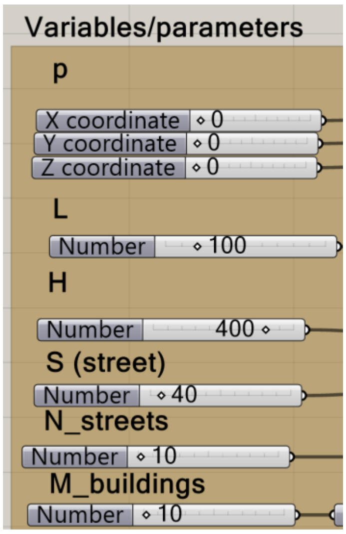


Figure 41. Parameters of the city in VPL.

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 (*Figure 42*).

```
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 42. Street function in TPL.

The same relation between the variables happens in VPL and are presented in workflow of *Figure 43*. The same operation "`vx(l+s)`" is inside of loop start and loop end of anemone components.

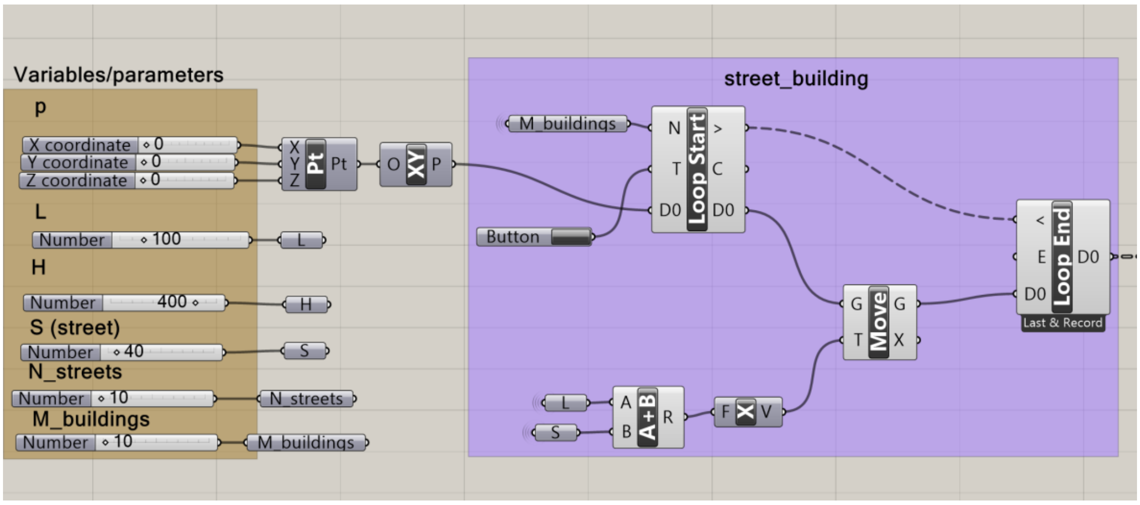


Figure 43. Street function in VPL.

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 (*Figure 44*)

```python

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, l, h, s)

```

Figure 44. City function in TPL.

Again, the same relation between the variables happens in VPL and are presented in workflow of *Figure 45*. The same operation "`vy(l+s)`" is inside of loop start and loop end of anemone components.

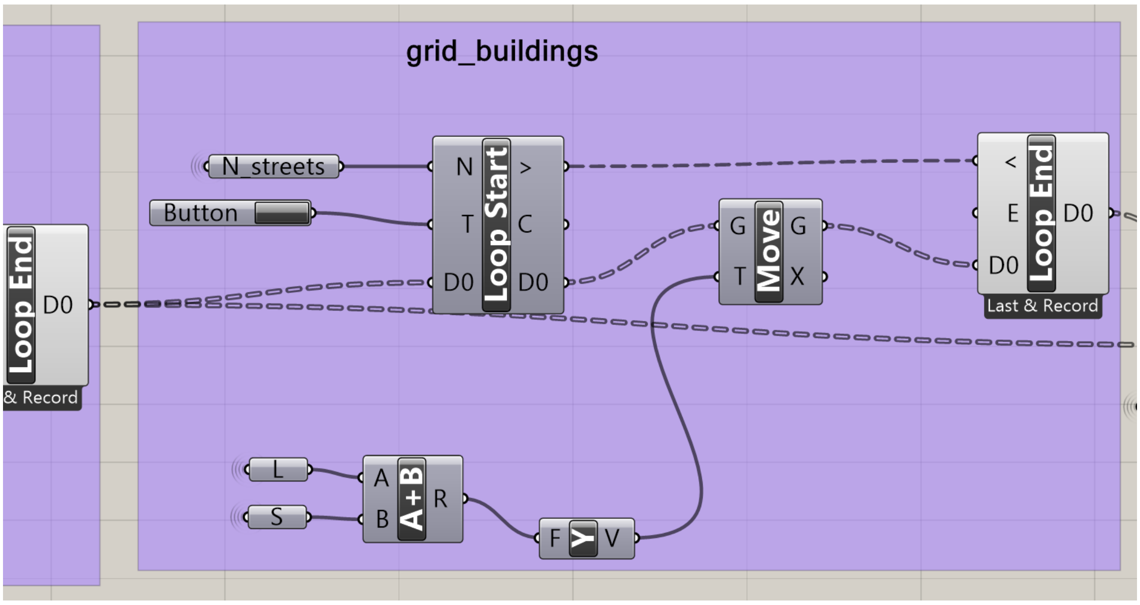


Figure 45. City function in VPL.

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 (*Figure 46*).

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

Figure 46. Building function in TPL.

For VPL it was designed a box baser on a rectangle (*Figure 47*).

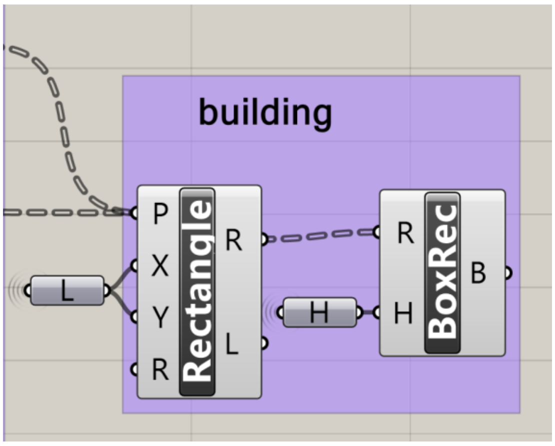


Figure 47. Building function in VPL.

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 (*Figure 48* and *Figure 49*).

```python
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, 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 48. TPL final script.

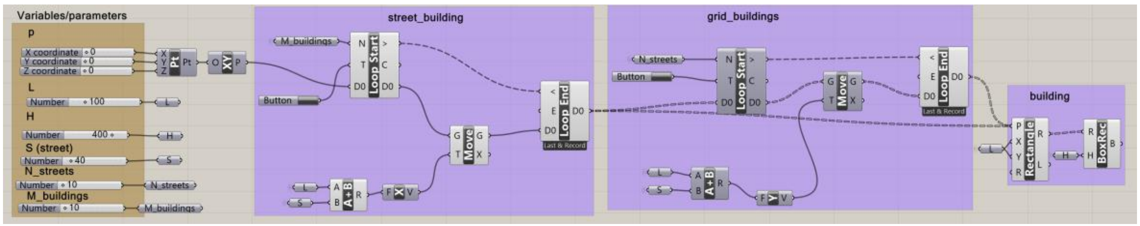


Figure 49. VPL final script.

3.4.3. Analyses

Both of languages designed the monotonous city, again applying the same logic using the computational thinking. *Figure 50* shows the final result for both TPL and VPL languages.

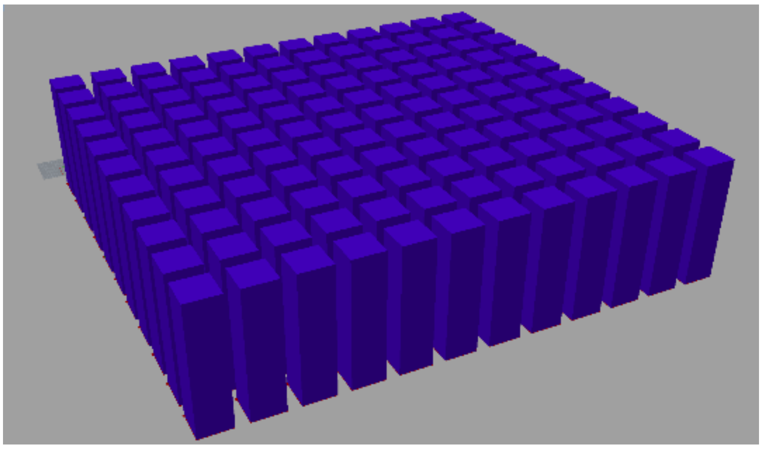


Figure 50. Monotonous city by TPL or VPL.

3.4.4 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 (*Figure 51*).

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

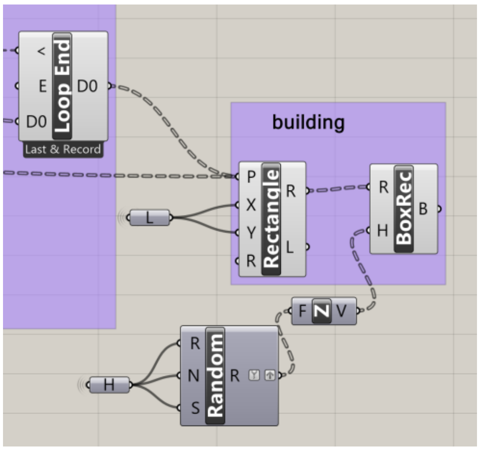


Figure 51. Random buildings using TPL or VPL.

3.4.5 Final script

*Figure 52*and *Figure 53* show 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.

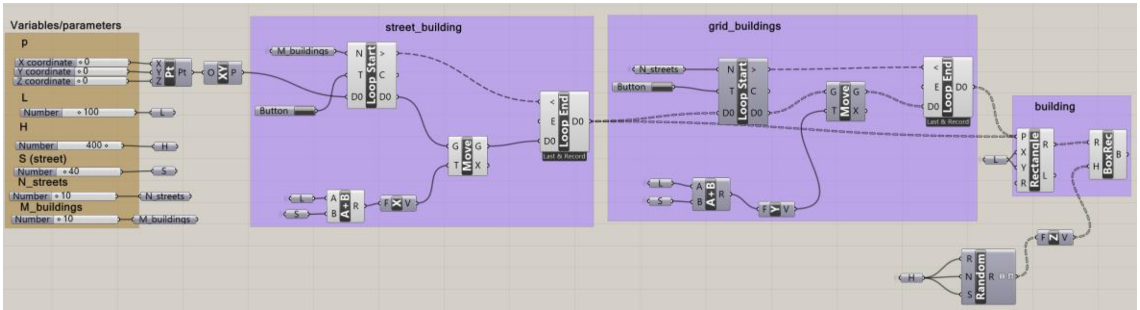


Figure 52. Final city script in VPL.

```
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, 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 53. Final city script in TPL.

The virtual models generated of the city, from VPL or TPL, will be always different from each other (*Figure 54*). Every time the function is called again in phyton script, 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.

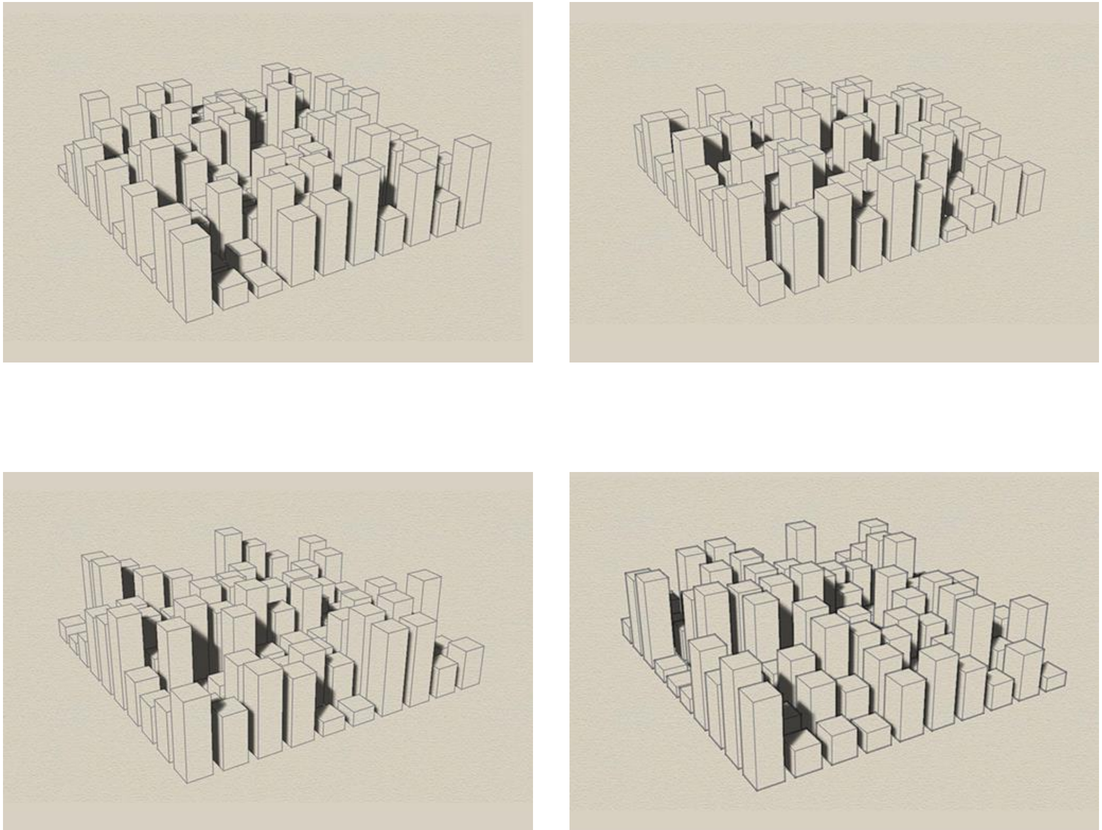


Figure 54. Variation of city script with random buildings.

3.5 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 become 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, rather than 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 first abstractions of the problem.

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

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Chapter 4. Parametrical Design Tool and Production of Technical Data for SuperAdobe Domes

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The paper presented in this chapter[4] shows the development of the parametric tool prototype. The outputs of the first and second papers (earthbag architecture and programming languages) present the knowledge background to develop the mentioned tool, which is the first experimental phase of this thesis. Additional data such as screenshots of the tool and validation inquiries results are presented in Appendices 3 and 4.

The goal of this paper is to develop a prototype of a parametric tool to design earthbag domes (including the generation of quantitative material descriptions). The output of this part of the research is a prototype of CICERO tool (Creative Interface for Constructing Earthbag Resource Objects).

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[4] This chapter is a slightly modified version of "Santos, D. M. dos, & Beirão, J. N. (2019). Parametrical design tool and the production of technical data for SuperAdobe domes. *Gestão & Tecnologia de Projetos*, 14 (1). ISSN: 1981-1543" and has been reproduced here with the permission of the copyright holder.

Parametrical design tool and the production of technical data for SuperAdobe domes

Ferramenta de desenho paramétrico e a produção de dados técnicos para domos de SuperAdobe

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Resumo

O interesse em construir domos de SuperAdobe (também conhecido como sacos de terra compactada) tem aumentado desde que se tem desenvolvido uma consciência mundial em prol de uma sobrevivência sustentável para o equilíbrio do planeta. O objetivo principal desta pesquisa é desenvolver uma ferramenta paramétrica que ajude os arquitetos a criar modelos virtuais de domos de SuperAdobe, na fase de estudos de criação e construção. Este desafio foi abordado pela adoção de uma metodologia experimental que explora o desenho gerativo paramétrico, com o uso de uma linguagem de programação visual (VPL). Neste artigo apresentamos o desenvolvimento de uma ferramenta para a fase de idealização que é capaz de antecipar os quantitativos da obra. O modelo gerativo produz informações técnicas de saída destinadas a informar a obra relativamente a condições técnicas e quantidades de material. A usabilidade da ferramenta foi validada com uma amostra aleatória internacional de especialistas. Futuro desenvolvimento dessa pesquisa pretende integrar a ferramenta proposta em ambiente BIM.

Palavras-chave: construção em terra; modelagem geométrica; building information modelling (BIM); linguagem de programação visual (VPL); arquitetura sustentável

Abstract

The interest in earthbag dome construction (also known as earthbag or SuperAdobe) has been increasing as the world consciousness develops to achieve the planet's equilibrium for sustainable living. The main objective of this research is to develop a parametric tool to help architects modeling virtual earthbag domes from conception to construction phase. This challenge has been addressed by adopting an experimental methodology that explores parametric generative design with the use of a visual programming language (VPL). In this paper we present the development of a tool for the ideation level including features that allow for the calculation of material quantification. The generative model outputs technical information to support construction, namely material quantities. The usability of the tool was validated by a random international sample of experts. Future work in this research aims to integrate the proposed tool with BIM.

Keywords: earth construction; 3D modelling; building information modelling (BIM); visual programming language (VPL); sustainable architecture

4.1 Introduction

This research aims at facilitating the virtual modeling of SuperAdobe domes by architects and also the quantification of resources for construction. It is also an indirect way to encourage the adoption of ecological materials used in ancient construction techniques into our current construction practices.

In face of the finitude of natural resources and accelerated environmental degradation, recently many researchers (Fathi, Saleh, & Hegazy, 2016; K. Kensek, Ding, & Longcore, 2016; Rahimian, Iulo, & Duarte, 2018; Salgueiro & Ferries, 2015) have explored the use of digital technologies in various phases of design and planning to improve the development of resilient, sustainable, and environmentally-friend architecture.

Other researchers have also published work regarding the combination of earth architecture and digital technologies (Di Mascio, 2013; Fujii, Fodde, Watanabe, & Murakami, 2009; Muñoz & Jové, 2014; Varela, Paio, & Rato, 2013). It is pertinent to associate the use of digital technologies with the development of these kind of projects because they cause less damage to the environment and should therefore be facilitated. Inside the universe of earth architecture, research merging digital technologies and earthbag techniques is hardly found.

SuperAdobe is also known as earthbag, sandbag or superblock. It is the construction technique where the walls are built out of stacked bags filled with earth, interspersed with barbed wire to improve clamping between layers (Hart, 2015; Hunter & Kiffmeyer, 2004; Minke, 2006; Santos & Beirão, 2016). These constructions are durable, strong, climatically efficient, and formally flexible (Hunter & Kiffmeyer, 2004). They are low cost and quick to build. They are composed with renewable and reusable resources, hence promoting sustainable development (Barnes, Kang, & Cao, 2006).

Regarding formal composition, the SuperAdobe buildings assume shapes like domes, arches or conventional linear designs (Santos & Beirão, 2016). Only with the dome composition, the construction can be build up almost exclusively with SuperAdobe, including roofing and foundations.

Because at all those qualities, the earthbag dome has been widely applied for different purposes. One of them is an answer to the housing crisis, like the temporary village to receive Iraqi refugees made in 1995 by The United Nations Refugee Agency - UNHCR (Albadra, Coley, & Hart, 2018). Besides the housing solution, the earthbag dome has also been adopted in contemporary constructions, like "casa Vergara" (José Andrés Vallejo, 2011), built in Bogotá in 2011, a project that integrates the earthbag dome in a contemporary design, creating an innovative project. Many eco-communities and ecovillages have also adopted de earthbag dome because of its ecological potential of resilient design. During the year 2017 we have cataloged a generous amount of earthbag dome figures in social media (Instagram) with the hashtags #earthbag and #SuperAdobe, there were more than 6.000 figures of each descriptor. Some of them have their location identified by the authors, which refers to different locations of the world, such as: Japan, Russia, Venezuela, United States, Australia, India, Brazil, and others.

Although earth construction is recognized as a low environmental impact solution, the existing software tools are still limiting factors in this specific type of project and especially for dome composition, which requires to follow more specific design rules. Considering this, we formulated the hypothesis that the virtual modeling of the domes could be aided by a parametric tool specifically developed for the purpose.

This paper offers an overview of the SuperAdobe dome constructive rules and a practical contribution through an application in a computational tool named "CICERO" (Creative Interface for Constructing Earthbag Resource Objects). It is a parametric generative dome design tool developed with the use of a visual programming language (VPL) that generates earthbag designs considering the geometric limitations of the construction technology guiding the designers towards consistent solutions. It also presents BIM (building information modelling) characteristics, since it provides automatically technical data while the model is being generated parametrically.

4.2 Methods

The research adopted an experimental methodology exploring the advantages of parametric generative design with the use of VPL through a computational thinking approach.

4.2.1 Computational thinking

Computational thinking is an analytical way of thinking that can solve any (solvable) problem (Wing, 2008). The use of computational thinking has to follow three key aspects: abstraction, automation, and analysis (Lee et al., 2011; Wing, 2008). This paper is structured according to this approach and the methodological procedures are:

a) Abstraction: after collecting from existing literature an extensive set of earthbag building technical characteristics, the task is generalized, and the unnecessary details are removed to design a general problem comprehension in the form of a generic diagram. It presents the main parameters to generate earthbag domes;

b) Automation: this action corresponds to the design of the code. In this case, to the development of a parametric model able to generate the earthbag domes and associations of various apses. For better formatting purpose, we present the pertinent data collection, together with the automation section, in this paper.

c) Analysis: Checking if the results match the expectations. This was done via online testing with a sample of specialists from different parts of the world.

4.2.2. Research Validation

Visual programming languages may be argued to have begun in the sixties, when a computer graphic experiment named GRAIL (graphical input language) was presented as computer programming via flowcharts (Ellis, Heafner, & Sibley, 1969). Nowadays, the most successful VPLs work as plug-ins in a CAD or BIM modeling system, such as Dynamo for Revit and Grasshopper for Rhinoceros (Grasshopper also connects to ArchiCAD and VisualARQ). In this research, the adopted is the second one.

The methodological procedures used to validate CICERO were:

Insert CICERO in a web-based platform to implement online tests;

Submit the tool to architects with experience in earthbag construction to experiment the tool and answer an inquiry;

Evaluate the survey and their results. Conclude regarding tool validation.

4.3 Abstraction

Aiming to solve the challenge of designing a parametric system for earthbag domes, a generic code diagram was designed (*Figure 55*) identifying the changing variables, the kind of shapes that can be generated and the expected associated technical data outputs.

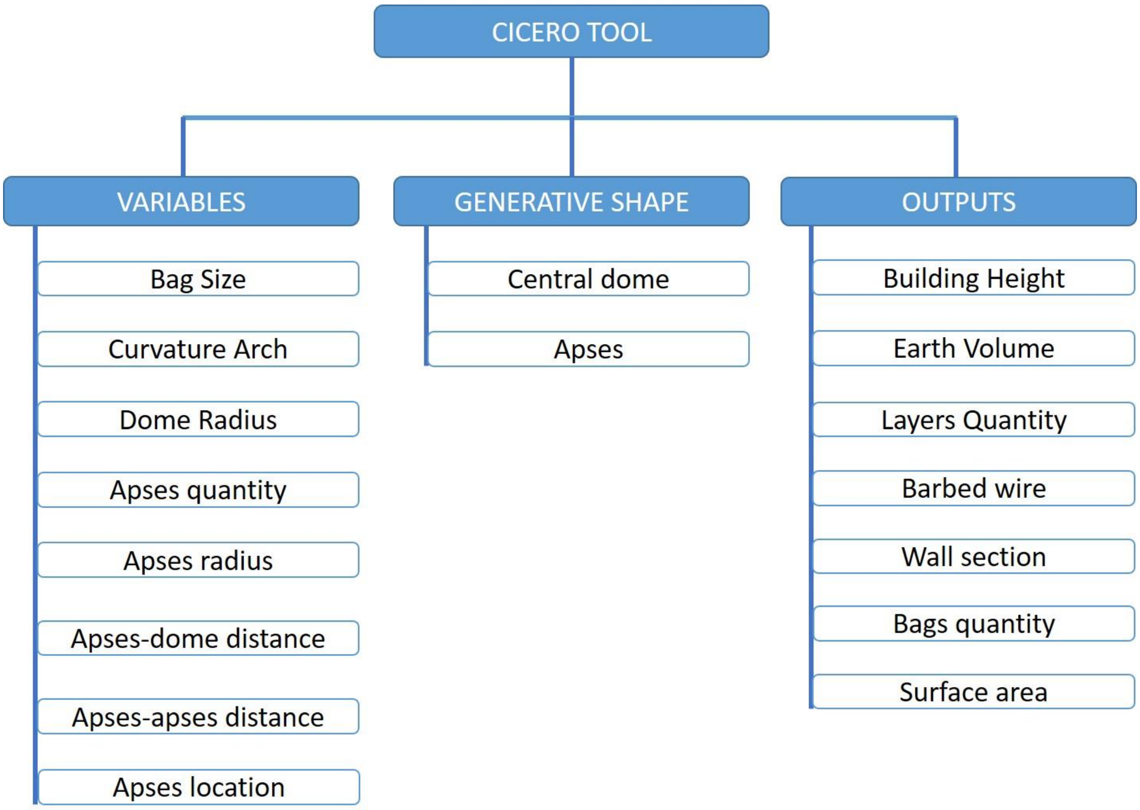

Figure 55. Generic code diagram.

4.4 Data Collection and code implementation (Automation)

Finding the data collection needed as input is one of the main problems of computer architectural design when used for graphic output (Rybnikar, 1985). To develop the VPL code for the earthbag dome construction, two general steps were necessary.

Firstly, a literature research on earthbag construction was performed to identify technical rules, constructive constraints, and general characteristics of earthbag domes.

Secondly, we devised a way to insert all technical variables into the code parameters. The goal was to provide a tool where the user could provide inputs and receive an interactive response from the model. The identified inputs refer to: bag size, curvature arch, radius of the dome, quantity of apses (smaller domes) to assemble around the first one, distance of the apses to the center, the angle to locate the apses, and finally their radius (*Figure 56*).

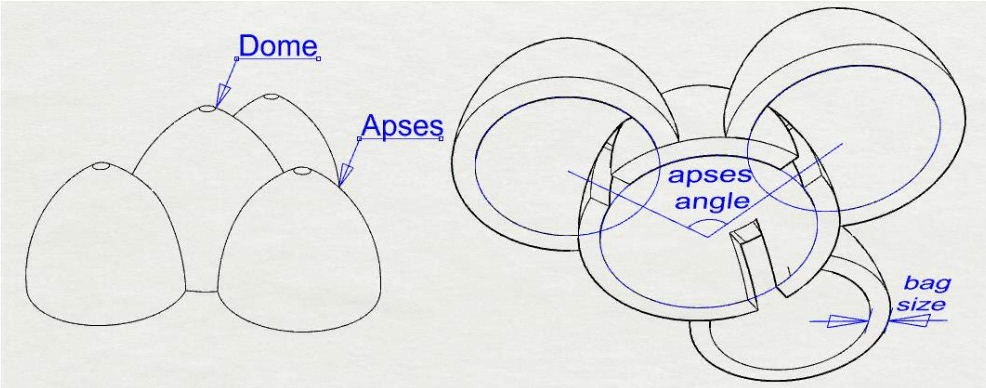

Figure 56. Schematic design of dome and apses.

4.4.1 Variable Inputs and their relations

The tool inputs are inserted resorting to number slider interfaces (*Figure 57*). These sliders were predefined, constrained to specific limitations resulting from the survey on the structural constraints of the constructive technique.

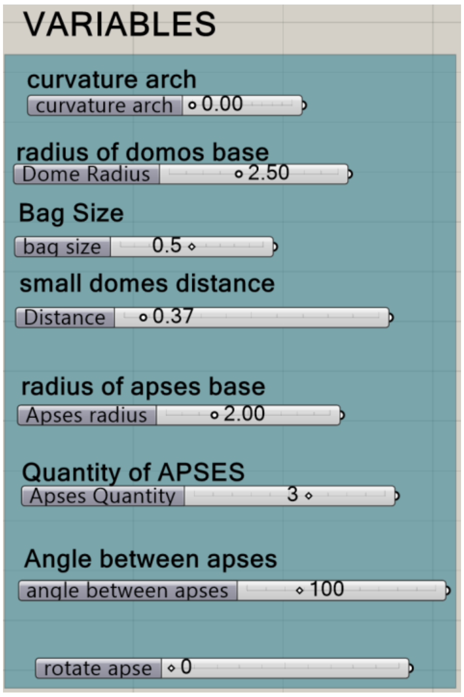

Figure 57. CICERO inputs.

4.4.2 Dome design

Bags

The purpose of the bag is to retain the earth during the construction process. They can be acquired in tubes as continuous bags or individual bags. Polypropylene bags are more recurrently used; however other kinds can be used like burlap which has the advantage of being made also of natural and environment friendly material. Polypropylene is the cheaper alternative and is not as environmentally toxic as the polyvinyl chloride (PVC) (Wojciechowska, 2001); besides, it can be recycled. For construction, the disadvantages are related with fragility resulting from direct ultraviolet sunlight. There are some polypropylene bags with ultra violet protection, but it only delays the degradation process a few weeks in case the bags are left exposed to sunlight. The indication then is that they must be protected as much as possible, for instance by plastering. After plastering, the polypropylene bags are the strongest option and do not deteriorate (Hart, 2015).

The wall width is the variable with greatest influence on structural safety (Canadell, Blanco, & Cavalaro, 2016), then the bags chosen must be bigger than 12 inches (30,48cm) wide, when flattened in each layer (Hart, 2015; Hunter & Kiffmeyer, 2004). Khalili suggests a roll of 14 to 16 inches (35,56 to 40,64cm) wide SuperAdobe tubing (Khalili, 2008). For individual bags, Hart suggests bags around 18 inches (45,72cm) wide when flat and 32 inches (81,28cm) long (Hart, 2015). After the survey about available bag sizes we considered the sizes that match the structural constraints: 40, 50, and 60 centimeters wide bags (after compaction).

Radius

For a self-supporting single dome, the ideal interior diameter suggested by Khalili is: 2,5 to 3,5 meters (Khalili, 2008). However, new studies simulated a diameter of 6,0 meters (Canadell et al., 2016; Hunter & Kiffmeyer, 2004).

Arch curvature

Earthbag domes are supposed to work with the force of gravity, rather than against it, it is structurally made by the revolution of the most stable design: the dome. The design of self-supporting dome section was created by the observation studies of a hanging chain under tension, once it is reversed is under maximum compression (Khalili, 2008; Wojciechowska, 2001) and becomes a catenary arch (Khalili, 1986). Even though the catenary arch is the strongest and most stable arch in gravity, it is hard to reproduce it on site in real scale. Because of the structure and method of building a self-supporting earthbag dome has a taller "Lancet" or "Ogival" profile design (González, 2006; Khalili, 2008).

Two kinds of arches were already studied and validated by theoretical studies as the better structural designs for earthbag domes: *Figure 58* shows the pointed arch, originally proposed by Khalili, and the variable arch, proposed by recent structural studies (Canadell et al., 2016). The variable arch is more steepen aiding extra stability to structure (Hunter & Kiffmeyer, 2004).

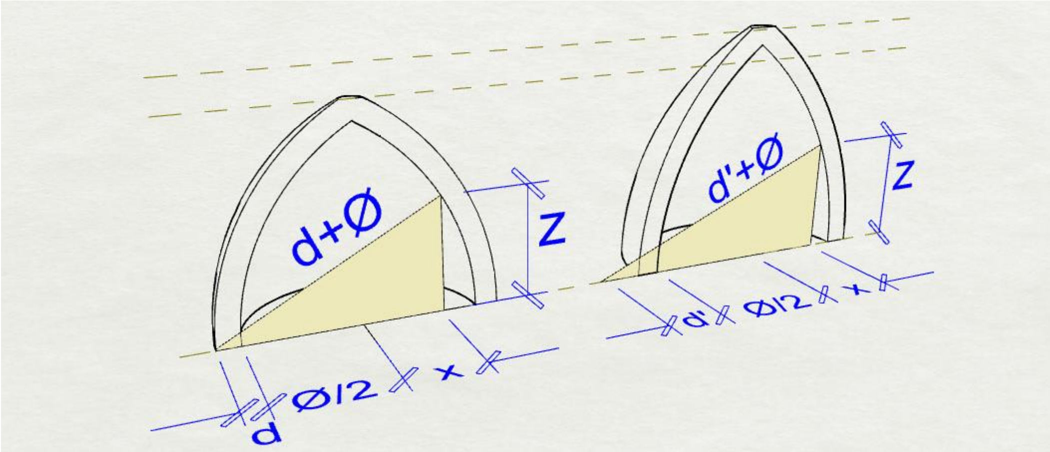

Figure 58. relations for dome design. Pointed arch and variable arch.

Source: Adapted from Canadell *et al.*, 2016.

During the construction, it is required the use of two cords as a compass to define the geometry, the center compass to adjust each layer, and the height compass to design the arch curvature.

For the pointed arch, the compass must be stacked touching the entrance door covering a cord equivalent to the internal diameter plus bag size. For the variable arch (Figure 4), according to literature, the distance (d') to stack the cord to the dome entrance can be increased up to 1,50m (Canadell *et al.*, 2016).

Based on the arches' curvature equations, it is possible to find the dome height and design the dome section.

Dome code design

Based on the previous collected data, the volumetric dome geometry was codified in Grasshopper (*Figure 59*).

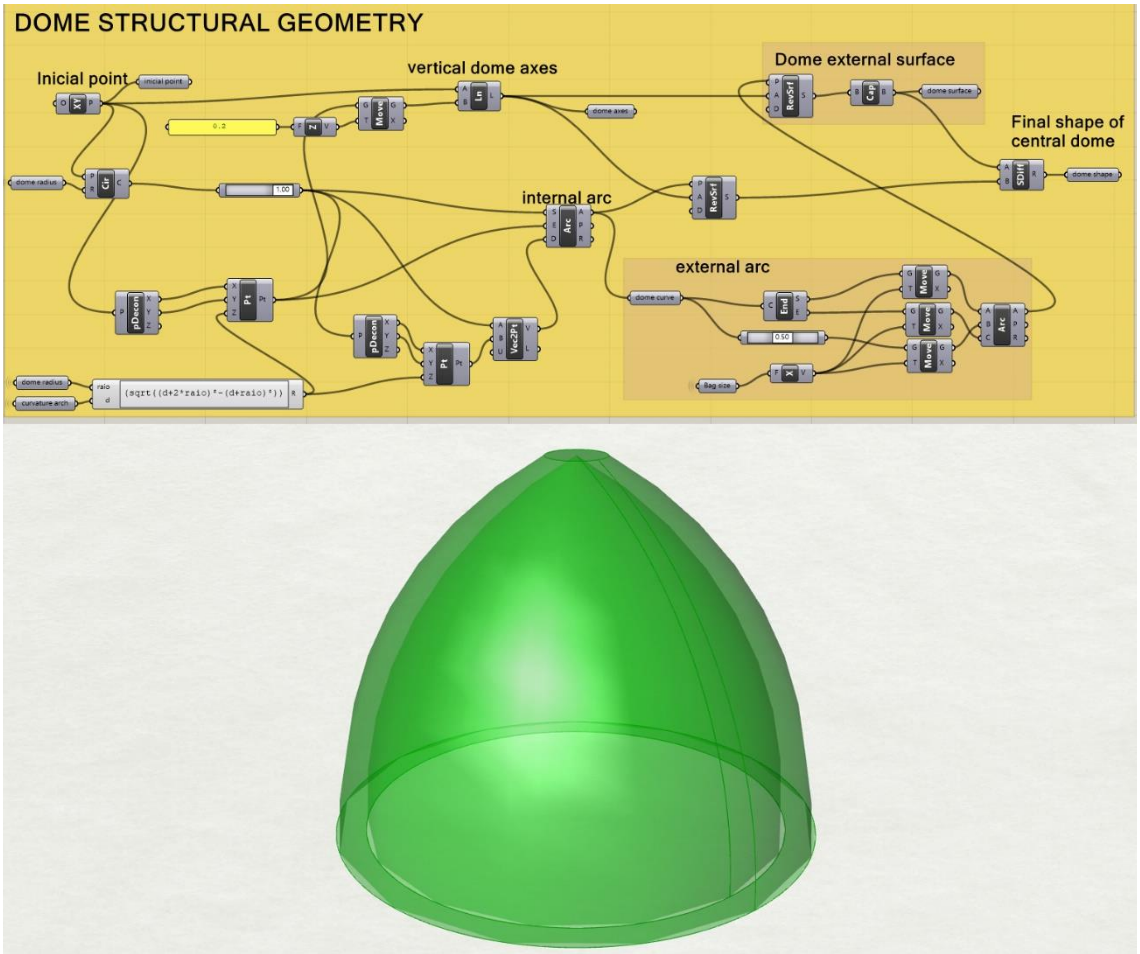

Figure 59. Parametric dome design.

4.4.3 Apses design (Clustering)

To achieve designs with a bigger living area, it is recommended to build several interconnected domes instead of a bigger one (Hunter & Kiffmeyer, 2004). This strategy is also a good structural resource, building additional semi-domes (apses), assembled around a big central one acting as buttresses, like in the historical Byzantine constructions (Cowan, 1977).

The dome connections are build interlocking bags by overlapping alternate rows. The apses will work as a buttress for the larger dome, adding stability to the overall design (Cowan, 1977; Khalili, 1986). Together they will counterbalance each other permanently. It is a praxis recommendation to insert at least one third of the apses projection inside the cluster to work as a buttress.

Based on the previous collected data, the volumetric apses geometry was codified in Grasshopper.

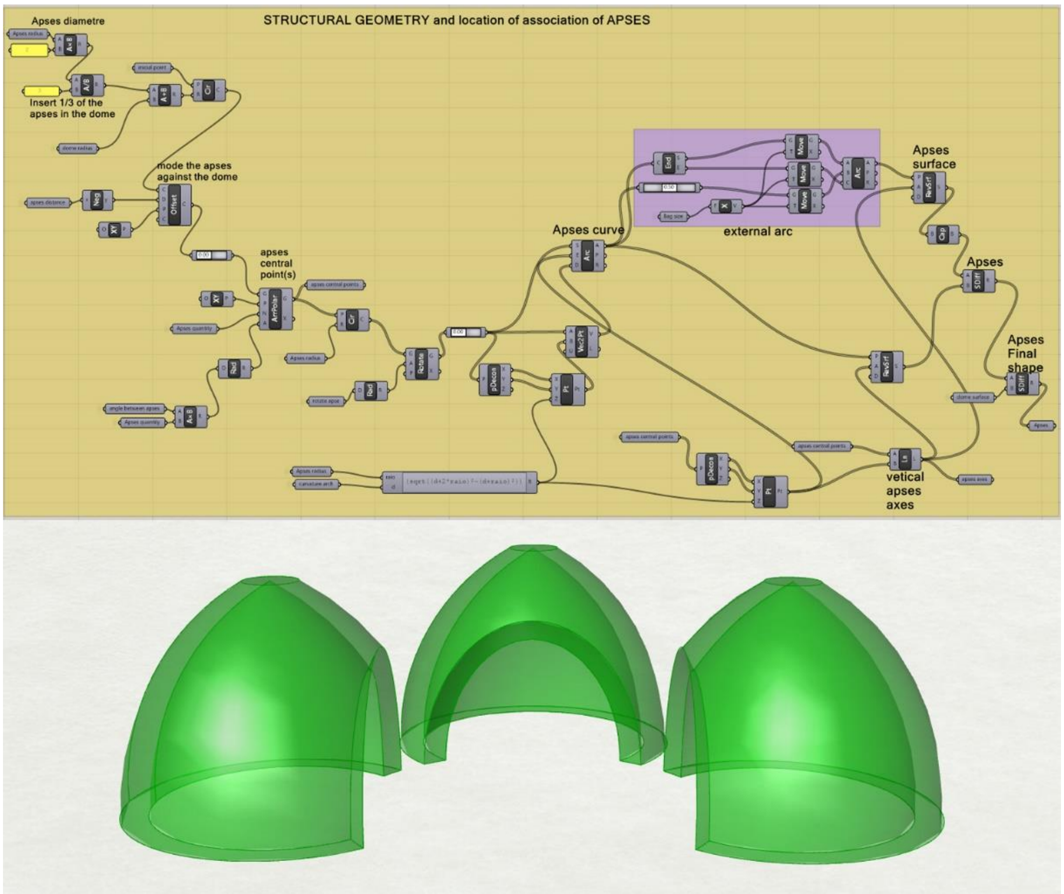

Figure 60. Parametric apses design.

Summary Inputs Board

Table IV shows a summary of all inputs needed for the generation of the central dome and apses.

Table IV

Summary inputs board.

Variables	Numerical values	Unit
Bag Size (compacted)	0.4 - 0.5 - 0.6	Meters
Curvature Arch	1 to 1.5	Meters
Dome Radius	0.75 to 5.00	Meters
Quantity of apses	0 to 5	Integers
Radius of apses	0.75 to 5.00	Meters
Distance (apses to center)	≥0	Meters
Angle location (apses)	0 to 360	Degrees
Rotate apses	0 to 360	Degrees

4.4.4 Outputs

Building height

If the radius is known, the height of the building can be extracted by resorting to basic trigonometry, using the Pythagorean theorem (*Figure 61*). Then the height (h) is given by the equation $h = \sqrt[2]{(bag + 2*radius)^2 - (bag + radius)^2}$.

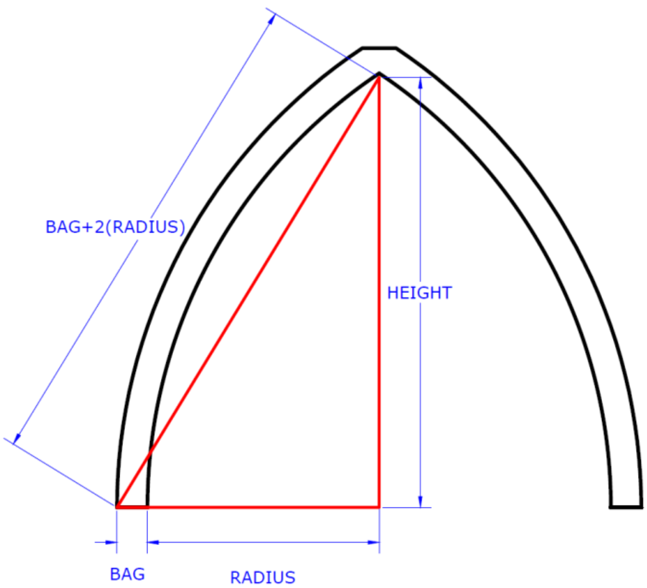

Figure 61. Diagram of equation to find building height.

Volume of earth

The volume of earth consumed in the construction is extracted from the 3D model. However, it is necessary to calculate two variables: the relation between the compacted and uncompact soil and the composition plus percentage of soil mixture. As the conditions can change according to each site, the final user has to do this calculus.

The volume extracted from the model refers to the compacted mixture when the soil particles are pressed together. Therefore, for calculating the earth amount needed in the construction process it is necessary to calculate the uncompact mixture quantity when the soil is loose and mixed with air.

The trivial praxis in quantification engineering calculus is to add 40% to discover the uncompact soil volume Ve. So, we developed the equation that multiplies the earth compacted volume (Vc) per a compression factor (f) to obtain the needed earth volume (Ve). $Ve = Vc + (Vc \times f)$. When the factor (f) is unknown one adopts the 40% addition as standard value, $Ve = 1{,}4Vc$.

As bags contain soil, any soil type can be used, except highly organic soil, increasing the chance to use on-site material (Calkins, 2009). However, the ideal mix for earthbag construction is approximately 30% of clayed soil and 70% sandy soil (Calkins, 2009; Geiger, 2011; Hart, 2015; Hunter & Kiffmeyer, 2004). Most of the world’s oldest remaining earth constructions were built with this soil mix ratio. Sometimes it is not possible to achieve the ideal ratio depending on the site soil; in such a case the builder needs to insert different proportions of natural hydraulic lime.

Layers quantity

After the tamping process, the layers lose height up to 12 cm (Geiger, 2011). After the conclusion of higher layers, the underlying rows can flatten down also. They can variate a little between themselves.

For empirical studies, it was defined that, considering representations necessities, the height of each earthbag layer must represent by the rate of ten centimeters (Hunter & Kiffmeyer, 2004). Then, to identify the number of layers the equation is given by dividing the total height by 0,10 meters.

Barbed wire

Ideally two threads of 4-point barbed wire are applied, parallel to each other, between the layers along the entire length of the wall to increase bag to bag friction and overall stability (Geiger, 2011; Hart, 2015; Hunter & Kiffmeyer, 2004; Wojciechowska, 2001). The wire combined with the woven polypropylene fabric add a high tensile strength to the structure. Therefore, the total length of barbed wire is twice the length of all bag layers, except the last one.

Bags quantity

The bags quantity is extracted from the model. The total of bags in linear meters is the length of all bag layers, plus at least 20cm of loose material for each cut, to tie off the ends (Hart, 2018; Hunter & Kiffmeyer, 2004).

Wall section

The wall section is derived from calculating the bag width plus inner and outer covering material (2,5cm thick plastering). When the bags are full and tamped, the wall presents layers of 10 cm of height. A 2,5cm thick layer of plaster regularizes the wall surface, both inside and outside. The mathematical expression for the wall section is presented in *Figure 62*. The bag diameter corresponds to twice the bag size.

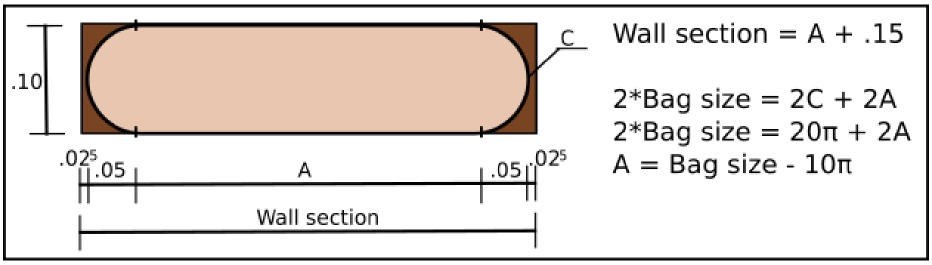

Figure 62. Wall section expression.

Surface area

The quantity of external surface is extracted directly from the model. Knowing the total external surface is important to calculate the quantities of coating material to protect the structure. The covering materials can variate according to each project. However, it is often used chicken wire or synthetic mesh to wrap the entire dome surface providing more adherent surface for usual covering materials, including stucco and earthen plaster (Hart, 2015, 2018; Hunter & Kiffmeyer, 2004).

The chicken wire or synthetic mesh quantity is calculated depending on the way selected to attach it into a bag wall. One way to do it is installing lengths of tie wires into the barbed wire between layers, to project beyond the wall more than 5 cm, during the construction (Hunter & Kiffmeyer, 2004). When the walls are built, the chicken wire is stretched over the walls, including doors and windows, then it is cinched tight and tacked down. The chicken wire consolidates the plaster coating and its surface corresponds the 1,1 times the wall surface (inside surface plus outside surface). These values consider chicken wire overlaps are needed to guarantee a continuous consolidation of the plaster coating.

Outdoor plasters need stabilization to avoid erosion or degradation by weather. Some examples that can be added to the mixture are Portland cement, lime, flour, and cactus juice (Hart, 2018). The ratio of lime mixture is 1 part of hydrate lime to 3 parts of sand.

The quantity of plaster used to cover inside and outside wall surfaces is taken from the geometric model (inside plus outside surfaces) and multiplied by the 2,5cm thickness. The additional grooves generated by the bag layers correspond to four times ($r^2 - \pi r^2/4$) multiplied by the sum of all layers' perimeters. In this equation r corresponds to half the bag layer thickness, in other words to 5cm.

Therefore, the geometric model outputs an accurate list of all material parts and their quantities, including bags, barbed wire, earth divided in its constituent parts, chicken wire and plaster. Any additional outside surface finishing like painting or lime whitewash can be also taken directly from the geometric model.

4.4.5 Results and discussions (Analysis)

The code structure provides a generative design interface, based on changing the input variables bounded by the known structural constraints and generate a volumetric model together with the necessary constructive information outputs, namely those informing material quantities which enable the calculation of construction costs.

CICERO tool was designed after some preliminary code prototypes based on a systematic literature review process and several trial implementations until an idealized usability was achieved. There is a rectangle box interface on the right side of the interface providing the variables, or the inputs to be changed per project by the user. On the left side, there is the generated simplified 3D model providing the constructive information as outputs. They are given in real time to help decision making while the creative process is under development.

At first, we tried to design the model revealing the detailed design of walls, including the layers, barbed wire and covering, but the algorithm became slow and the tool used to crash depending on the computer. Then we decided to provide a schematic visualization to have the benefit of an algorithm that runs faster. However, the tool still informs the number of layers as output. Only geometry is simplified. This method of simplification and high simplification - the use of only primitive forms - of buildings representation, to the detriment of better user experience by algorithmic design, have been indicated and adopted by well-known researchers (Shaviv, Gavish, & Amir, 1990).

We had the same crash problem when applying windows and doors parametrically, then we decided include fixed internal doors between rooms. Windows and doors can be added later on when a design is fixed, in the algorithm, and then the calculations of material quantities are updated.

4.6 Validation

Later on, an evaluation was made resorting to online users, using the 'ShapeDiver' (www.ShapeDiver.com) platform to host the tool (*Figure 63*). In this way, the users did not need to download anything, and they could do the entire procedure online.

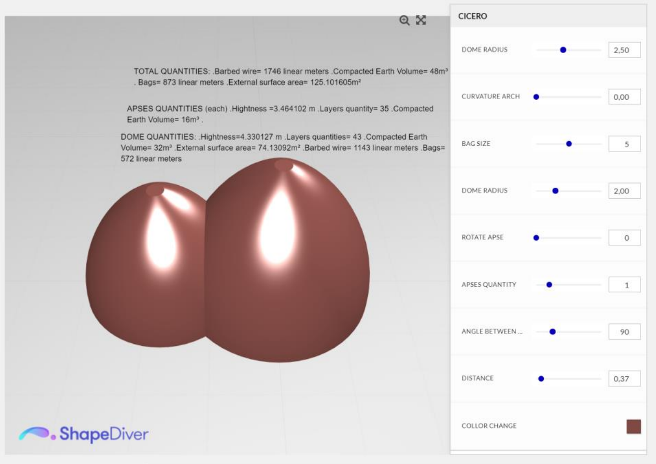

Figure 63. CICERO tool.

The tool was embedded in a website (www.cicero.earth) with a video-tutorial and an inquiry to answer after its use. The inquiry was available in English and Portuguese and was divided into three larger categories: user characterization, user interaction and subjective suggestions for improvements.

The website was disclosed aiming at experts in earthbag construction and planning for validating the technical data, the tool usage and establish a general profile of the target audience for the final tool. It was also necessary to collect data from lay people (not just from experts) to evaluate the tool user experience.

4.6.1 User Characterization

There were seventeen people, with different working nationalities (Brazil, United States, Guatemala, Turkey, Portugal, and Italy), recruited for the research sample. The age variations were: 47% between 26 to 35 years, 35% between 36 to 45 years, 6% between 46 to 55 years and 12% over 66 years old.

Five of them were specialists in planning, had constructive experience in earthbag buildings and still work in this field. One works in Europe, two in Brazil, and two in the United States. One has less than five years of experience, two have five to seven years, and two have more than ten years. Two usually plan by hand, and three use CAD software. When it was asked how much time they usually need to design a virtual volumetric model, most of them answered differently: two never did, one needs minutes, one needs hours, and one needs days.

There was one retired (did not specified the career), and only one student in the sample, all the other persons were architects, designers or professors in these fields. Two of them did not know about earthbag construction before this research, the others learned it in University, books, workshops, conferences, websites, video programs and manuals.

4.6.2 User interaction

There were three exercises to evaluate the tool performance for time and comprehension of the tool, and ten objective questions based on the 10 Nielsen's heuristics (Nielsen, 1995).

The exercises were designed to recreate three different known volumetric dome models, extracted from the literature (*Figure 64*). Technical images and respective information to feed the tool were given. After finishing the experiment, users were requested to sign how much time they took to design the virtual model.

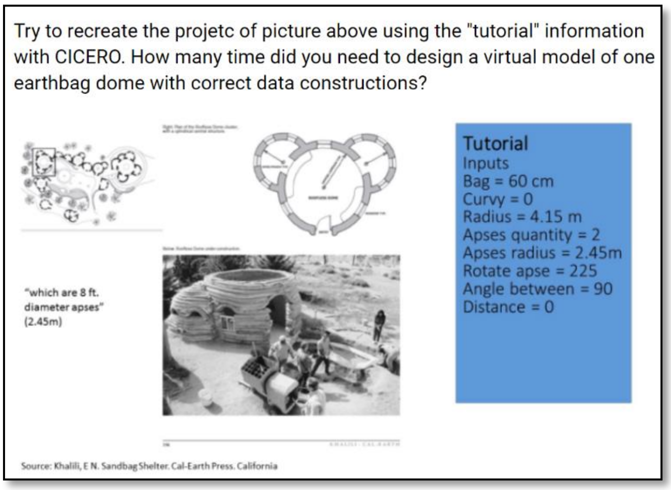

Figure 64. Example of the exercise given to validate the tool.

The exercises were given in an ascendant difficulty scale, where they needed to change progressively more variables to generate more complex dome clusters. Eighty-eight percent, did the exercises in less than ten minutes using CICERO. Only two people took more time to do them. The first because he was doing other things during the exercise, the second was a Brazilian and said that he had difficulties to understand the parameters in English and had to check their translation first.

The questions are based on Nielsen's heuristics and are guidelines to evaluate the user interaction. They regard: visibility of system status; match between system and real world; user control and freedom; consistency and standards; error prevention; recognition rather than recall; flexibility and efficiency of use; aesthetic and minimalist design; help users and documentation.

All fourteen people answered this part. All heuristics parameters were well ranked in evaluation (more than 85%). The only parameter that took less was about the help documentation, where just 71% said it was enough for their CICERO understanding.

4.6.3 Suggestions

The last comments and suggestions given by the participants were: insert in Cicero additional data regarding buttressing (besides the included apses), openings and safety factors; improve the explanation on the parameters with auxiliary documentation; insert the measurement units in the parameters and finally translate the tool to other languages.

4.7 Is CICERO a BIM tool?

During presentations in conferences and research groups, it was discussed that CICERO could be seen as a BIM tool, due to the technical outputs that it gives. That statement makes sense considering that building information modelling (BIM) are not an exclusive set of software programs, it is a process. To be specific, a modeling technology and a set of processes associated to produce, communicate and analyze constructive models (Eastman, Teicholz, Sacks, & Liston, 2011) and we would add, whilst providing associated technical data.

After a deep review of the meaning of acronyms BIM, Gaspar and Ruschel (2017) understood as a first reference that to be a BIM, this technological process must fill three items: a) object-based design; b) parametric manipulation; c) relational database. To put in another way, Building Information Model is a three dimensional geometric and parametric model with embedded data (K. M. Kensek, 2014; Lima, Araújo, Paz, & Oliveira, 2017; Turk, 2016).

As CICERO offers an object-based design, with parametric manipulation and some relational database, their utilities match with the presented definitions of BIM (*Figure 65*). However, CICERO can still be improved with additional technical documentation for construction management.

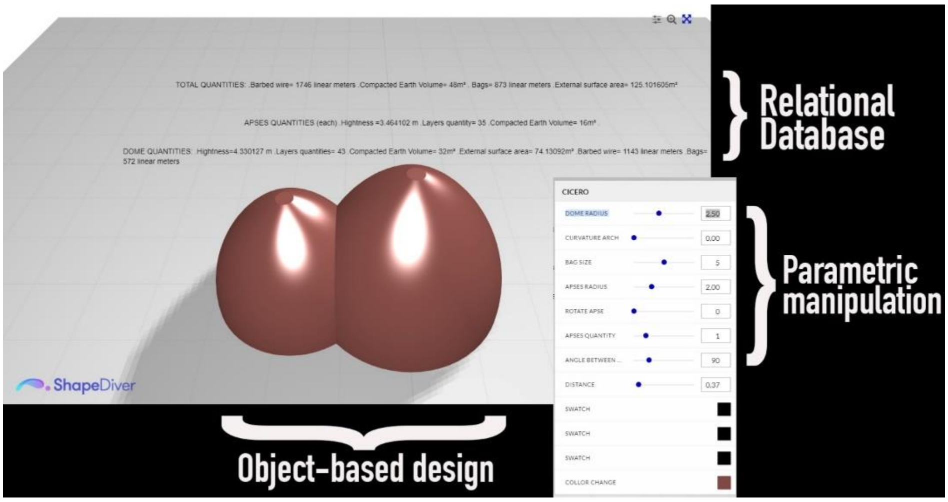

Figure 65. Correlations between CICERO and BIM.

4.8 Conclusion

The results of the validation process confirmed the hypothesis that the use of a parametric modeling tool can improve and aid the design of earthbag domes providing new useful tools to designers. The user can create complex models, with one or more domes associated by just changing a few numeric variables, receiving the construction specification outputs, in a short period, with high efficiency. As a practical contribution, this tool is expected to help architects to design earthbag building domes, in an easier and faster way while generating automatically the necessary documentation for construction. Additionally, the generated model provides also 3D models that can be used together with digital fabrication tools to fabricate 3D scaled models that are otherwise difficult to fabricate. Finally, we also expect that the use of this tool may increase the promotion of this form of sustainable building. Future work includes improving the tool by embedding it in a BIM environment and combining dome solutions with other constructive techniques creating hybrid architectural solutions.

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Chapter 5. BIM and Sustainability: A Review of the Architecture Field

The paper presented in this chapter[5] shows the second literature review about the relation between BIM and Sustainability. The parametric tool presented in the previous chapter was a prototype of the actual output of this PhD research. On the initial stages, CICERO delivered earthbag building designs in a Grasshopper environment. Further research was necessary (on BIM and earth architecture) to make CICERO a BIM compatible tool.

The goal of this paper is to identify previous researches regarding the use of BIM for designing with earth construction techniques. This paper presents the second part of the literature review for this research and identifies a gap on the researched field (BIM and earth architecture), also listing the publications that are more related with this research.

[5] This chapter is a slightly modified version of "Santos, D. M., & Beirão, J. N. D. C. (2019). BIM and sustainability: A review from the architecture field. *Modern Environmental Science and Engineering*, 5 (5). ISSN: 2333-2581" and has been reproduced here with the permission of the copyright holder

BIM and Sustainability: A Review from Architecture Field

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Abstract[6]

Can BIM technology be applied to create sustainable architectural designs based on ancient constructive materials and techniques? What work has already been developed in this field? Motivated by these questions, this paper offers an overview of the evolution and tendencies of BIM papers in architecture field in academia regarding its relationship with sustainability. The quantitative method of bibliometric analysis was adopted. More than 40 papers, from journals and conferences were examined after a previous selection filtering by combining two keywords: BIM and Sustainability or BIM and Sustainable. None of the previous existing bibliometric studies approached the combination of these two topics. By generating and analyzing these quantitative data, research aims to improve the focus on fields of study that have not been yet properly addressed hence contributing to improve the respective field of knowledge. This analysis offers also new insights indicating gaps and possibilities of themes for future unpublished works.

Keywords: BIM, building information modelling, sustainable, sustainability, architecture, bibliometric analysis, literature review

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5.1. Introduction

Is it possible to apply BIM technology in the design of sustainable architecture using ancient materials and techniques? Is there any previous literature addressing this question? What work has already been developed in this field? Those questions motivated a research, that seeks to find what has been published about BIM for sustainable traditional construction processes.

The paper aims to offer an overview of the evolution and tendencies of BIM papers in architecture category, to elucidate its relationship with sustainability and discover if the particular use of earth construction systems has already been approached. In this paper we have in mind the use of earth construction techniques, and in particular earthbag construction processes, because of their advantages regarding sustainability and easiness of the construction process. Also, because this type of material was not found in BIM software standards.

This challenge has been addressed by adopting a bibliometric analysis method, an objective tool by which the state of science and technology can be observed by searching through the overall production of scientific literature (Okubo, 1997). There are some previous bibliometric analysis publications regarding BIM and others regarding sustainability topics, but this is the first time that both topics are presented together.

This specific bibliometric analysis offers new insights, indicating the gaps in the literature, regarding our present developments in the use of BIM for representing traditional sustainable earth construction technologies.

5.2 Background

Traditionally, in order to build up a construction it was necessary to generate, during the conceptual design phase, a large set of design documents, essentially drawings describing the formal aspects and materials of the building, and after that, for describing all the technical construction requirements, a set of technical documents defining constructive details, material prescriptions including performance requirements of such materials, construction phases, contractual conditions and so on. In other words, designing and construction planning were tasks that used to happen separately, sometimes involving different teams and representation models that consequently were prone to errors. This division has been changing due to BIM implementation.

The use of BIM by architectural design firms is increasing, also, because the needs of visualization, communication, and design productivity are supported by BIM (Gokuc & Arditi, 2017). During the schematic stage of an architectural design process it is also possible to use BIM methodology into integrating the environmental dimension of sustainability (Salgueiro & Ferries, 2015; Ma, Le, Li, *et al.*, 2018).

BIM is an acronym standing for building information modelling, building information model or building information management (Turk, 2016). In architecture papers, the first definition seems to be the more applied. In BIM software, the design models are representations of real-world items (object-based design), they have identity and quantitative constructive data associated [Lima *et al.*, 2017; Gaspar & Ruschel, 2017; Eastman *et al.*, 2011). To put in another way, the building Information model is a three-dimensional geometric model that is data rich (Kensek, 2014).

5.3. Methodological Procedure and Data

5.3.1 Bibliometric Methods

Bibliometric or Scientometrics analysis has become a generic term for a whole range of specific measurements and indicators on scientific literature (Okubo, 1997). It is mostly defined by the quantitative study of bibliographic material. This literature analysis involves counting and tracking papers with attribution by country, by author, the number of citations (to measure the impact of papers), elucidates the evolution of the quantity of papers and highlights the main journals and conferences in a research field. In our case, the period searched was from 1900 until October of 2018. By analyzing these data, this research aims to find objective information on what topics this research field has more intensive work and which topics still provide large gaps still open for new or more intensive research.

5.3.2 Selected Data

To analyze the bibliographic information, the elected database was a well-known online repository named Web of Science (WoS), which considers papers from journals and conference proceedings. The database includes material from a wide range of research areas. Currently, it contains more than 140,000 conference proceedings and more than 20,000 journals (Claravite Analytics, n.d.a).

Because the conferences usually reveal emerging trends and new ideas before they appear in journals, it is valuable to include proceedings in the analysis.

At first, we searched for the descriptors "BIM" plus "earth" and found 18 papers among journals and proceedings from diverse categories, but no architecture. After an accurate analysis of these papers, all of them were excluded from this research. Sometimes because BIM was an acronym for other science fields, such as "Binary Ability Mechanism", "Born Iterative method", "bisindolylmaleimide-based protein" or "Biologically induced mineralization", and other terms, because the descriptor "earth" would not relate to a construction material, but to the planet earth or "google earth". There was just one paper where both descriptors had the meaning that we meant, but it was not related with architectural constructions (Rodrigues, Nicieza, Gayarre, *et al.*, 2015). In this case the topic was in civil engineering category and discussed geotechnical properties of earth-filled dams. This first search made us more confident to restrict this search just to architecture category.

WoS has a specific research category dedicated to architecture, then it is reasonable to select all the journals and proceedings from this category. Currently, architecture category covers 49 journals, and:

> "(…)[it] covers resources that are concerned with the study of the art and science of the building, particularly the design and construction of habitable structures. Also covered in this category are resources on architectural history, landscape architecture as well as urban and country planning and design" (Clarivate Analytics, n.d.b).

If we search for the descriptor "BIM" in WoS, we can find 8986 papers among journals and proceedings, 342 from the architecture category. When doing the same thing with the descriptor "sustainable" we find 215801 papers among journals and proceedings, 2390 from architecture category. Then, with the descriptor "sustainability" we find 117815 papers among journals and proceedings, 1504 from architecture category. Such amounts and its increasing curves allow us to affirm that these became trendy topics of research during the last decade (*Figure 66*).

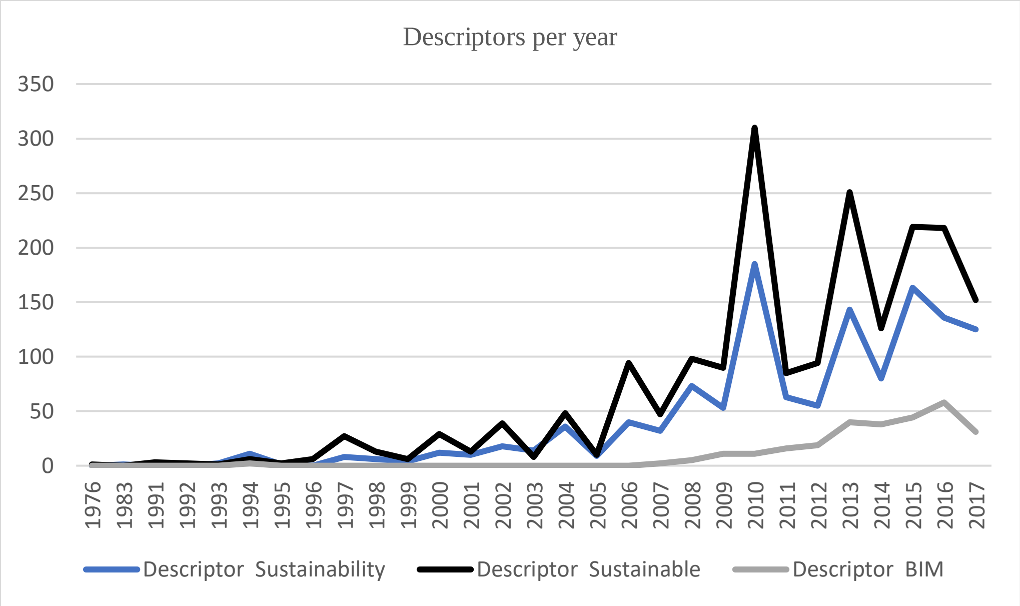

Figure 66. Descriptors of papers published in journals and conference proceedings per year in the architecture category.

However, these numbers abruptly decreased when searching for research relating two or more descriptors. For this purpose, we selected papers containing the topics “BIM” plus “sustainable” and found only 250 papers among journals and proceedings. We also tried the topics “BIM” plus “sustainability” and found 224 papers. Every paper covered by the WoS collection is assigned to at least one subject category. The results of this search were categorized through over than 100 different fields of research.

Architecture appears in sixth place with 26 papers (*Figure 67*) in first search, following the respectively categories: construction building technology, civil engineering, green sustainable science technology, environmental sciences, and energy fuels.

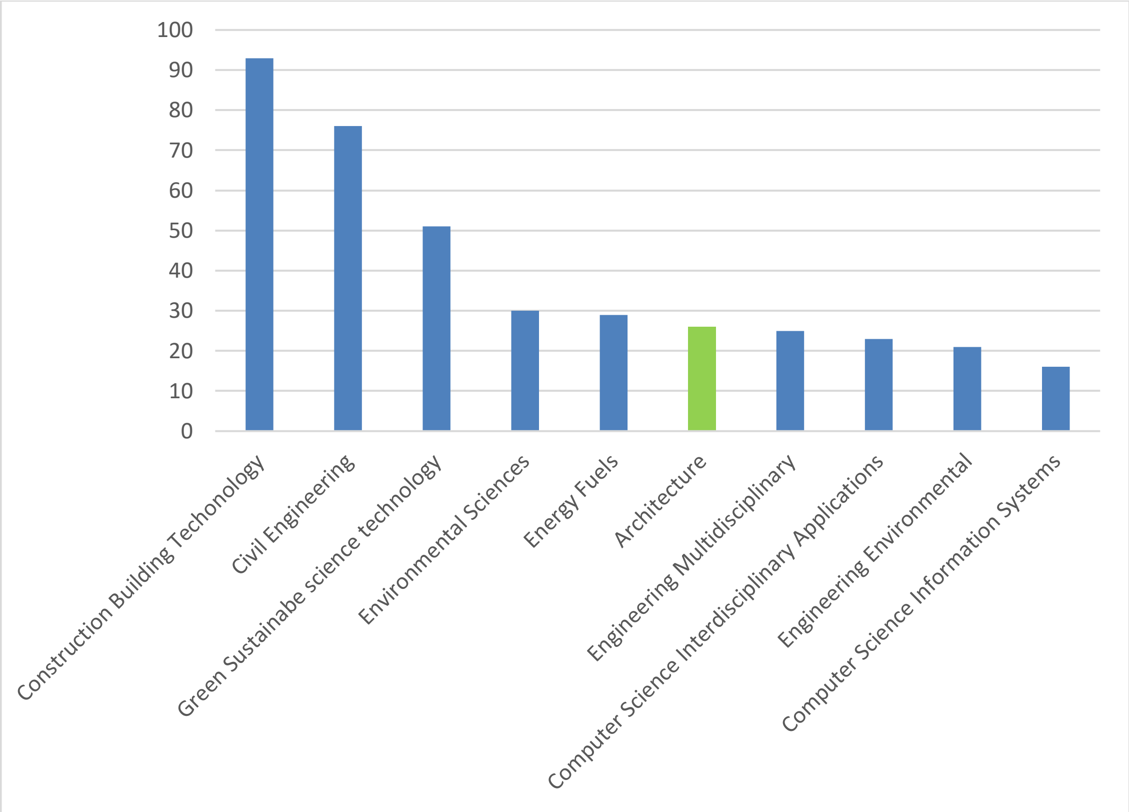

Figure 67. Top 10 categories search BIM + Sustainable.

Searching with the descriptors “BIM” plus “sustainability”, architecture appeared this time in fifth place, with 24 papers, following some of same categories as before. The categories that follow architecture, suffer a slight difference of order and nomenclature (*Figure 68*).

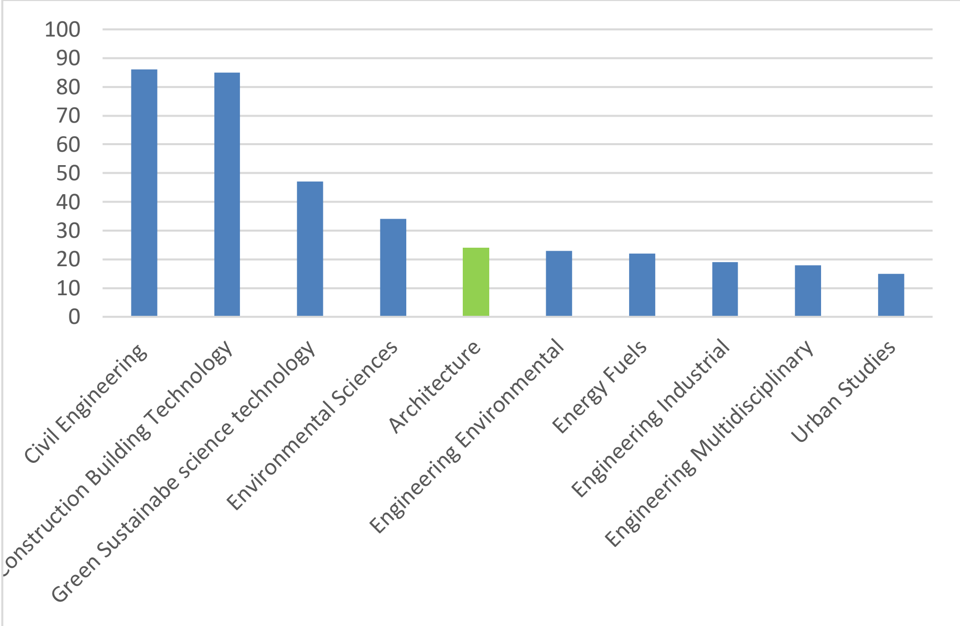

Figure 68. Top 10 categories search "BIM" + "sustainability".

As the intention of this research is to present an architecture point of view, the selected data considered only the architecture category. When considering the results of both searches ("BIM" + "sustainability" and "BIM" + "sustainable"), we found 5 duplicated papers, because they were presented in more than one search. Eliminating these duplicates, we have 45 papers in total from journals and conferences in architecture category.

5.4. Literature Analysis

5.4.1 The Language Factor

Clearly, the research accent today is in English, and the system is self-perpetuating (Okubo, 1997). To be in WoS, it is mandatory that journals and conferences present their titles, abstracts, keywords and cited references in English. Even considering that WoS accepts papers in other languages, papers have their keywords written in English, but still, most papers found in this analysis were entirely written in English even though many authors come from countries with other mother languages.

5.4.2 Number of Papers

The results show that the concern for these subjects in academic papers is recent. The first papers published devoted to the subject of “sustainable BIM”, appeared in the year 2008. That year, there was one paper published in the Oxford conference 2008.

The increase of papers on this subject have not been constant, and had peaks during the years 2011, 2013, and 2015 (*Figure 69*).

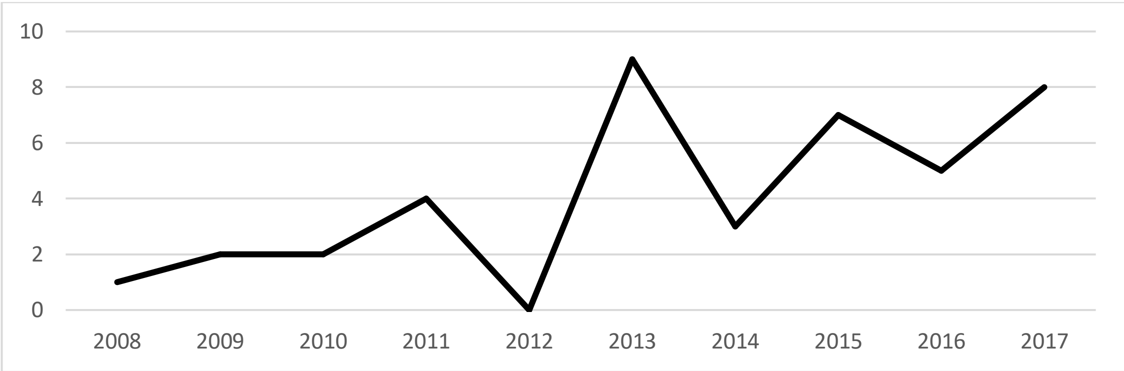

Figure 69. Number of papers per year.

5.4.3 Journal and Conferences

Most of the papers were published in specialized conferences, 32 from the total of 45. The other 13 papers were published in nine journals. The most relevant journals publishing papers regarding “sustainable BIM” are the “Journal of Green Building”, with 3 papers, and “Architectural Design”, with 2 papers (*Figure 70*). The other journals have one publication each. They are: Frontiers of Architectural Research, International Journal of Architectural Computing, Materia Arquitectura, Techne — Journal of technology for Architecture and Environment, International Journal of Architectural Heritage, Journal of Asian Architecture and Building Engineering, Megaron, and Estudios del hábitat.

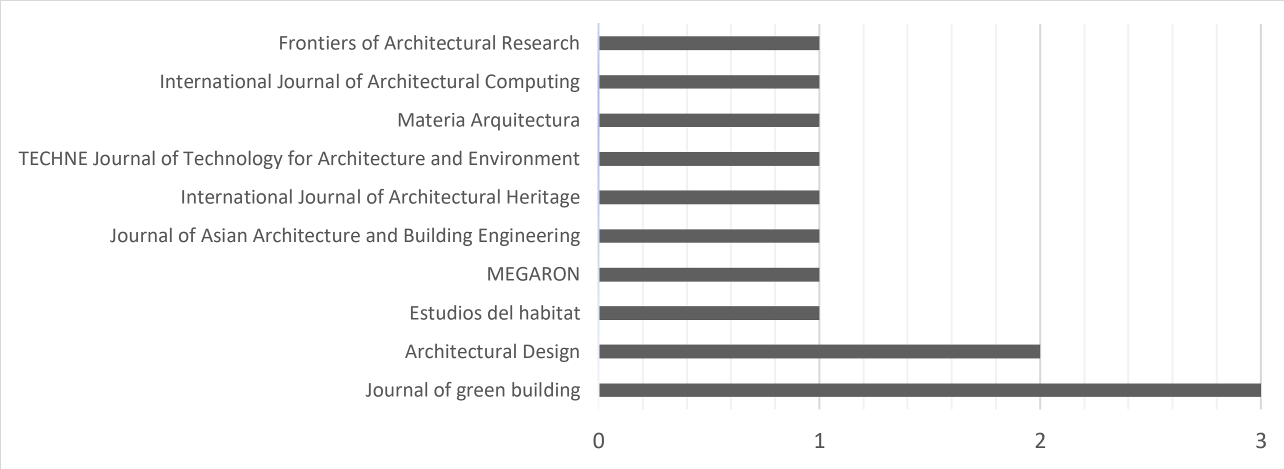

Figure 70. Number of papers per journal.

The two most relevant Conferences are the Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA), and the International Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe), with eight publications each (*Figure 71*); The World multidisciplinary civil engineering-architecture-urban planning symposium (WMCAUS), with four publications; The Conference on Central Europe towards Sustainable Building (CESB), with three publications; and the International Conference of the Architectural-Science-Association (ASA), with two publications.

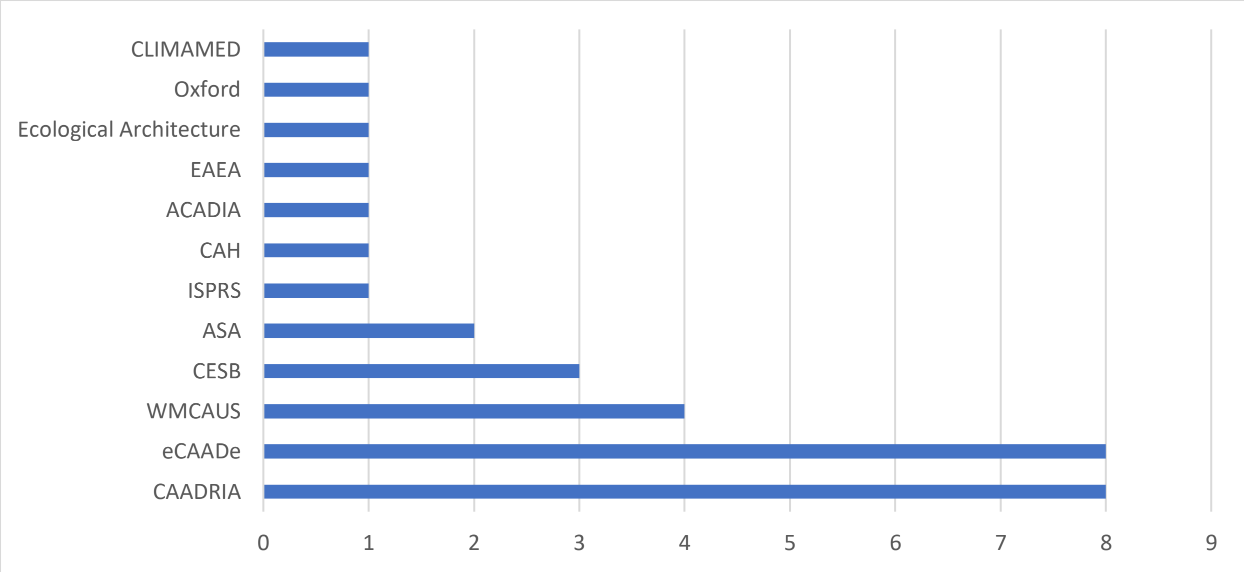

Figure 71. Number of papers per conference.

All the other conferences present a single publication. They are: International Society for Photogrammetry and Remote Sensing Congress (ISPRS); Conference on Conservation of Architectural Heritage (CAH); Association for Computer Aided Design in Architecture (ACADIA); Envisioning Architecture: Design, Evaluation, Communication (EAEA); International Conference on Ecological Architecture; The Oxford Conference; and Mediterranean Conference of HVAC Historical Buildings Retrofit in the Mediterranean Area (CLIMAMED).

We tracked also the countries where the conferences occurred and the journal editor countries (*Figure 72*). Among the 19 countries, Czech Republic stands out on the top of the list with seven publications. Followed by the United States of America and Italy with 6 papers each. The third place is shared with Australia, England and Singapore with 3 papers each. The fourth place is shared with Turkey, Switzerland, Slovenia, and Japan and with 2 papers each. The fiftieth place is shared with South Korea, Netherlands, Lithuania, Israel, Egypt, China, Chile, Canada, and Argentina with one paper each.

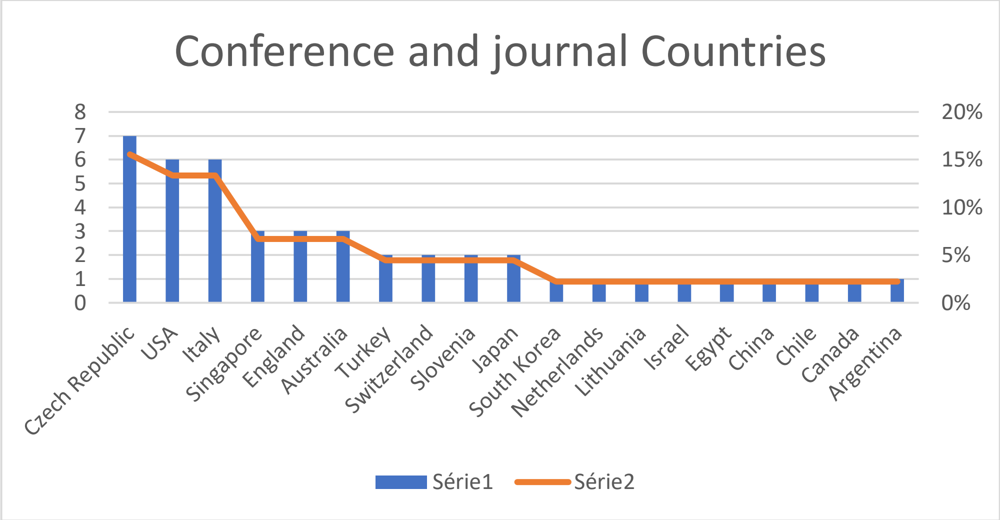

Figure 72. Conference and journal countries.

When grouping these events and Journal editor location per continents (locating Turkey in Asia and Egypt in Africa), Europe goes to the top of the list with 22 papers, Asia goes in second place with 10 papers, America goes to the third place with 9 papers, Oceania goes in fourth place with 3 papers, and Africa goes to fiftieth place with one paper (*Figure 73*).

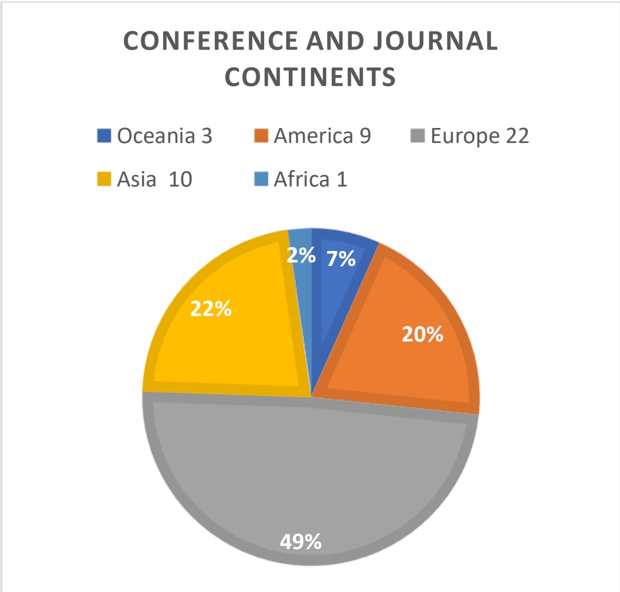

Figure 73. Conference and journal's origin.

5.4.4 Author's Origins

Among 21 countries with researchers publishing papers regarding the theme "sustainable BIM", the United States stands out at the top of the list with 9 papers. South Korea appears in second place, followed by Turkey, with 6 and 4 papers, respectively. Italy goes in fourth place with 3 papers. Poland, Spain, Czech Republic, and Slovakia has published two papers each. Egypt, Switzerland, Australia, England, Singapore, Germany, Lithuania, China, Nigeria, France, and Chile have published one paper each. In four papers, the author and co-authors are researchers from different countries, they are New Zeeland plus China, Italy plus England, Netherlands plus Portugal, and Finland plus Czech Republic (*Figure 74*).

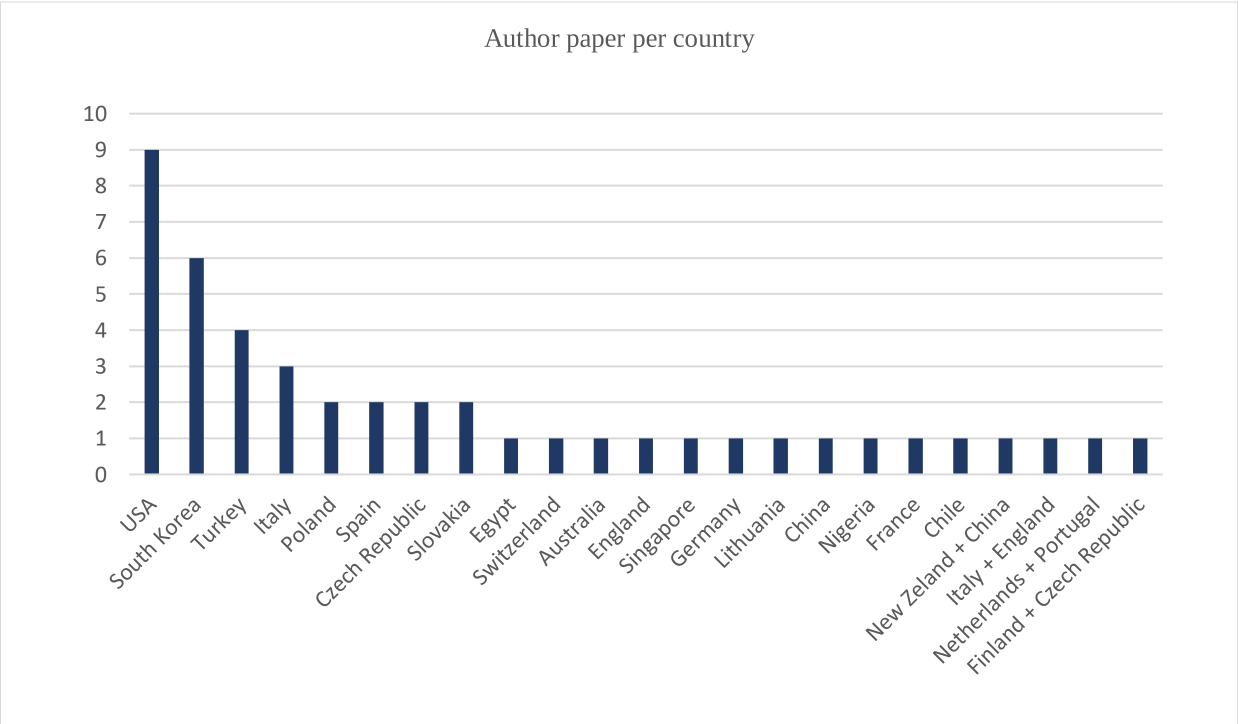

Figure 74. Papers per author country.

When grouping the publications by continent (locating Turkey in Asia), Europe goes to the top of the list with 42% of the papers. Asia appears in second place with 27%, America with 22% followed by and Africa and Oceania, with 4% each (*Figure 75*).

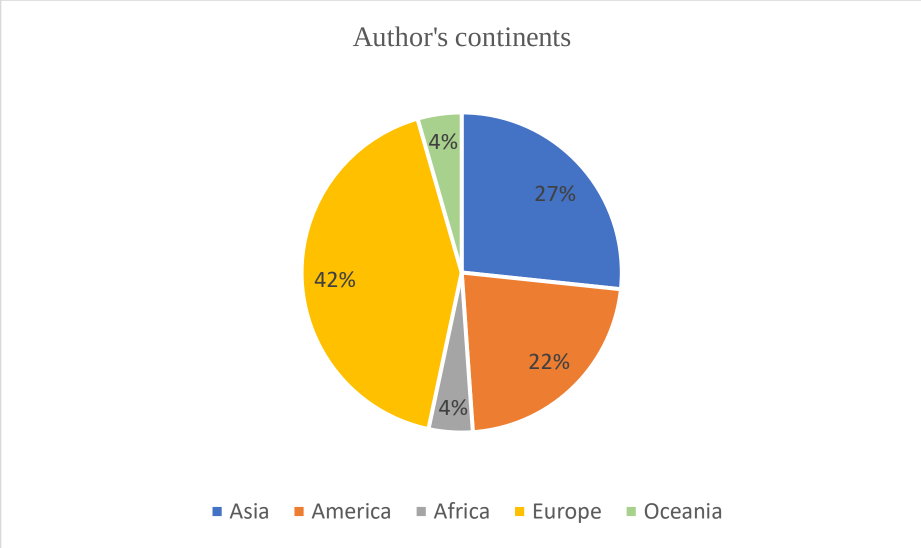

Figure 75. Papers percentage according to author’s continent.

5.4.5 Most Cited Papers Per Author

Some authors have made fundamental contributions to the development of this field. This section presents a summary of these contributions according to the information found in the web of science. These results include some of the most popular researchers in BIM plus Sustainability and BIM plus Sustainable.

From the total sample, 15 papers were cited by others in the Web of Science database. The top ten most cited authors are represented in Table V. The most cited of them has 5 citations and proposes a new design methodology for Hanok — traditional buildings of Korea — based on a parametric design using a BIM software (Revit) (Park, 2011).

The two second most cited has 5 citations each. One presents a case of study where the researcher experimented the use of a visual programming language (VPL) plus BIM (Dynamo + Revit) with a building energy simulation package (Kensek, 2015). The other presents some experiments and applications of 3D survey techniques, 3D scanning, building information modelling, and augmented reality applied to historical buildings (Chiabrando, Sammartano, &Spanò, 2016).

The third most cited has 3 citations and proposes a new informatic tool named “A thousand BIM”, that can quickly generate several buildings typologies (Park & Nakagura, 2013).

Table V

Top 10 authors.

	Authors	Paper title	Citations	Percent
1	Park, Jungdae	BIM-Based Parametric Design Methodology for Modernized Korean Traditional Buildings	7	19%
2	Chiabrando, F.; Sammartano, G.; Spano, A.	Historical buildings models and their handling via 3d survey: from points clouds to user- oriented HBIM	5	14%
3	Kensek, Karen	Visual programing for building information modelling: energy and shading analysis case studies	5	14%
4	Park, Juhong; Nagakura, Takehiko	A THOUSAND BIM A rapid value-simulation approach to developing a BIM tool for supporting collaboration during schematic design	3	8%
5	Kensek, Karen; Ding, Ye; Longcore, Travis	Green building and biodiversity: facilitating bird friendly design with building information models	2	6%
6	Pazhoohesh, Mehdi; Shahmir, Raja; Zhang, Cheng	Investigating thermal comfort and occupants position impacts on building sustainability using CFD and BIM	2	6%

7	Vital, R.; Cory, J	Digital documentation integrated in BIM for building reuse and sustainable retrofit	2	6%
8	Asl, Mohammad Rahmani; Zarrinmehr, Saied; Yan, Wei	Towards BIM-Based parametric building energy performance optimization	2	6%
9	Gil, Jorge; Beirao, José; Montenegro, Nuno; Duarte, José	Assessing Computational Tools for Urban Design Towards a "city information model"	2	6%
10	He, Yi; Schnabel, Marc Aurel; Chen, Rong; Wang, Ning	A parametric analysis process for daylight illuminance. Influence of Perforated Facade Panels on the Indoor Illuminance	1	3%
11	Samuel, Egwunatum I.; Joseph-Akwara, Esther; Richard, Akaigwe	Assessment of energy utilization and leakages in buildings with building information model energy	1	3%
12	Nyvlt, Vladimir; Pruskova, Kristyna	Building Information Management as a Tool for Managing Knowledge throughout whole Building Life Cycle	1	3%
13	Rea, Pierluigi; Pelliccio, Assunta; Ottaviano, Erika; Saccucci, Marco	The Heritage Management and Preservation Using the Mechatronic Survey	1	3%
14	Fathi, Ahmed; Saleh, Ahmed; Hegazy, Muhammad	Computational design as an approach to sustainable regional architecture in the Arab world	1	3%
15	Salgueiro, Inti Baeza; Ferries, Bernard	An "Environmental BIM" Approach for the Architectural Schematic Design Stage	1	3%
	Total		36	100%

Five papers share the fourth position with 2 citations each, their themes are: (1) To present an educational tool applied to Dynamo + Revit that characterizes whether a proposed building design can avoid bird collisions (Kensek, Ding, &Longcore, 2016); (2) To present an intelligent control system to automate the thermal comfort decisions focusing on the knowledge of the occupants (Pazhoohesh, Nizam, & Zhang, 2015); (3) To present a case of study on the documentation and design intervention in a historical building in Israel using BIM software — Revit (Vital & Cory, 2015); (4) To create a tool "Revit2GBSOpt" to facilitate integration between parametric BIM and building energy performance simulation (Asi, Zarrinmehr, & Yan, 2013); and (5) To evaluate software tools for sustainable urban design in a perspective of having a CIM — City Information Model (Gil, Beirão, Montenegro, *et al.*, 2010). This last paper focuses on the topic of urbanism and not exactly architecture.

The last six papers share the fifth place with one citation each.

From the 15 most cited papers, Karen Kensek appears authoring two papers. This means this author have combined 7 citations, sharing, the first place of most cited author in this field, with the author Jungdae Park.

5.4.6 Sustainable BIM

Sustainability is a subject that involves every knowledge field, including architecture. One of the most acceptable definitions of sustainability was published in a report, after the 1987 World Commission on Environment and Development (WCED). It says: "'development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987).

In architecture the term Sustainability has been applied with diverse meanings. Since 1987 other derivates of the term were created to characterize sustainable architecture, such as: "green architecture", "ecologic architecture", low-impact architecture", "bioconstructions", "bioclimatic architecture", "Net Zero Energy Buildings", and others. However, within this diversity of terms, most of them agree that sustainable buildings must have minimal environmental impact and energy efficient use. One way to achieve this is using ancient techniques with natural materials, the other is developing materials that cause less harm to the environment.

Keeping this in mind, we classified the consulted literature between those resorting to new and those resorting to ancient techniques. In this case, the “new” category regards the research that explores the use of BIM related to applications of new materials to decrease the environmental impact, like improving the building energetic performance, or recycling construction waste for the development of new sustainable materials. The “ancient” category explores the use of BIM related with use of ancient materials and techniques (like earth construction) or cultural heritage.

Seven papers were excluded from this classification because it was not possible to find any relations with the mentioned topics. From the 38 papers remaining, 6 were categorized as “ancient” and 32 were categorized as “new”. In the “ancient” category, the five objects studied were: Historical Buildings (Chaibrando *et al.*, 2016), Historical buildings and historical center of Frigento — historic town in the province of Avellino (Gigliarelli, Calcerano, & Cesari, 2017), Regional Islamic Architecture (Fathi, Saleh, and Hegazy, 2016), Historical buildings in Israel (Vital & Cory, 2015), Hanok (Traditional buildings in Korea) (Park, 2011), and Valcomino historical city in Italy (Rea, Pellicio, Ottaviano, *et al.*, 2017).

5.5 Conclusion

The first objective of this paper was to present a literature review of BIM and sustainable/sustainability research in order to find whether there was already any research on the implementation of ancient/traditional construction techniques in BIM. There were find 6 papers matching with this premise that presents studies of historical buildings using some BIM tool in their methodological procedures.

The review used a bibliometric analysis to select a sample of more than 40 papers from the Web of Science, considered to be the most reliable source for academic publications. In this analysis it was confirmed that the subjects of BIM, Sustainability and sustainable had been increasing during the years but when combined together, the increase was not constant and had peaks in some years.

Among the WoS's categorization, architectural journals and conferences have been taking the sixth or fifth place in research combining the topics: BIM and sustainable/sustainability. Authors have preferred to publish more in conferences than in journals, 71% of the papers came from conferences, and the other 29% came from journals.

Considering the geographic scope, it is interesting to verify that Africa, the continent where earth construction has always been most applied, actually has the lowest percentage index in hosting conferences, editors, and authors in this field. The percentage of author publications per continent is close to the percentage of the location of publication per continent. This fact would evidence that there is a tendency for authors to publish on their geographical area or in other words that researchers' mobility tends to be mostly within the continent where their affiliation resides. Still, because authorship is related to affiliation and not nationality of the authors, the analysis may be misleading in regard to the researchers' nationality.

Furthermore, other than conventional bibliometric analysis that usually is restricted to quantitative data, we also presented a subjective analysis on the papers, pointing those referring to ancient materials and techniques. Those papers present less than 16% of the total. Most of them are dedicated heritage architecture, even though the examples were considered sustainable, this was due to the memory preservation and not because of the materials applied, which were essentially not natural materials.

Regarding the initial objective, to show if there was any research relating BIM to the use of earth construction, we concluded that in the architectural category on WoS database, there are no publications relating these topics, and the publications of other categories the given keywords did not have the same meaning as meant in this research. This conclusion evidences a gap in research showing that there is no work involving the development of BIM tools for earth construction techniques. It might be possible to find some publication in this topic out of the database used here. Nevertheless, considering the world wide acceptance of WoS, it is valid to affirm that this is not a well explored topic in literature and it would be a challenge to find some consistent work on this matter.

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Chapter 6. Integration of BIM And Generative Design for Earthbag Projects

This chapter is an expanded version of a book chapter[7]. The outputs from chapters four and five (the prototype parametric tool and the second part of the literature review) present some knowledge background to start the second experimental phase of this thesis. Due to the short dimension of the original paper, it was necessary to expand the contents for a better understanding of the technical details of the research.

The goal of this chapter is to make the prototype parametric tool compatible with the BIM environment. This compatibilization will increase the capabilities of the prototype parametric tool, which will present the usual BIM functionalities such as quantity maps and construction prescriptions.

This chapter presents the evolution of CICERO tool, from a parametric design environment to a BIM environment with the inclusion of an adequate library, associated technical prescriptions, and quantitative database. CICERO tool is capable of designing domes with earthbag construction, integrating earthbag construction in any other earthbag variants as identified in Chapter 2.

[7] This chapter is a slightly modified version of "Santos, D. M. Beirão, J. N. D. C. (2020). Integration of BIM and Generative Design for Earthbag Projects. In: Almeida H., Vasco J. (eds) *Progress in Digital and Physical Manufacturing*. ProDPM 2019. Lecture Notes in Mechanical Engineering. Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-29041-2_13 ISBN: 978-3-030-29041-2"

Integration of BIM and generative design for earthbag projects

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Abstract

Although earthbag construction is recognizably a low environmental impact solution, existing software tools are limiting factors, since they do not have enough technical data to support its building information model. We propose a visual programming language code to generate earthbag domes inserted in a BIM environment, where these structures can be associated with other design and structural elements, producing the required technical data to inform construction including technical specifications as well as material and task quantification. This research adopted an experimental methodology exploring the advantages of the combination of building information modelling with parametric generative design in the design of earthbag buildings or hybrid constructions involving earthbag walls with different geometries. It was validated resorting to a simulation process where it was possible to redesign and 3D print a scaled model of an existing earthbag building that merges different shapes in the same building, including the automated generation of the associated technical data. The developed tool allows designing different types of earthbag buildings providing a typical BIM model including both geometric model and technical specifications.

Keywords: Earthbag, Building Information Modelling (BIM), Visual Programming Language.

6.1 Introduction

This research adopts an experimental methodology, and addresses the advantages of combining a visual programming language (Grasshopper) with a BIM software (VisualARQ) to produce earthbag architectural designs.

In 1984, a new earth construction technique was created: the earthbag building. Also known as sandbag, SuperAdobe or superblock technique, it consists in a construction system where the walls are essentially built by staking bags filled with inorganic soil and consolidating them with barbed wire between layers (Geiger & Zemskova, 2015; Hart, 2015; Khalili, n.d.; Minke, 2001; Wojciechowska, 2001). They are durable, strong, and climatically efficient. They are more advantageous than other earth building techniques because they do not require formwork, are capable of organic forms, are more resistant in earthquake-prone zones, benefit from lower maintenance and construction time and are self-supporting up to double storey typologies. This technique is also faster to build than most of other earth construction techniques.

The material of earthbag buildings are almost all natural (earth, clay, and water). If a construction becomes obsolete, those materials can return to nature or even be reused to build up another building, guaranteeing a sustainable cycle. The earthbag constructions fill also resilient design principles. Resilience, in context of engineering design, is defined as the ability to provide required capability in the face of adversity, like natural disasters (Jackson, 2016). The earthbag building is statically strong, durable, and safe even to extraordinary climate conditions and natural calamities like earthquake, flood, windstorm, storm, and fire (Kamal & Rahman, 2018; Ross, Willis, Datin, & Scott, 2013).

Although earth construction methods are low environmental impact solutions (Husain, 2018; Kumar et al., 2007; Morel et al., 2001), existing software tools continue to be limiting factors regarding this type of project and specifically regarding earthbag construction. CICERO (Creative Interface for Constructing Earthbag Resource Objects), is a specific tool developed to generate the volumetric virtual model of earthbag dome shapes, recently created and presented during the conference Sigradi 2017 (Santos & Beirão, 2017; Santos & Beirão, 2019b). However, this tool can be improved since earthbag constructions allow the production of other morphological types than domes, namely, compound forms of construction involving several techniques. Furthermore, the volumetric shape, as was presented in the mentioned paper, is not enough to produce all construction documents that should include plans, sections, elevations together with the necessary construction technical specifications, specifically, material descriptions and quantifications required for planning the construction procedures, and producing the required and desired qualitative results.

This paper presents the evolution of what was presented at Sigradi 2017 and addresses the last part of a larger research proposing an alternative approach to produce earthbag designs, based on the use of an algorithmic (parametric) approach, associated with a building information modelling (BIM) environment.

BIM software can work together with programming languages (scripting or visual) to create generative, parametric models. Since CICERO was previous developed in Grasshopper visual programming language, the BIM environment studied here was VisualARQ because their integration is already provided by the same supplier.

This research is a part of a larger investigation that encompasses the following steps: 1- Developing a constructive classification of earthbag buildings (Santos & Beirão, 2016a); 2- Understanding the logic of visual and textual programming languages to define the parametric approach of the experiment (Santos, Pontes, & Leitão, 2019); 3- Developing a parametric experiment to support architectural design decision of earthbag building domes using CICERO tool (Santos & Beirão, 2017; Santos & Beirão, 2019b); 4- Presenting a bibliometric analysis that approaches the combination of descriptors BIM and sustainability, concluding that there is no published work involving the development of BIM tools for earthbag construction techniques; and 5- Developing a computational experiment, to propose a visual programming language code to generate hybrid earthbag designs including earthbag domes and walls, as an interface to obtain a BIM model of the design.

This paper is focused on step 5. The goal is the improvement of CICERO tool, integrating the parametric tool in a BIM environment to generate different types of earthbag designs.

6.2 Pre-tests

Some preliminary tests were necessary to identify which BIM environment could fit better the purpose of this experiment, namely which is compatible with CICERO and able to improve its resources. Just after that, the coding experiment could begin.

6.2.1. Alternatives parametric dome design in BIM

At first, the design of a regular dome wall was tested in three BIM software: VisualARQ, ArchiCAD, and Revit. The objective here was just to check if it is possible to design a dome with wall characteristics. Secondly, the integration with a programming language was checked.

Revit is possibly the most popular BIM software. In this software, it is possible to design domes per profile revolution. But the integration with Grasshopper is limited. We tried some plugins, but we could not achieve the expected results. We also considered a textual programming approach to work in this environment, however, after consulting some specialists in informatics we figured out it was not possible at that time, as the software above-mentioned are not compatible yet.

ArchiCAD has a specific ad-on for Grasshopper with their own components, with which it can be synchronized. Nevertheless, the only way found to design a regular dome is through the command 'morph', which does not allow inserting doors or windows.

VisualARQ works as a plugin for Rhinoceros, and also has a specific ad-on for Grasshopper with their own components. Grasshopper's domes can be transformed into BIM walls resorting to the "Wallsolid" command. There is an issue though, when trying to insert doors and windows, the openings generate holes in the wall behind too. To solve this and close the extra opening, the user has to click in "parameters/Cut Depth" and substitute the automatic option by the necessary cut/depth dimension.

After installing and testing all three BIM software possibilities, VisualARQ seemed to be the most adequate tool to design the earthbag domes in association with CICERO, which already runs in Grasshopper. That is why it was elected to run this experiment.

6.3 Development

The logic behind CICERO interface for earthbag/SuperAdobe domes is the same as explained in 0 (page 121). We used the same inputs data for dome design (Bag size, curvature arch, dome radius, quantity of apses, apses distance to centre, angle location, and rotate apses), calculus logic, system outputs, and others. The development of the tool aimed to improve the code, making it more compatible for BIM environment (detailed in subtopic "6.3.3. Inserting the new material" page 185). We introduced the possibility to create other morphological variants of earthbag/SuperAdobe walls and to include other constructive techniques in the project with the adoption of BIM existent libraries.

As previously referred earthbag walls are built by staking bags filled with inorganic soil and consolidating it with barbed wire between layers. The so called inorganic soiled might be composed by specific amounts of earth (taken from local ground), clay, sand, water, all mixed in proportions capable of producing a stable and durable wall. This wall can be finished with a plaster coating reinforced with the application of chicken fence wire or similar reinforcement. Hence, a BIM technical description of such a wall should be able to provide quantitative descriptions of all the needed materials (1) and respective technical prescriptions describing the details and procedures for the production requirements (2) better described in the next two topics.

6.3.1. Needed material

This topic further explains the Earthbag/SuperAdobe materials. They require quantitative calculation from the BIM model:

Quantity of the compound mixture of earth (taken from local ground), clay, sand and water. This quantity is taken from the geometric model of the wall considering its volume and calculates the amount of each material considering (a) the proportion of each element in the mixture and (b) the increase in volume due to the difference of the materials in supply format (loose) or in the finished compacted form.

Quantity of bags. This quantity takes a bag section based on the wall thickness and calculates (1) the number of layers; (2) a theoretical length per bag (a manageable bag length for manual construction procedures; (3) the amount of extra bag length taken to provide bag closure at each bag's extremes.

Total length of barbed wire considering the application of two parallel threads between layers.

Total surface to plaster. This value is taken to calculate the amounts of materials composing, the finishing plaster coating, and the surface of chicken fence wire needed to reinforce the plaster. Considering the desired sustainability of the construction, we assume the plaster coating to be of a traditional nature, excluding cement as principle, and involving the addition of lime, to develop a strong protective and resistant coating. Amounts of chicken wire are given as surface with a 10% increase for overlaps, and plaster coating are given considering (a) the proportion of each element in the mixture and (b) the increase in volume, due to the difference of the materials in supply format (loose), or in the finished plastered form.

6.3.2. Technical prescriptions

Most of the desired technical data for earthbag walls, was generated automatically by VisualARQ. Such as style, length, thickness, area (that was renamed as surface area), and volume (that was renamed as volume of compacted earth). However, there was still missing information such as: number of bag layers, barbed wire and bags.

The logic to calculate the layers is based on Hunter and Kiffmeyer empirical studies (Hunter & Kiffmeyer, 2004). They assume that bag layers can vary according to the tamping process, and under layers can flatten down after conclusion of higher layers. According to their observation the average measurement is 10 centimeters, then, for representations and calculus purposes it should be considered a height of 10 centimeters for each layer.

Because bags are built in rows, the calculus is made in meters measuring the length of the rows. The logic to calculate the total amount of bags is to extract from the model the length of all bag layers, adding at least 20cm of loose material, for each cut, to tie off the ends (Hart, 2018; Hunter & Kiffmeyer, 2004).

The barbed wire, combined with the woven fabric of the bags, adds a high tensile strength to the wall structure. Some authors point that this application should be made in two parallel threads of 4-point barbed wire for each layer (Geiger, 2011; Hart, 2015; Hunter &

Kiffmeyer, 2004; Wojciechowska, 2001). This premise is put into the calculation of the total barbed wire length.

6.3.3. Inserting the new material

It is relatively easy to insert a new material in a BIM platform, because they are equipped with user-friendly interfaces to do it. There is a Wall style dialog box (command: _vaWallStyles) in VisualARQ, where it is possible to create a new type of wall, with a new material using the available new style button (*Figure 76*).

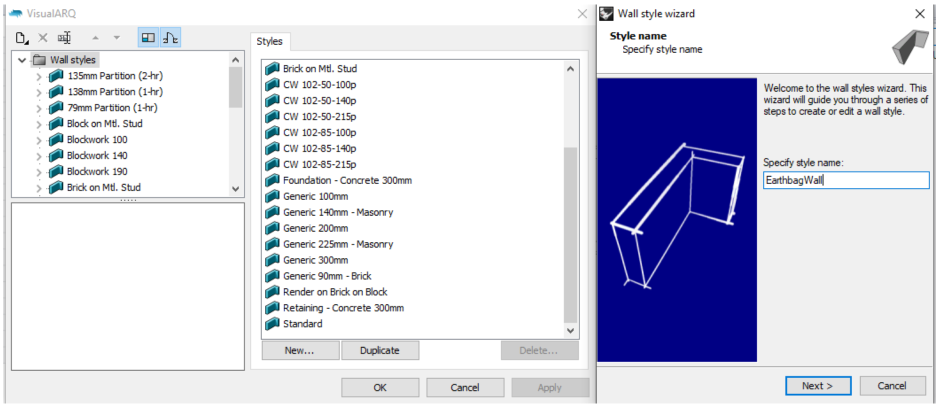

Figure 76. Creating a new Wall Style with VisualARQ interface.

Unfortunately, the interface still has some limitations regarding the addition of new variable parameters in materials. For now, it is possible to add just static new parameters. Consulting the assistance, it was said that it is in their plans offer a way to add calculated values in future VisualARQ versions. It was created the wallstyles: EarthbagWall 30cm, EarthbagWall 40cm, EarthbagWall 50cm, and EarthbagWall 60cm. For this new wall styles, it was possible to include the following parameters: quantity, style, length, area, wall height. and volume.

It was expected to include also the parameters: layers quantities, barbed wire, bags, and surface area. We could include this after the modeling process with the use of the visual programming language, Grasshopper, where this information was calculated following the mathematical model described above and published in our previous paper (Deborah Macêdo Santos & Beirão, 2017).

In order to transform the parametric dome generated with CICERO into a VisualARQ wall, the Grasshopper component for "wallSolid" VisualARQ command was added to CICERO code (*Figure 77*). This component converts Breps (Boundary representations) into VisualARQ walls. In CICERO tool, the user has just to change the parameters until it reaches the desired shape. When the parameter is changed, the preview of the model and respective technical data appears in Rhinoceros/VisualARQ. After deciding the desired parameters to insert the dome wall, the "bake" command in the wallSolid box is used so that the following design steps may occur in the BIM environment. It might be necessary to have a solid loft dome, with the same dimensions of the walldome, to subtract from the linear earthbag walls generated in the VisualARQ interface resorting to a typical wall object. This is just an auxiliary process used in the generation of the intersection of the dome with the remaining earthbag walls of the design.

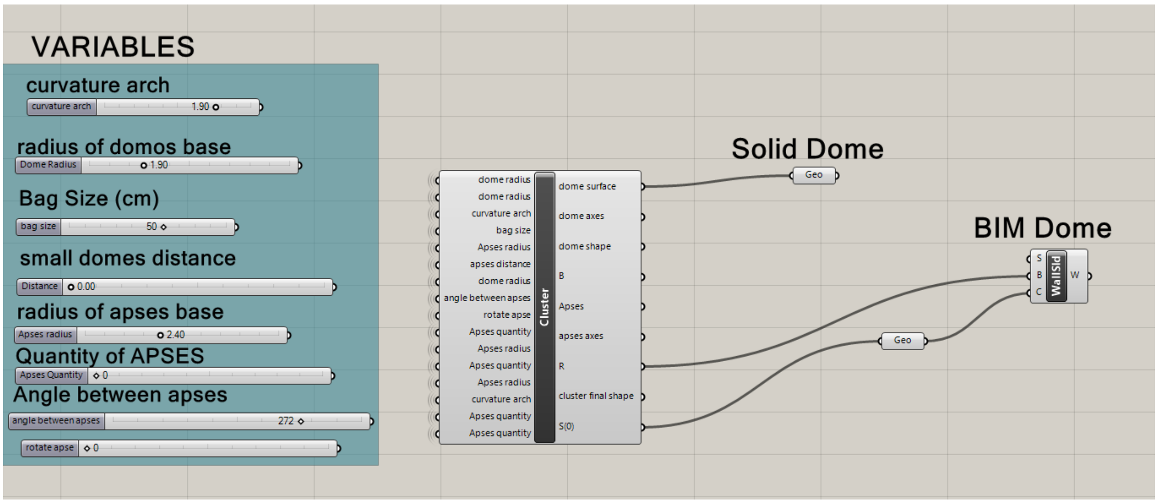

Figure 77. Conversion of the parametric dome into a VisualARQ "WallSolid".

At this time, the only way to insert the desired missing technical data is using Grasshopper (*Figure 78*). In Grasshopper, it is possible to create a custom parameter and assign a value to the objects, as generated by the software according to the mathematical model calculating materials' quantities.

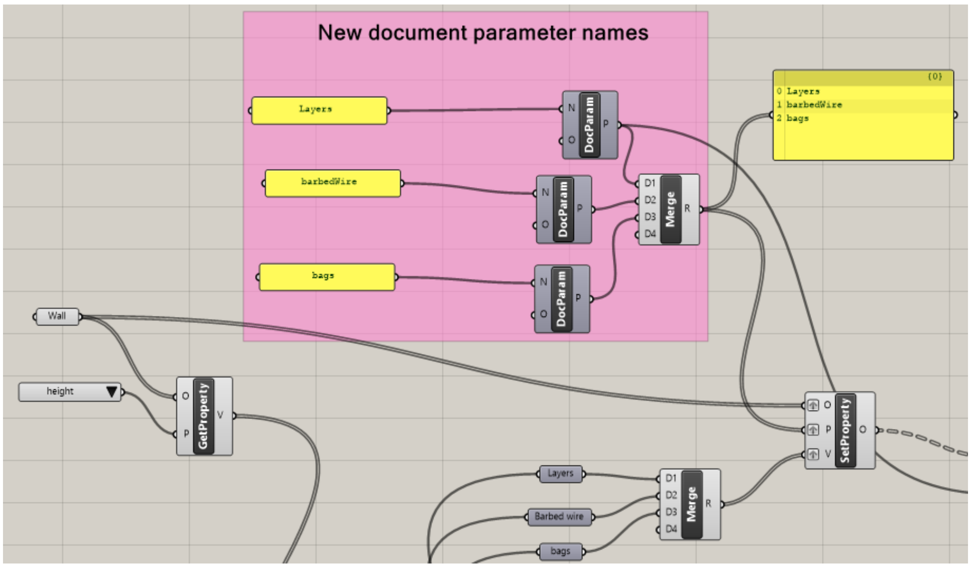

Figure 78. Example of how to insert the missing technical data with VisualARQ components in Grasshopper.

After modeling the whole building, the user needs to import the VisualARQ/Rhinoceros walls into the Grasshopper code and use the command "bake" in the "setProperty" box. By doing this, the system sends the same walls to VisualARQ/Rhinoceros including the technical data that would be missing without following this step.

6.3.4. Inserted technical data

Most of the desires technical data for earthbag walls, was generated automatically by VisualARQ. Such as style, length, thickness, area (that was renamed as 'surface area' in technical tables), and volume (renamed as 'volume of compacted earth'). However, there was still missing information, such as: number of layers, barbed wire, and bags.

The logic to calculate the layers is based on Hunter and Kiffmeyer empirical studies (Hunter & Kiffmeyer, 2004). They assume that bag layers can variate according to the tamping process and under layers can flatten down after conclusion of higher layers. According to their observation the average measurement is 10 centimeters, then, for representations and calculus purposes it should be considered a height of 10 centimeters for each layer.

Because bags are purchased in rows, the calculus is made in linear meters. The logic to calculate the total amount of bags is to extract from the model the length of all bag layers, adding at least 20cm of loose material, for each cut, to tie off the ends (Hart, 2018; Hunter & Kiffmeyer, 2004).

The barbed wire, combined with the woven fabric of the bags, adds a high tensile strength to the wall structure. Some authors point that this application should be made in two parallel threads of 4-point barbed wire for each layer (Geiger, 2011; Hart, 2015; Hunter & Kiffmeyer, 2004; Wojciechowska, 2001). This premise is put into the calculation of the total barbed wire length.

6.4 Results and validation

The research resulted in CICERO tool (organized in two Grasshopper files) that works using a BIM platform composed of Rhinoceros, plus Grasshopper (Visual programming language environment), and VisualARQ (BIM plugin of Rhinoceros). In the next paragraphs it is briefly explained how to design earthbag projects with these tools and for the validation process we used a specific earthbag building to check its workability and capacity of generating earthbag designs with compound construction technologies and earthbag wall shapes.

6.4.1. Procedure to design earthbag projects with a parametric dome in BIM

The logic to design earthbag buildings in this improved CICERO tool is: first, generate the earthbag domes and solid domes (for subtraction purposes) by changing the numerical parameters in Grasshopper (First CICERO file); second, export (using the bake command) to VisualARQ, and there insert, the other walls, doors, windows roof, beams, etc.; third, go back to Grasshopper (Second CICERO file) to calculate the missing documentation aspects (those missing in VisualARQ); fourth, after the calculation of the new properties, import to VisualARQ all the documentation, generate the tables and blueprints (*Figure 79*).

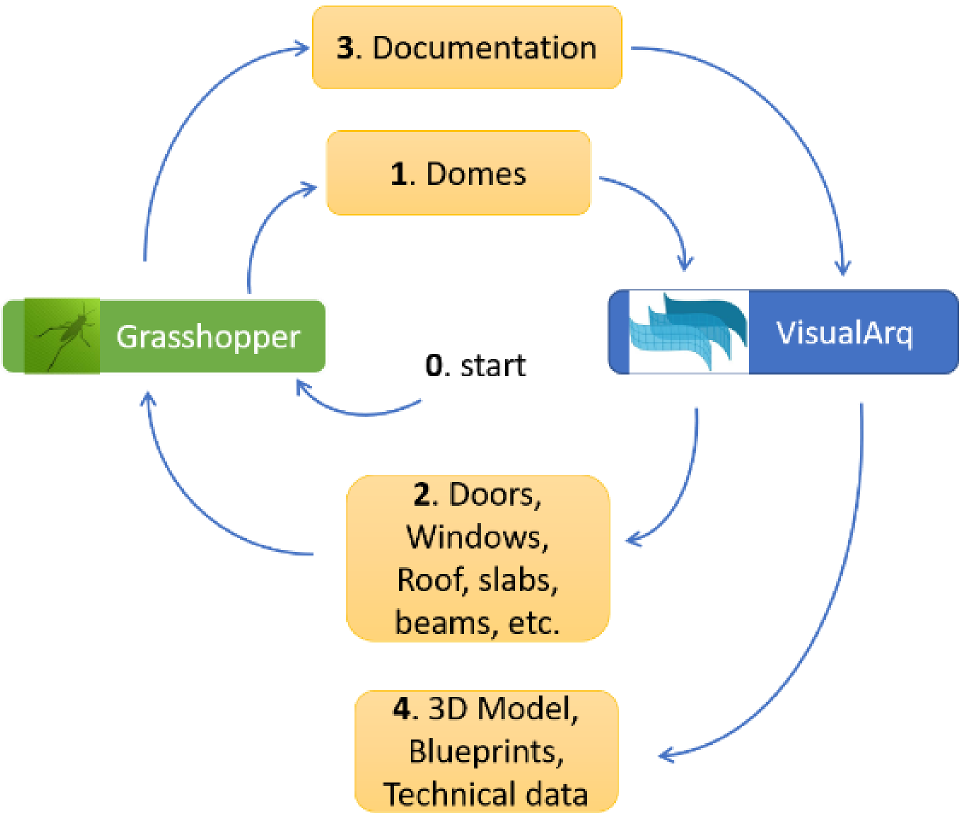

Figure 79. Logic to design earthbag buildings.

6.4.2. Validation through simulation process

The chosen model for the study case validation was "La casa Vergara", designed by the architect Andreas Vallejo, and built in Sopó, Cundinamarca, Colômbia in 2011. The project presents 85sqm, as a self-supporting earthbag linear wall structure and two earthbag domes (José Andrés Vallejo, 2011). Blueprints, pictures of construction and of the building can be easily found in the architect’s personal website (Jose Andres Vallejo, 2011). This house was chosen because it is composed by all elements that we wanted to proof to be able to design, in other words, a design with a compound set of construction technologies and several earthbag wall shapes including the dome.

The procedures to model this house are presented in eleven steps in *Figure 80*, and include designing the walls, slab, beams and roof, and openings. For each step it was necessary to solve some issues, described in the following sections.

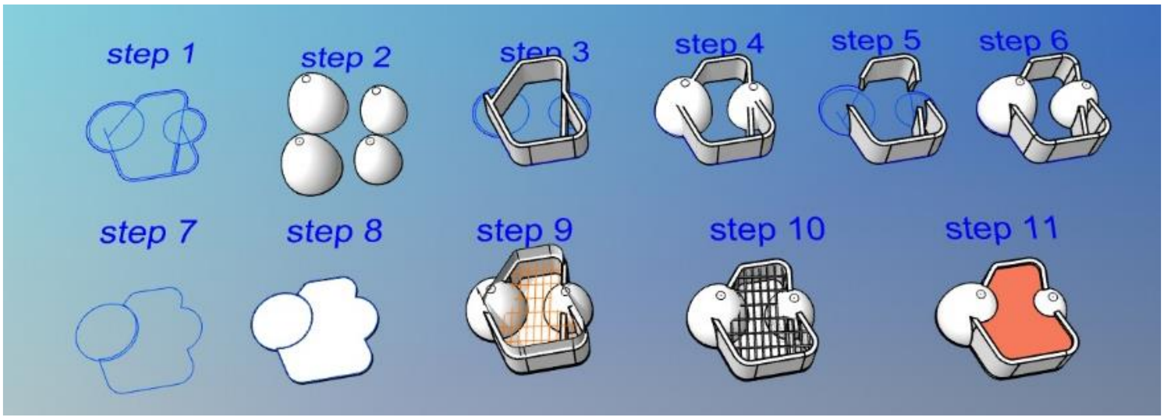

Figure 80. Steps to model "la casa Vergara”.

The simulation process led us to a final 3D model (Fig. 3) of "La casa Vergara". It was possible to generate the two domes quickly, by just changing the parameters. It was also a straightforward process to insert the domes into BIM software environment. The other walls were generated using the “earthbag wall” material, created for this purpose. In general, the results were quite similar to the existent building.

To help the comparative process, it was also made a 3Dprinted scaled model (*Figure 81*). Many authors wrote about the good impact of elaborating a physical model of the design for the evaluation process, specifically using rapid prototyping (Groat & Wang, 2013).

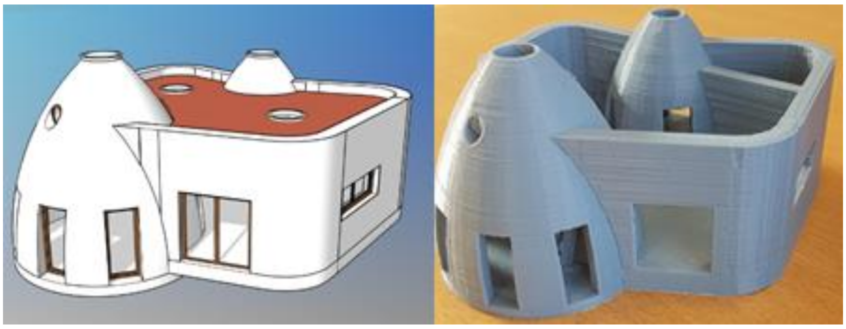

Figure 81. Final model simulation of "La casa Vergara". 3D printed model using a FDM printer with PLA filament.

Once the BIM model is done (with associated quantitative data), it was easy to make scaled models through 3D printing and use them in a normal exploratory design process.

6.5 Discussions

With the developed CICERO code and new BIM material, it is possible to design various types of earthbag projects. The proposed interface is able to design earthbag buildings resorting to hybrid construction technologies involving earthbag walls of different shapes including domes. The tool was developed with Grasshopper (visual programming language) and VisualARQ components (BIM). After creating the tool, the whole process was tested with an existing case, to check whether the design model could design the features of the real one, with satisfactory results.

Using CICERO, one can quickly generate an earthbag dome by changing some numeric inputs; CICERO constrains results to all the dome known rules pre-defined in the code. The dome models work fine in VisualARQ environment, and they can receive the openings using the standard or customized BIM library. A special attention was required to apply the doors and windows in the domes, though. As the domes were generated as “wallSolid”, it was necessary to edit all the numerical data of their cut depth. Otherwise, the software would produce holes in the wall behind.

It was possible to assemble orthogonal walls with the domes, however some more steps were needed than we were expecting. The adopted method was to generate auxiliary dome solids, in addition to the dome walls (step 2, *Figure 80*) and subtract its volume from the intersecting walls (steps 4 and 5, *Figure 80*). The wall domes were then added (step 6, *Figure 80*).

The main contribution was to add technical data regarding the construction of earthbag walls which is produced while modeling the building. This technical data is specific of earthbag construction and constitutes an extension of BIM objects and BIM technical data (*Figure 104*, page 251) .

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Chapter 7. General Discussion and Conclusion

This chapter presents the general thesis discussion and conclusions. It is divided in the following subtopics: Main conclusion; Contributions; Dissemination; Extra publication and Future works.

In the ‘Main conclusion’ topic it is presented the summary of the obtained results and the adopted methodology. In ‘Contributions’ topic the contributions are presented and related to all specific objectives of the thesis. In ‘Dissemination’ topic we present the publications and presentations that were done during the PhD studies about the thesis subjects. In ‘Extra publication’ topic additional publications made during the PhD studies but not directly related with the thesis are presented. The last topic, “future work”, presents suggestions of related works that can derive from this research.

7.1 Main conclusion

The hypothesis of this research is that *it is possible to develop a digital modelling tool in a BIM environment to help the design phase of earthbag constructions, with quick simulation capacity, while informing the necessary constructive specifications, also enabling the rapid prototyping of accurate physical scaled models.* We confirm this hypothesis by presenting CICERO, a tool set, developed observing the scientific methods of research and validation, that runs in BIM environment and it is capable to generate quick simulations of earthbag/SuperAdobe dome models, while informing simultaneously a preview of constructive specification (even before inset the documentation). It offers also the possibility to create other morphological variants of earthbag/SuperAdobe walls, and interact with other materials and libraries that already existents in BIM environment.

CICERO runs in Rhinoceros+VisualArq+Grasshopper (BIM environment integrated with parametric plug-in) and it is capable of generating parametric earthbag/SuperAdobe domes and apses as BIM Walls, by changing some input numerical variables. Automatically produces a preview sample of the model and a preview quantitative data of the materials associated to the geometric model. After the simulation process, the user can transform the preview sample model into BIM wall, compiling it with a command in grasshopper named "bake".

Simulating the preview sample of the volumetric model allows quick design decision based on the available feedback on constructive requirements. Other possible advantage is the generation of estimated quantities of construction material (see *Figure 90*, page 244), which helps to estimate the construction cost during the beginning of the design process.

When the earthbag/SuperAdobe model is decided, the next procedure is to transform it from preview model to BIM wall (using the grasshopper command named "bake"). Now, as a BIM model, it is possible to integrate de model with other morphological types as well as the domes, that can involve also other construction techniques. Working in a BIM environment, the model can also benefit from the default library making easier the process to insert doors, windows, foundations, sanitary installations, and others.

At last, the automatic generation of documentation is a BIM advantage itself. Furthermore, using the CICERO tool, it is possible to include more than BIM default documentation data (style, length, thickness, area - that was renamed as ‘surface area’ in technical tables, and volume - renamed as ‘volume of compacted earth’). They were included through programming in VPL the following outputs: layers quantities, barbed wire, bags, and surface area. With the CICERO tool, the documentation (default and additional data) can be included in the blueprints by the default VisualArq interface resorting to wallStyles. The produced BIM model can be exported and shared in a standard format (IFC), providing model interoperability.

Once the BIM model is done, it is easy to make scaled physical models through 3D printing and use them to a normal exploratory design process, to present the project to a client, and to help the constructor to understand the overall structure and building shape, minimizing possible constructive errors.

A PhD thesis must bring three main contributions to its specific body of knowledge. First, the thesis should be innovative in the science field, adding new information to its theme. Second, it should offer a positive impact within the community where the research is supposed to be applied, bringing positive contributions to the society. Third, the research should be replicable, presenting a clear methodology, well-organized structure, and clear rationale to support causal relations between experimental parts and conclusions. This thesis addresses the three above mentioned aspects.

Innovative and add new information to scientific community. This thesis provides CICERO, a new tool, for the design of earthbag architecture, hitherto nonexistent in previous search (D. M. Santos & Beirão, 2016; Deborah Macedo dos Santos & Beirão, 2019a). The thesis general objective was achieved by pursuing strategically five complementary small objectives, presented here as five related outcomes of complementary published papers, detailed and explained in next topic. Furthermore, beyond the innovative tool to aid earthbag/SuperAdobe architectural project practice, the papers production enlarged the science field itself. Even though earthbag constructions are explored and practiced in many countries, it is still poorly explored in scientific literature. Before this research has started, only 2 scientific papers (with blind review process of evaluation) were found regarding this subject, in a total universe of more than a hundred databases (D. M. Santos & Beirão, 2016).

Currently, four years later, all of these published papers already have citations. If we search in google scholar or researchgate platforms with the descriptor “SuperAdobe”, the papers presented in this thesis appears in the top 10 ranking, among other diverse publications, not necessarily just peer reviewed scientific papers. One of them with more than 900 reads.

Positive impact on society which the research is inserted. The thesis offers to architects a practical outcome to help earthbag buildingdesign. The CICERO package has two complementary downloadable files that run in VisualARQ (a BIM software). The first helps to generate earthbag domes by changing numerical variables; the second, inserts the final model’s technical earthbag documentation. Before the package, we developed an online tool for earthbag dome studies to run some validation tests with online users. It runs directly in the ShapeDiver platform - a platform where anyone can upload and share their grasshopper parametric models (Shapediver, 2020). It was decided to keep this part of CICERO available online for free (https://app.shapediver.com/m/cicero-1), for people wanting to test a quick earthbag dome design and get a quantitative description of materials, with no need to download any device.

Regarding society benefits, it is important to emphasize that the online tool has received some compliments during diverse public presentations and during the inquiry's application on the parametrical experiment with architects, designers, and earthbag experts, stating that the tool is useful and easy to deal with. This includes the comments of Kelly Hart, author of the book "Earthbag architecture" (Hart, 2015), who participated in testing phase and asked us to insert the tool in his personal website. He published together with the tool, the comment "*I tried this out and it is relatively simple to do once you figure out how the data entry works (...), there is obviously a lot of cleverness put into the project"* (http://www.naturalbuildingblog.com/earthbag-dome-building-online-calculator/).

Replicable with clear methodology. The general research methodology resorted to experimental methods of development (OECD, 2015), conducted in informatic laboratories, based on the development of tools to support earthbag architectural design.

This general experimental methodology is a merge of five methodological steps presented in different related papers. It encompassed literature review made with qualitative (Marconi & Lakatos, 2006) and quantitative (Okubo, 1997) analyses, embracing a computational thinking approach (Lee et al., 2011; Papert, 1980; Wing, 2008), and validated by inquiries based on Nielsen's heuristics (Nielsen, 1995) and by simulation through an analogue model (Groat & Wang, 2013). All of these methods were previously adopted by several other researchers. They are all published in different books, and papers which were identified and explained in this research in the introduction chapter and individually paper per paper.

Regarding the overall structure, the thesis was planned to be a compound of peer reviewed papers, each responding to one of the sub-objectives of the thesis, and altogether responding to the research questions and validating the hypothesis which in this case corresponds also to the validation of a BIM design tool for earthbag building design. A set of publications corresponding to incremental steps concluding on the sub-objectives were progressively published confirming each sub-objective and ultimately the hypothesis. Those steps were, in order: (1) to provide a classification of earthbag constructions; (2) to understand which programming language (TPL or VPL) could fit better in the thesis experiment after the thesis author acquired the programming knowledge; (3) to create a parametric tool for earthbag domes; (4) to understand how far in literature scientists have developed BIM tools for earth construction; and (5) to enhance CICERO's development to work in a BIM environment.

The six correlated published papers, organized together with a general introduction and conclusion, attends the college minimal rules required for a 'thesis by a collection of papers': "At least five scientific papers, as first author, published or accepted for publication in journals or book chapters".

The output of the experimental phase of this research is a tool that includes a new construction material (the earthbag) on BIM libraries. This tool assists the design of earthbag domes that can then be exported in an ".ifc" format, compatible with different BIM software.

The following sections present a deeper discussion on the thesis contribution and dissemination of the work, extra publications that did not enter the thesis corpus, and considerations for future work.

7.2 Contributions

This thesis achieved the initial main objective to offer an alternative design tool to systematize the design process of earthbag buildings. In order to undertake this main objective, this thesis encompasses five specific correlated research papers, all of them presenting contributions that are concomitant to the thesis specified objectives. They are specifically:

Paper 1. Meets the first specific objective: *To characterize and categorize earthbag buildings – a systematic characterization of earthbag building types*

The first paper of the research focused predominantly on organizing the earthbag buildings according to their morpho-typological variants. The data collection for this paper includes a survey for the descriptors “SuperAdobe” or “earthbag” (examined separately) in 123 scientific data bases. The fact that this survey found just two papers reveals the lack of information of this construction material in scientific bibliography. Because of that, books and specialized websites were included in the review process.

The main contribution of this paper for science is to present the overview of earthbag buildings and to propose a summary classification table based on their building shape and constructive material variants. The paper expands the scientific information on this field, that is underexplored, as demonstrated by the little amount of published papers. Indirectly, it also contributes to help the promotion of constructing with sustainable and natural materials. For the thesis, this paper helps to (1) understand the technique; and (2) with the building classification it helps to assimilate the constructive rules needed to implement into generative codes in the following steps.

Paper 2. Meets the second specific objective: *To test parametric modelling versus textual programing languages to find out which one of them could be more suitable to create* *the tool.* The second paper of this research contributes with a systematic comparison between TPL and VPL programming languages. The paper's results served to help electing the most suitable option to continue the thesis experiment.

This paper also provides a larger contribution to the architectural field. The paper shows a set of examples developed in both TPL and VPL languages, that follows the same programming logic. These examples clarify the advantages and disadvantages of visual and textual programming languages for architectures.

Paper 3. Meets the third specific objective: *To develop a parametric tool to design earthbag domes (including the generation of quantitative material descriptions)*

The third paper presents the first experimental phase of the research. As a contribution it offers a tool that works online (www.cicero.earth), using parametric manipulation, generating automatically the volumetric model, and the set of material quantities for the construction of earthbag domes. The tool was developed and validated with inquiries and it was well ranked by the peers during the validation.

Paper 4. Meets the fourth specific objective: *To identify previous research regarding the use of BIM for designing with earth construction techniques*

This paper proves that scientific data on combining earthbag construction and BIM is scarce, evidencing the innovative character of the tools proposed in this thesis. There are no publications relating the use of earth construction and BIM, in the architectural category, on WoS database. In other categories, the findings were excluded because the given descriptors had a different meaning than desired.

The terms "BIM" and "sustainability" were used in the search, and presented some results. However, when the descriptors are not combined, the results reveal that the interest in those subjects have been increasing during the years individually, evidencing the fields relevance to diverse scientific communities.

The paper also evidences the multidisciplinarity of the research field. In descending order, the main fields of research that present scientific works with the earthbag construction theme are construction building technology, civil engineering, green sustainable science technology, environmental sciences, energy fuels, and architecture. This evidences the multidisciplinary of the research field.

The paper also identifies the main authors, journals and conferences in the field of BIM and earth construction increasing the interest in their research and to the research field itsellf. The three main authors are respectively: Jungdae Park; Chiabranto *et al;* and Karen Kensek. The two main journals are: Journal of green building; and Architectural Design (*Figure 70*, p. 161) . The two main conferences are: the Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA), and the International Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe) (*Figure 71*, p.162)

Those specific findings contribute to evidence the innovative approach of the thesis, presenting a general classification of the main topics and fields related to scientific research on eathbag construction.

Paper 5. Meets the fifth specific objective: *To connect the parametric tool to design earthbag domes in a BIM environment inserting the expected BIM functionalities such as parametric constructive data.*

This paper presents the second phase of the PhD research. This phase encompasses the addition of data regarding earthbag material in BIM environment, together with the compatibilization between the BIM environment and the prototype tool.

CICERO tool allows the design of different types of earthbag buildings that runs in a BIM, parametric environment (Rhinoceros, Grasshopper, and VisualARQ). The tool generates a typical BIM model with both a 3D model with design specifications and the technical specifications on earthbag material.

Two advantages of the compatibilization between the prototype tool and the BIM environment are: 1) the possibility to include standard materials and libraries from the BIM environment in the earthbag building models and 2) the possibility to export the model in IFC format, a standard BIM format.

7.3 Dissemination

This thesis is a compilation of published (or accepted to publish) papers. The work presented here is already disseminated through scientific vehicles such as journals, book chapters, conference proceedings, and scientific meetings. Some of these published papers are already cited by other researchers.

Part of the work is mentioned in the natural building blog (http://www.naturalbuildingblog.com/earthbag-dome-building-online-calculator/). This blog is an important platform managed by Kelly Hart, an expert in earthbag subjects with books published in this field.

During the Ph.D. progress, the research received positive feedback when presented in scientific meetings with specialized audience, such as DCG lectures (Design and Computation Group), ADA lectures (Algorithmic Design for Architecture), ENIA (*Encontro Nacional dos Investigadores de Arquitetura,* Architecture Researchers National Meeting - Portugal), SIGraDi (*Sociedad Iberoamericana de Gráfica Digital* – Ibero-American Society of Digital Graphics), and others.

CICERO tool is now partially available online for general public with a parametric online tool for domes (www.cicero.earth), and after the thesis approval, the complete tool, that runs in BIM environment, will be entirely available for free download.

7.4 Extra publications

During the Ph.D. required courses, the students have the opportunity to discuss different subjects. Therefore, it is common the production of scientific work not related directly with the thesis subject. In the following paragraphs, it is presented published papers, developed during Ph.D. time of studies, exploring other research problems.

The first extra papers are about accessibility subject. The first one was published in the ENEAC proceedings (Encontro Nacional de Ergonomia do Ambiente Construído, National Meeting of the Built Environment Ergonomics - Brazil) and after that, was invited to compose a chapter in the book: *Ergonomia e Acessibilidade* (Ergonomics and Accessibility).

Santos, D. M., Pontes, T. B. & Landim, C. B. P. (2018). O Cego e a cidade (The blind and the city). In: *VII Encontro Nacional de Ergonomia do Ambiente Construído / VIII Seminário Brasileiro de Acessibilidade Integral*, 2018, Fortaleza. Blucher Design Proceedings. São Paulo: Editora Blucher, p. 489. ISSN 2318-6968; doi 10.5151/eneac2018-038

Santos, D. M., Pontes, T. B. & Landim, C. B. P. (2019). O cego e a arquitetura da cidade (The blind and the architecture of the city). In: Anna Paula Lombardi. (Org.). *Ergonomia e Acessibilidade*. 1ed. Ponta Grossa: Antonella Carvalho de Oliveira, v.1, p. 33-44. ISBN: 978-85-7247-147-3; doi 10.22533/at.ed.473191902

While taking the textual programming course in college, there was also the opportunity to collaborate in a paper called *‘a programação de computadores para alunos de arquitectura: uma análise do uso da linguagem racket para protótipos 3D’* (Computer programming for architecture students: an analysis of racket language for 3D prototypes), published in the proceedings from the international conference TIC EDUCA 2016. After that, it was selected as one of the best conference papers and invited for publication as a book chapter of the book ‘Digital Technologies and Future School’.

Pontes, T. B., Miranda, G. L. & Santos, D. M. (2016). A programação de computadores para alunos de arquitectura: uma análise do uso da linguagem Racket para protótipos 3D (Computer programming to architecture students: An analysis of the use of Racket language for 3D prototypes). In: *IV Congresso Internacional das TIC na Educação*.

Pontes, T. B., Miranda, G. L., & Santos, D. M. dos. (2016). A programação de computadores para alunos de arquitectura: uma análise do uso da linguagem Racket para protótipos 3D (Computer programming to architecture students: An analysis of the use of Racket language for 3D prototypes). In: Neuza Pedro, Ana Pedro, João Filipe Matos, João Piedade, Magna Fonte. (Org). *Digital Technologies & Future School*, 2016, 197–208. ISBN 978-989-8753-36-6. Retrieved from https://cld.pt/dl/download/e7500488-3c2a-4d99-9de0-ade4c5cc9aba/Livro_Artigos.pdf

In addition, while coursing PhD, I had the opportunity to write a paper about previous teaching experience. This paper was published in the SIGraDi 2018 proceedings.

Santos, D. M. (2018). 3D modeling in the design course context: A didactic experience. In: *XXII Congresso internacional da sociedade iberoamericana de gráfica digital*. São Carlos. Blucher Design Proceedings. São Paulo: Editora Blucher, p. 711-716. ISSN: 2318-6968; doi 10.5151/sigradi2018-1455

Finally, this last extra paper is about an innovative design of luminaries produced reusing disposal plastic brackets. This subject was developed at first supervising Ana Paula Trindade in her bachelor final project thesis, at Federal University of Cariri. Later on, the bachelor's thesis was further developed and formatted in a scientific paper and the outcoming was accepted for publication in 2019.

Trindade, A. P. Santos, D. M. (Forthcoming). Uma solução contra o descarte de cantoneiras plásticas com base no design de produtos (A solution for the disposal of plastic brakets based on the product design). In: *Ciência e Sustentabilidade.* ISSN: 2447-4606; doi 10.33809/2447-4606.51201972-89.

This Ph.D. is therefore finished with eleven published papers evaluated by different scientific committees with blind review process, produced during the research period. Four in scientific journals, three as books chapters and four in conference proceedings.

7.5 Future work

Constructive technologies with earthbag is an underexplored scientific field, with few publications available. This section presents a list of alternatives for further research that could be carried in this thesis' research field. It is important to mention that most of these future work proposals, were suggestions received during inquiries, experiments or presentations in conferences, and scientific meetings.

CICERO Tools package. We intend to share in online communities, the CICERO developed tools, as a package, with their respective tutorials.

To include analysis software within the 3D modelling software to perform structural analysis and environmental analysis. The investigation hypothesis here is: The generated models could offer structural and environmental analysis if integrated with analysis tools.

*To develop a downloadable app.*Typically a small, specialized program downloaded onto mobile devices to make quick simulations outside the office, and also to help the architects that still produce work by hand to generate quick dome 3D models. This suggestion was given by an expert in earthbag buildings during the mentioned surveys, 'to transform the parametrical tool into a downloadable app'.

To further validate the tool, constructing an actual building. Some rules adopted in this research were based on theoretical studies. It would be pertinent to test the tool constructing a real new earthbag building, to compare the actual building with the project, checking for example: Physical limitations beyond pre-established studies; Possible deformities of the building that can variate the final height.

To further develop the tool, constructing a grasshopper component. Once CICERO tool is working and all the logic behind is already determined, the tool can be improved to facilitate the user experience. With a collaborative interdisciplinary team of programmers and architects, it is possible to develop a pair of grasshopper components with the functions presented in this thesis.

To further validate the tool, designing buildings with different uses. Test limits of the tool with different necessities programs, like hotels, mixed uses buildings, villages, schools, etc.

Post-occupancy studies. This kind of evaluation can offer whether the user satisfaction with the final product (earthbag building), and sustainability achieved variables, like energy consumption for example.

Legal issues. As presented in the first paper, there are few countries that include earth as a construction material in their building codes. It would be useful to establish a qualitative standard of this material to guarantee its quality control and to help its inclusion in other building codes around the world.

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Appendix 1: Paper published in SIGraDi proceedings

Paper published in 2017, in SIGraDi conference proceedings[8]. One of the most important conferences in the field of design and computation. Indexed by Cumincad (Cumulative Index about publications in Computer Aided Architectural Design). After that, it was selected as one of the best papers of conference and invited for a special issue (See chapter 4).

After-acquired programming knowledge. The first experimental part of the thesis could begin. This paper presents the SuperAdobe dome constructive and geometrical logic, and further, the development of a parametric tool to design domes.

[8] Santos, D. M. dos, & Beirão, J. N. (2017). Generative tool to support architectural design decision of earthbag building domes. Pp. 538-543. São Paulo, Brasil: Blucher. ISSN: 1981-1543; doi 10.5151/sigradi2017-083

Generative tool to support architectural design decision of earthbag building domes

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Abstract

The interest in earthbag dome construction (also known as sandbag, SuperAdobe, or superblock construction) is increasing as a world consciousness develops to achieve the planet's equilibrium for sustainable living. The main objective of this research is to develop a parametric tool to help architects modeling virtual earthbag domes from ideation to construction phase. This challenge has been addressed by adopting an experimental methodology that explores parametric generative design with the use of visual programming language (VPL). In this paper we present the development of a tool for the ideation level including features that allow for the calculation of material quantification. The usability of the tool was validated by earthbag constructors and architects.

Keywords: Visual programming language; Earthbag building; SuperAdobe; Sustainable architecture; Generative design.

Introduction

This research aims to facilitate the virtual modeling of earthbag domes by architects. It is a part of a PhD study that previously classified the constructive variation on the application of earthbag techniques (Santos & Beirão, 2016). It is also an indirect way to encourage the adoption of ecological materials used in ancient construction techniques into our current construction practices.

In face of the finitude of natural resources and accelerated environmental degradation, it is pertinent to associate the use of new technologies with the development of these kind of projects because they cause less damage to the environment.

Earthbag is also known as SuperAdobe, sandbag or superblock. It is the construction technique where the walls are built out of stacked bags filled with earth, with barbed wire layered between them (Hart, 2015; Hunter & Kiffmeyer, 2004; Minke, 2009). These constructions are durable, strong, climatically efficient, and formally flexible (Hunter & Kiffmeyer, 2004). They are composed with renewable and reusable resources, hence promoting sustainable development (Barnes, Kang, & Cao, 2006).

Although earth construction is a low environmental impact recognized solution, the existing software tools are still limiting factors in this specific type of project. Considering this, we formulated the hypothesis that the virtual modeling of the domes could be aided by a parametric tool specially developed for the purpose. “CICERO” (Creative Interface for Constructing Earthbag Resource Objects) is a parametric generative dome design tool developed with the use of a visual programming language (VPL) that generates earthbag designs taking in consideration the technology’s geometric limitations hence guiding the designers towards consistent solutions.

Methods

The research adopted an experimental methodology exploring the advantages of parametric generative design with the use of visual programming language (VPL systems). The VPL code was developed by resorting to a Computer aided design (CAD) software that most of architects already use, to generate designs of earthbag domes in a known environment, faster and more effortlessly.

The methodological procedures were:

- Collecting from existing literature an extensive set of earthbag building technical characteristics.
- Identification of the main parameters for the generation of earthbag domes.
- Development of a parametric model able to generate the earthbag dome and associations.
- Create a web-based platform to implement tests online.
- Submit the tool to architects with experience in earthbag construction to experiment the tool and answer an inquiry, to validate the tool.
- Evaluate the survey and their results.

Data collection

To develop the VPL code for the earthbag dome construction, two general steps were necessary in the first place.

Firstly, a data collection overview to identify the technical rules was done identifying constructive constraints and general characteristics of earthbag domes.

Secondly, we devised a way to insert all technical variables into the code parameters. The goal was to provide a tool where the user could provide inputs and receive an interactive response from the model. The identified inputs refer to: Bag size, curvature arch, radius of the dome, quantity of smaller domes to assemble around the first one, distance of the smaller dome to the center, the angle to locate the small domes, and finally their radius.

Inputs

The tool inputs are inserted resorting to number slider interfaces. These sliders were predefined, constrained to specific limitations that resulted from the overview of structural constraints of the constructive technique.

Bags

The purpose of the bag is to retain the earth during the process. Polypropylene bags are more recurrently used, however other kinds of material can be seen, like burlap. Polypropylene is the cheaper alternative, reciclabe, and is not as environmentally toxic as the polyvinyl chloride (PVC) (Wojciechowska, 2001)

The wall width is the variable with greatest influence on structural safety (Canadell, Blanco, & Cavalaro, 2016), then the bags chosen must be bigger than 12 inches (30,48cm) (Hunter & Kiffmeyer, 2004). Khalili suggests a roll of 14 to 16 inches (35,56 to 40,64cm) wide SuperAdobe tubing (Khalili, 2008). After an overview about bag sizes available to purchase, there were extracted the sizes that match with those structural constraints: 40, 50, and 60 centimeters wide bags after compaction.

Radius

For a self-supporting single dome, the ideal interior diameter suggested by Khalili is: 2,5 to 3,5 meters (Khalili, 2008). However, new studies simulated a diameter of 6,0 meters (Canadell et al., 2016; Hunter & Kiffmeyer, 2004).

Arch curvature

The earthbag dome is a solid revolution of a catenary arch and works with the force of the gravity, rather than against it (Khalili, 1986). The dome section was studied observing a hanging chain under tension, once it is reversed is under maximum compression (Khalili, 2008; Wojciechowska, 2001).

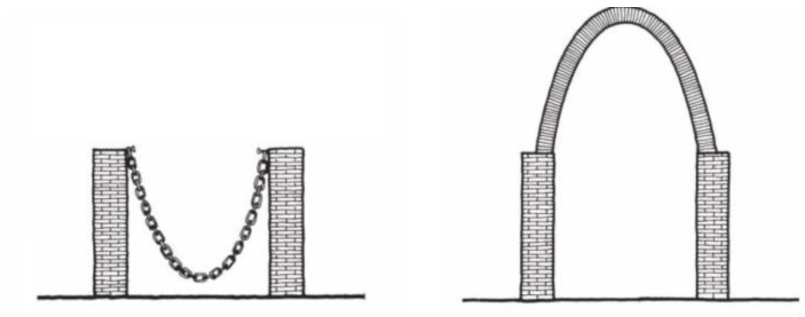


Figure 82. A hanging chain in tension is reversed to become a catenary arch

Source: Khalili, 2008.

There were studied two kinds of arches already validated by theoretical studies as a better structural design for earthbag domes: the pointed arch and the variable arch (Canadell et al., 2016). The variable arch is more steep adding extra stability to the structure (Hunter & Kiffmeyer, 2004).

During the construction, it is required two cords as a compass to define the geometry, the center compass to adjust each layer and the height compass to design the arch curvature (*Figure 83*).

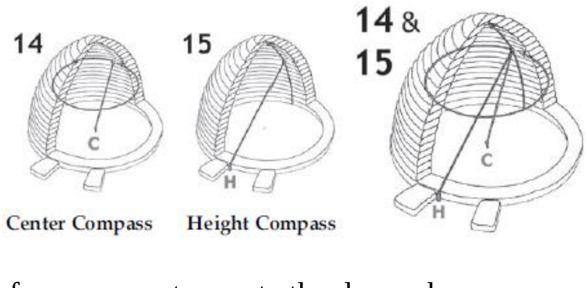


Figure 83. Association of compasses to create the dome shape.

Source: Khalili, 2008.

For the pointed arch, the compass must be stacked touching the entrance door covering a cord equivalent to the diameter. For the variable arch, according to literature, the distance (d') to stack the cord to the dome entrance can be increased up to 1,50m (Canadell et al., 2016).

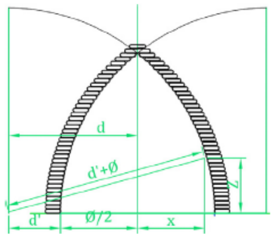
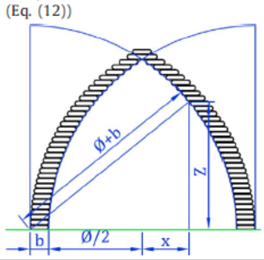
	Variable arch	Pointed arch
Equation	$x = \sqrt{(\frac{\varnothing}{2}+d)^2 - z^2} - d$ (Eq. (11))	$x = \sqrt{(\varnothing+b)^2 - z^2} - (\frac{\varnothing}{2}+b)$ (Eq. (12))
Cross section		

Figure 84. Fig. 3. Kind of dome designs and their equations for possible arch curvature in height.

Source: Canadell et al., 2016.

Based on the arch's curvature equations (*Figure 83*), it is possible to find the dome height and design the dome section.

Apses (clustering)

To achieve a bigger area, it is recommended to build several interconnected domes than a bigger one (Hunter & Kiffmeyer, 2004).

It is also a good structural strategy, building additional semi-domes (apses), assembled around a big central one acting as buttresses, like in the historical Byzantine constructions (Cowan, 1977).

These associations are built by interlocking bags and overlapping alternate rows. The apses will work as a buttress, for the larger dome adding stability to the overall design (Cowan, 1977; Khalili, 1986). Together they will counterbalance each other endlessly and permanently.

It is recommended to insert at least one third of the apses projection inside the cluster to work as a buttress.

Table VI

Summary Inputs Board.

Variables	Numerical values	Unit
Bag Size (compacted)	0.4 - 0.5 - 0.6	Meters
Curvature Arch	1 to 1.5	Meters
Dome Radius	0.75 to 5.00	Meters
Quantity of apses	0 to 5	Integers
Radius of apses	0.75 to 5.00	Meters
Distance (apses to center)	≥ 0	Meters
Angle location (apses)	0 to 360	Degrees
Rotate apses	0 to 360	Degrees

Outputs

Building height

If the radius is known, the height of the building can be extracted by resorting to basic trigonometry, with rectangle triangle proportions. (*Figure 85*) Then the height is given by the equation height= $\sqrt[2]{(bag + 2*radius)^2 - (bag + radius)^2}$.

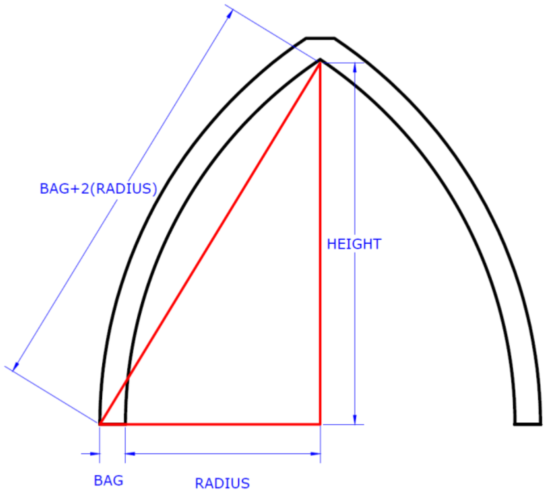


Figure 85. Diagram of equation to find building height.

Volume of earth

The volume of earth consumed in the construction was extracted from the 3D model. However, it is necessary to calculate two variables: the relation between the compacted and uncompacted soil and the composition plus percentage of soil mixture. As the conditions can change according to each site, the final user has to do this calculus.

The volume extracted from the model regards the compacted mixture when the soil particles are pressed together. Thought, for calculating the amount needed in the construction process it is necessary to calculate the uncompact mixture quantity when the soil is loose and mixed with air and water between soil particles.

The trivial praxis in quantification engineering calculus is to add 40% to discover the uncompact soil volume.

As bags contain soil, any soil type can be used, except highly organic soil, increasing the chance to use on-site material (Calkins, 2009). However, the ideal mix for earthbag construction is approximately 30% of clayed soil and 70% sandy soil (Calkins, 2009; Geiger, 2011; Hart, 2015; Hunter & Kiffmeyer, 2004). Most of the world's oldest remaining earth constructions were built with this soil mix ratio. Sometimes it is not possible to achieve the ideal ratio depending on the site soil; in such a case the builder needs to insert different proportions of natural hydraulic lime.

Layers

After the tamping process, the layers lose height up to 12 cm (Geiger, 2011). After the conclusion of higher layers, the underlying rows can flatten down also. They can variate a little between themselves.

For empirical studies, it was defined that, considering representations necessities, the height of each earthbag layer must represent by the rate of ten centimeters (Hunter & Kiffmeyer, 2004). Then, to identify the number of layers the equation is given by dividing the total height by 0,10 meters.

Barbed wire

Two threads of 4-point barbed wire are applied between the layers along the entire length of the wall, to increase bag to bag friction and overall stability (Geiger, 2011; Hart, 2015; Hunter & Kiffmeyer, 2004; Wojciechowska, 2001). The wire, combined with the woven polypropylene fabric, adds a high tensile strength to the structure.

Surface area

Knowing the total external surface is important to calculate the quantities of coating material to protect the structure. The materials can vary according to each project. However, it is often used chicken wire to wrap the entire dome surface providing adherent surface for materials like stucco, earthen plaster, or cement plaster (Hunter & Kiffmeyer, 2004).

Results

The code structure provides a generative design interface, based on changing the input variables, bounded by the known structural constraints, and generate a volumetric model together with the necessary constructive information outputs, namely those informing material quantities which enable the calculation of construction costs.

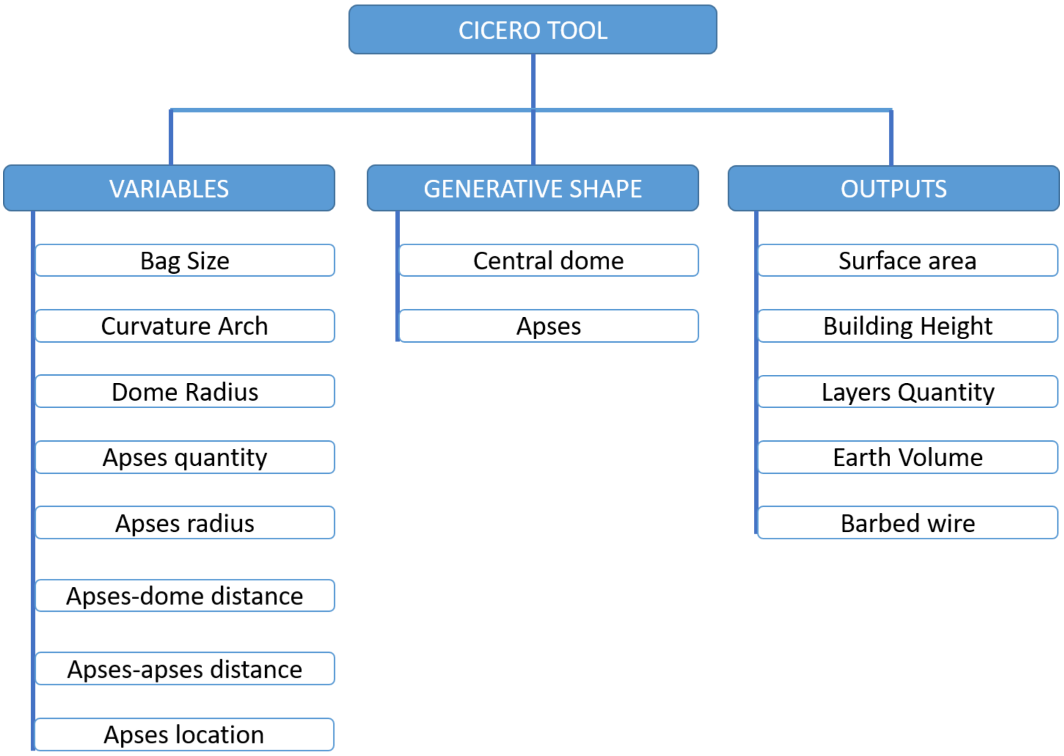


Figure 86. Generic code diagram.

CICERO tool was designed after some preliminary code prototypes based on a systematic literature review process and several trial implementations until an idealized usability was eventually achieved. There is a rectangle box interface on the right side providing the variables, or the inputs to be changed per each project by the user. On the left side there is the generated 3D model providing the constructive information as outputs. They are given in real time to help decision making while the creative process is under development (*Figure 87*).

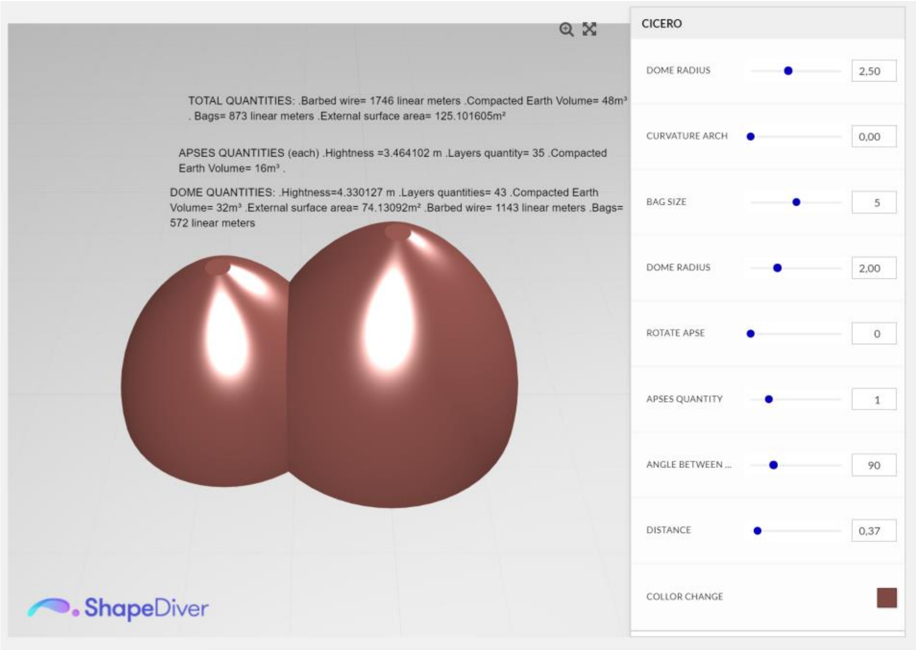


Figure 87. Cicero tool.

Validation

Later on, an evaluation was made with online users, using ShapeDiver platform to host the tool (*Figure 87*). In this way, the users did not need to download anything, and they could do the entire procedure online.

The tool was embedded in a website (www.cicero.earth) with a video-tutorial and an inquiry to answer after its use. The inquiry was available in English and Portuguese and was divided into three larger categories: user characterization, user interaction, and subjective suggestions for improvements.

The website was disclosed aiming at experts in earthbag construction and planning for validating the technical data, the tool usage, and establish a general profile of the target audience for the final tool.

It was also necessary to collect data from lay people (not just from experts) to evaluate the tool user experience.

User Characterization

There were sixteen people, with different nationalities, recruited for the research sample. The age variations were: 44% between 26 to 35 years, 37% between 36 to 45 years, 6% between 46 to 55 years, and 13% over 66 years old.

Five of them were specialists with planning, had constructive experience in earthbag buildings and still work in this field. One works in Europe, two in Brazil, and two in the United States. One with less than five years of experience, Two with five to seven years, and two more than ten years. Two usually plan by hand, and three use CAD software. When it was asked how much time they usually need to design a virtual volumetric model, most of them answered differently: two never did, one needs minutes, one needs hours and one needs days.

There was one retired in the sample, all the other persons were architects, designers or professors in these fields. Two of them did not know about earthbag construction before this research, the others learned it in University, books, workshops, websites, video programs and manuals.

User interaction

There were three exercises to evaluate the tool performance for time and comprehension of the tool, and ten objective questions and based on the 10 Nielsen's heuristics (Nielsen, 1995).

The exercises were designed to recreate three different known volumetric dome models, extracted from literature (*Figure 88*). It was given technical images and respective information to feed the tool. After finishing the experiment, they were requested to sign how much time they took to design the virtual model.

The exercises were given in an ascendant difficulty scale, where they needed to change more variables and to generate more complex domes clusters. Eighty eight percent did the exercises in less than ten minutes using CICERO. Only two people took more time to do them. The first because he was doing other things during the exercise, the second was a Brazilian and said that he had difficulties to understand the parameters in English and had to check their translation first.

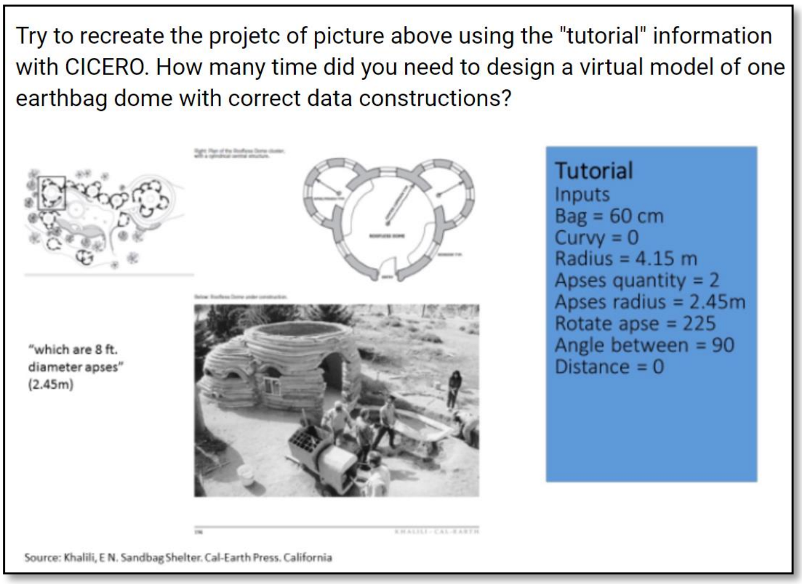


Figure 88. Example of the exercise given to validate the tool.

The heuristics questions are unformal guidelines to evaluate the user interaction. They regard: visibility of system status, match between system and real world, user control and freedom, consistency and standards, error prevention, recognition rather than recall, flexibility and efficiency of use, aesthetic and minimalist design, users' help, and documentation.

All fourteen people answered this part. All heuristics parameters were well ranked in evaluation (more than 85%). The only parameter that took less was about the help documentation, where just 69% said it was enough for their CICERO understanding.

Suggestions

The last comments and suggestions given by the participants were: insert in Cicero additional data regarding buttressing (besides the included apses), openings, and safety factors; improve the explanation on the parameters with auxiliary documentation; insert the measurement units in the parameters; and translate the tool to other languages.

Conclusion

The results of the validation process confirmed the hypothesis that the use of a parametric modeling tool could improve and aid the design of earthbag domes providing new useful tools. The user can create complex models, with one or more domes associated by just changing a few numeric variables, receiving the construction specification outputs, in a short period, with high efficiency. As a practical contribution, this tool is expected to help architects to design earthbag building domes, in an easier and faster way while generating automatically the necessary documentation for construction. Additionally, the generated model provides also 3D models that can be used together with digital fabrication tools to fabricate models that are otherwise difficult to make. We also expect that the use of this tool may increase the promotion of this form of sustainable building. Future work includes improving the tool by embedding it in a BIM environment.

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Wojciechowska, P. (2001). Building with earth: a guide to flexible-form earthbag construction.

Appendix 2: CICERO additional Images

This appendix presents additional information regarding CICERO tool. Namely, screenshots of CICERO working in a BIM environment.

The goal of this appendix is to present images of the user interaction simulation, showing the tool capacities.

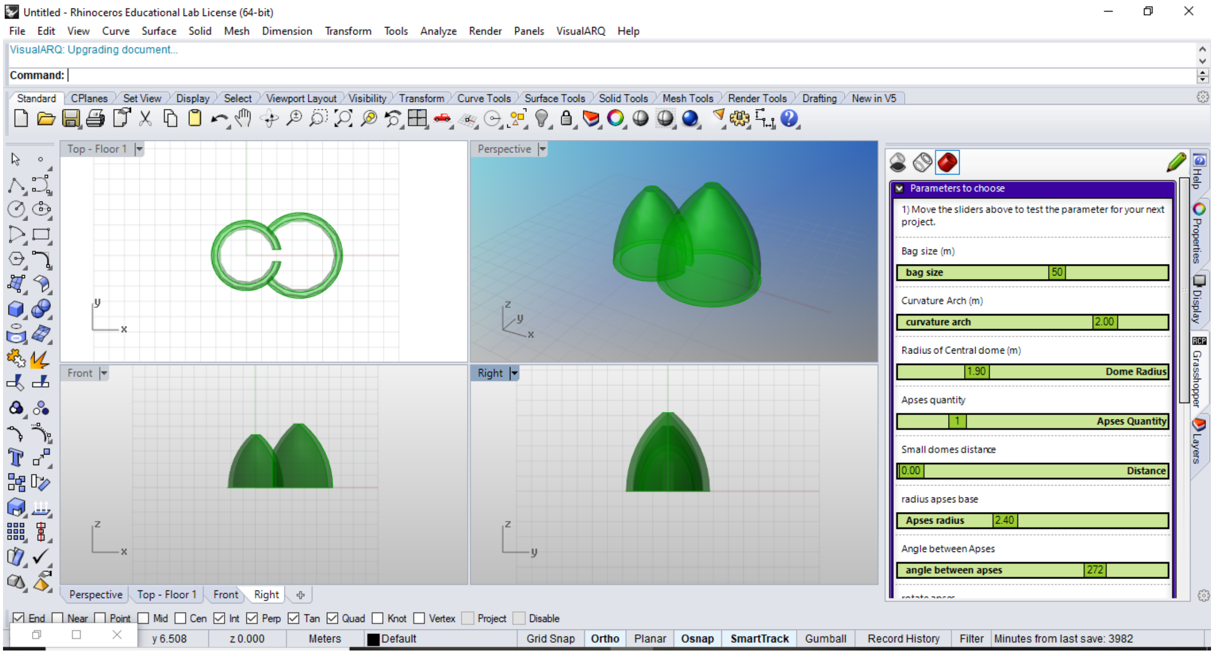


Figure 89. CICERO file 1. On the left presents the model preview, on the right the variables to change.

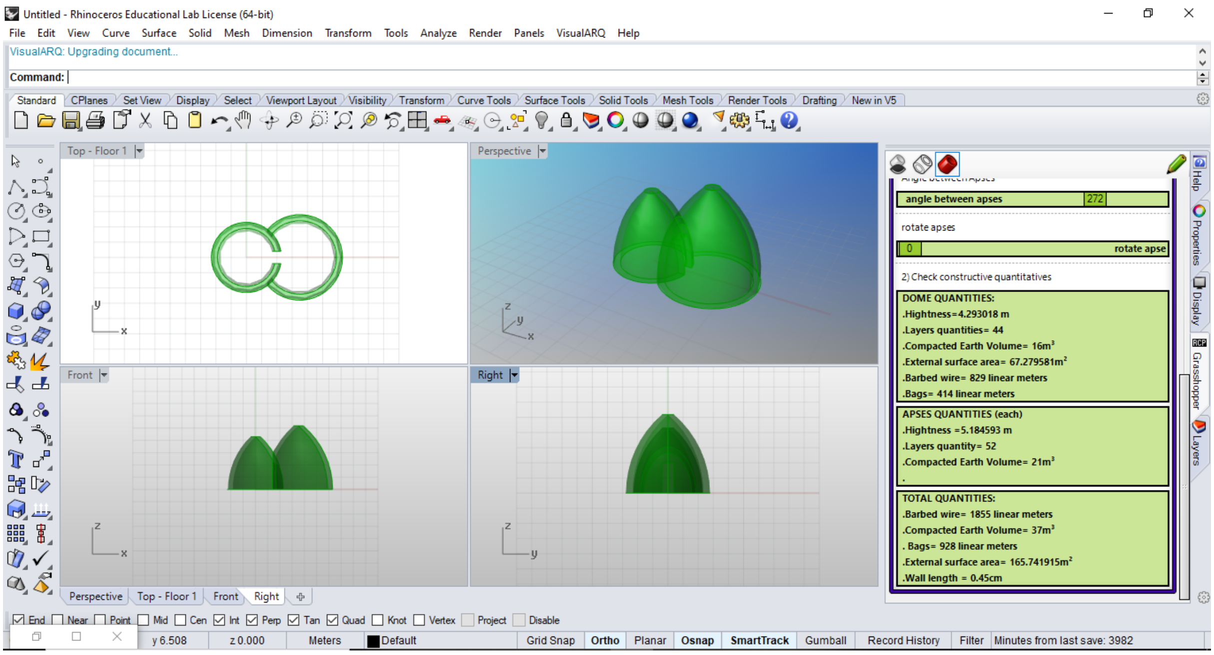


Figure 90. CICERO file 1. On the left presents the model preview, on the right the variables to change and the preview of quantitative data.

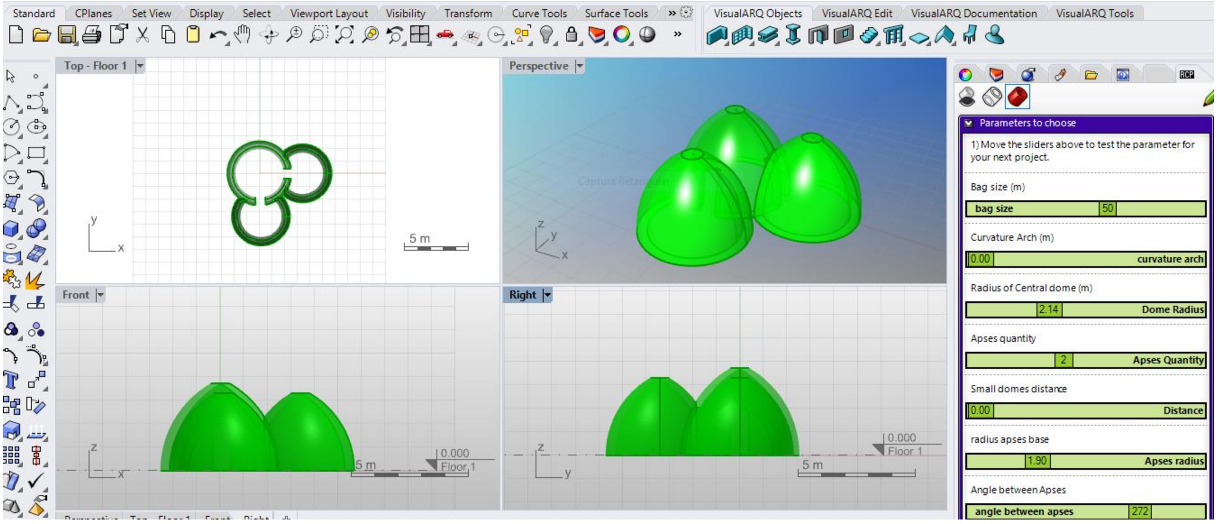


Figure 91. CICERO file 1 On the left presents other variation of the model preview, on the right the variables to changed and the preview of quantitative.

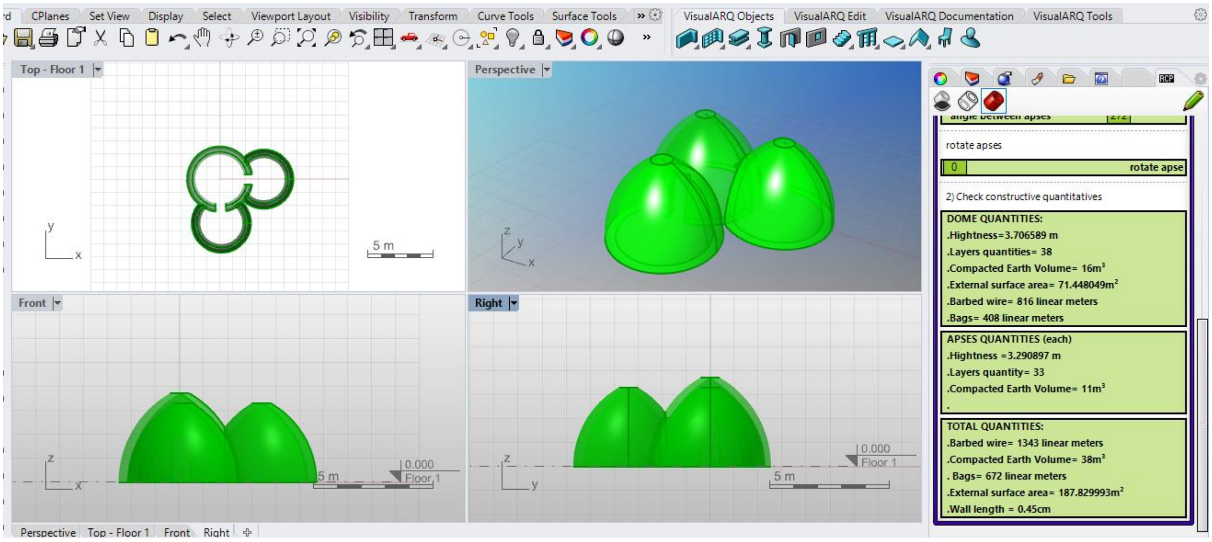


Figure 92. CICERO file 1. On the left presents other variation of the model preview, on the right the variables to changed and the preview of quantitative.

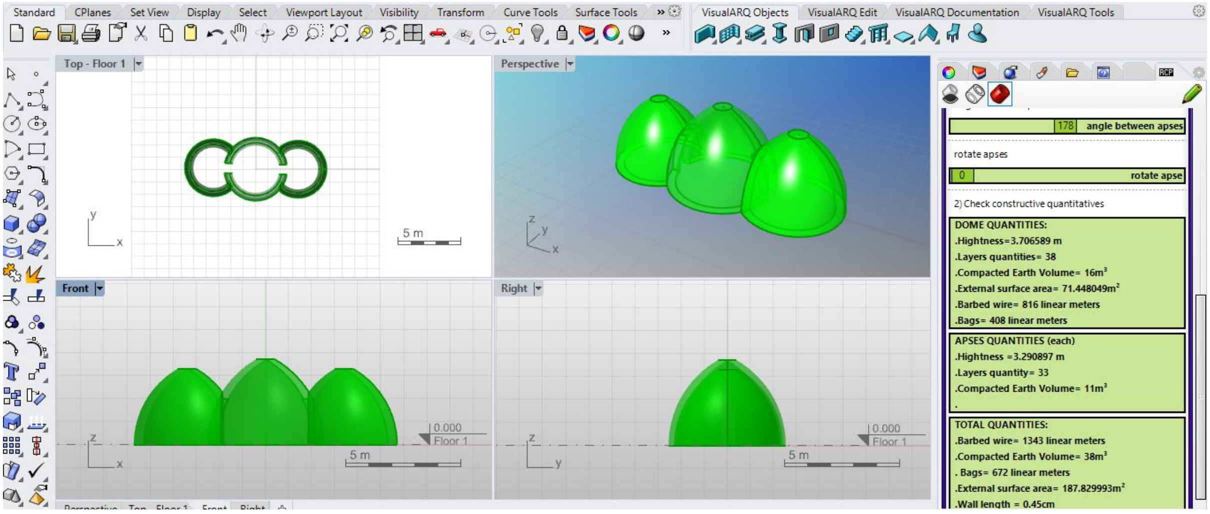


Figure 93. CICERO file 1. On the left presents other variation of the model preview, on the right the variables to changed and the preview of quantitative.

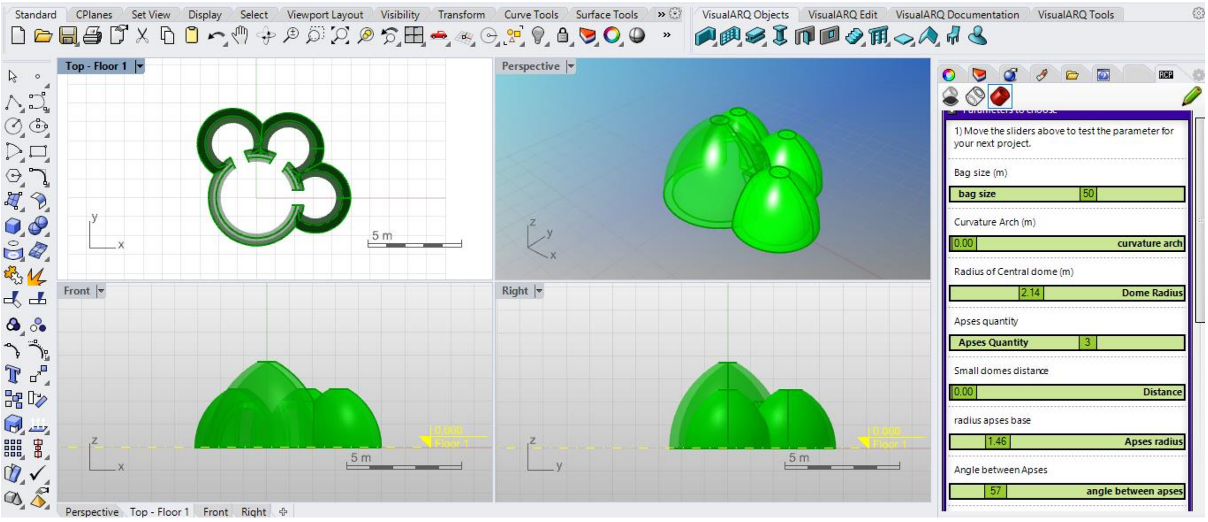


Figure 94. CICERO file 1. On the left presents other variation of the model preview, on the right the variables to changed and the preview of quantitative.

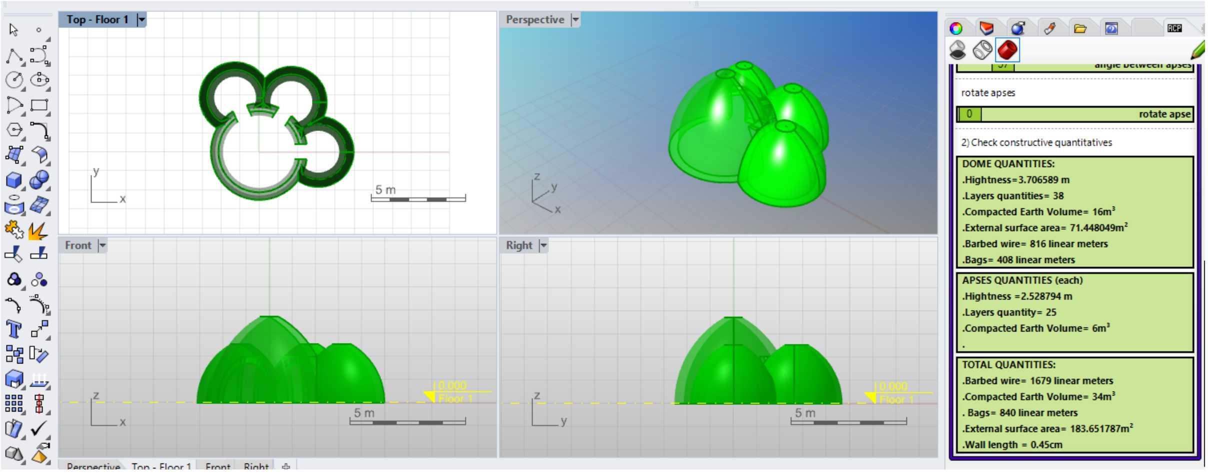


Figure 95. CICERO file 1. On the left presents other variation of the model preview, on the right the variables to changed and the preview of quantitative.

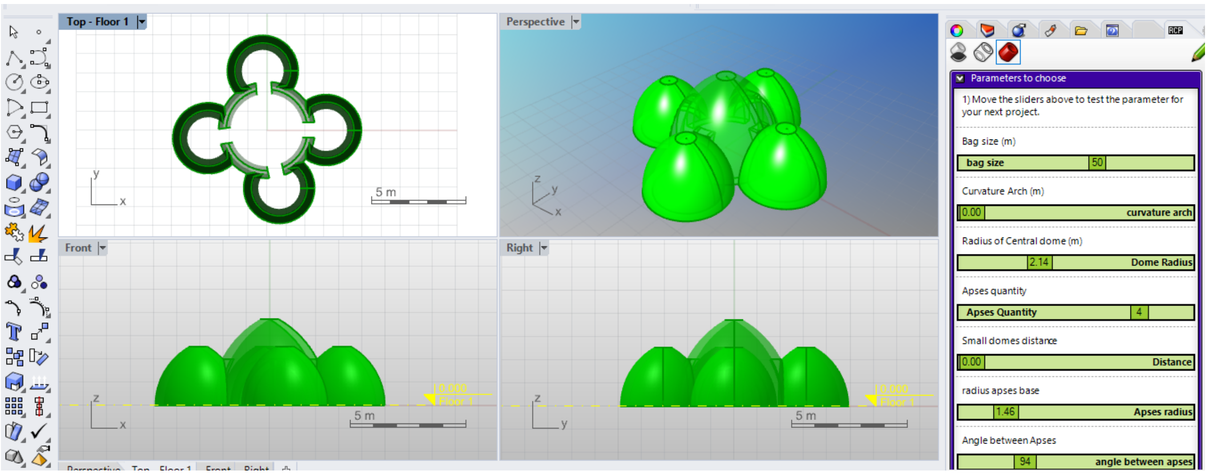


Figure 96. CICERO file 1. On the left presents other variation of the model preview, on the right the variables to changed and the preview of quantitative.

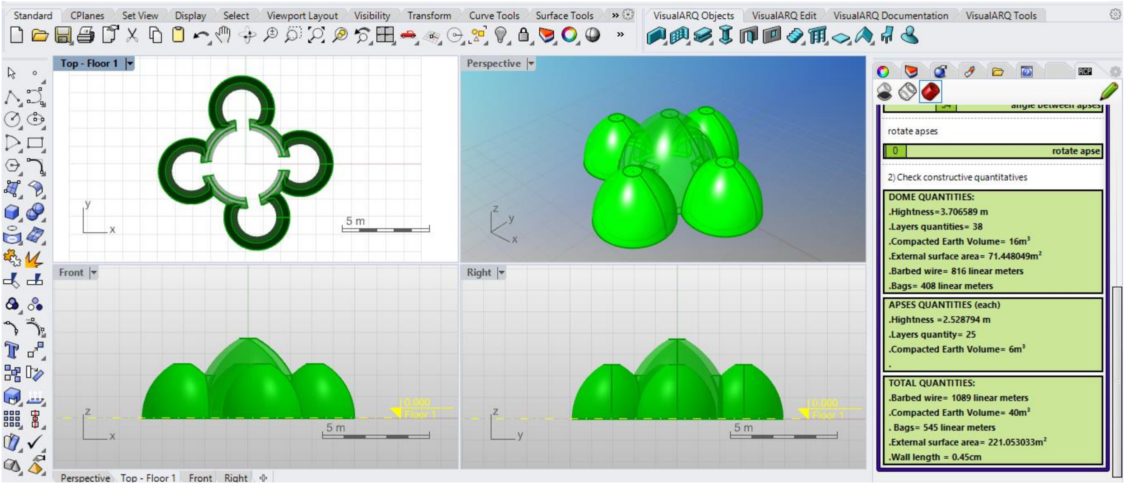


Figure 97. CICERO file 1. On the left presents other variation of the model preview, on the right the variables to changed and the preview of quantitative.

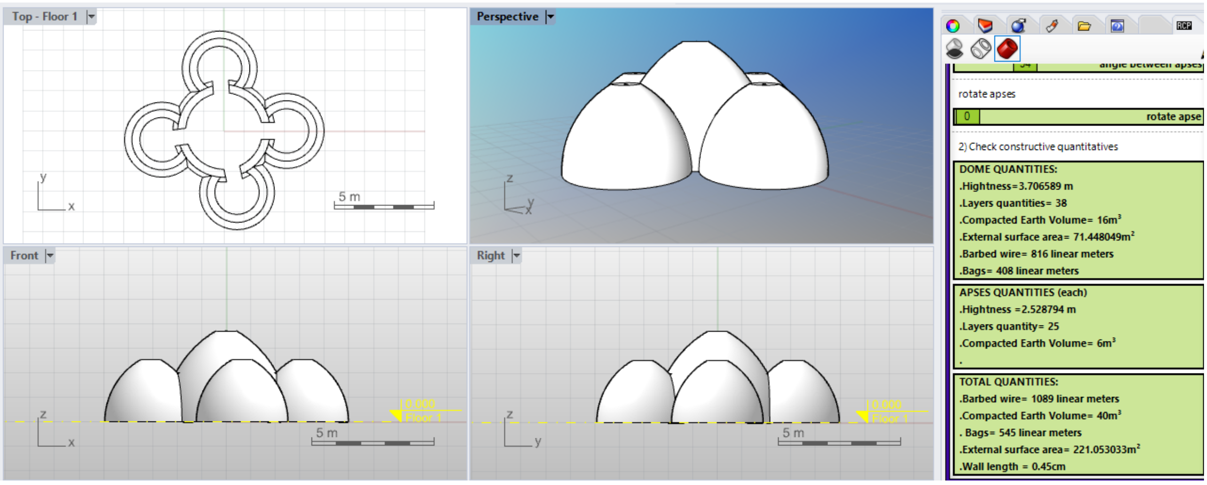


Figure 98. Example of visualization of a BIM earthbag/SuperAdobe dome cluster wall

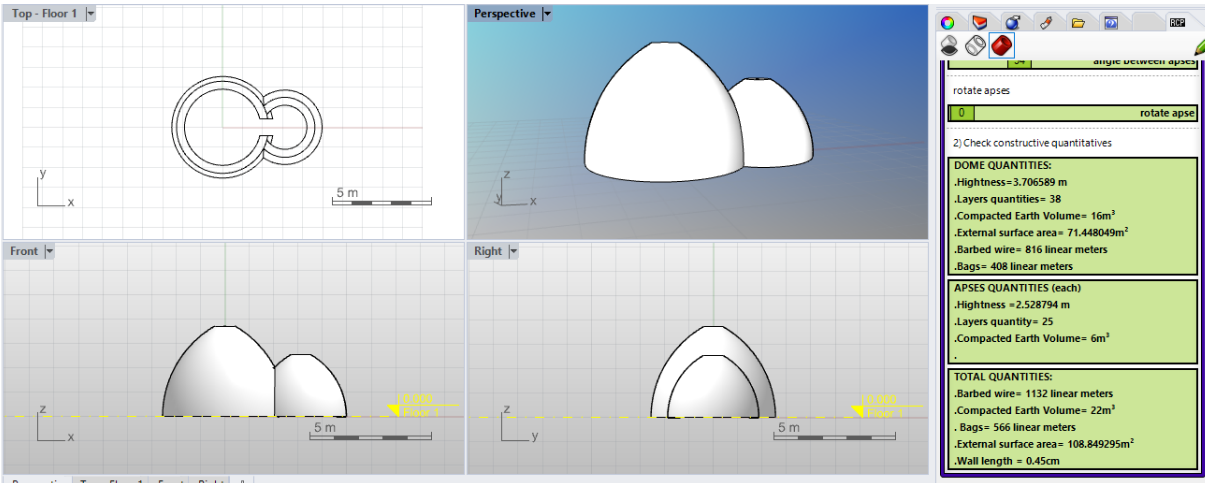


Figure 99 . Example of a BIM earthbag/SuperAdobe dome cluster wall, after compilation (bake command in grasshopper0

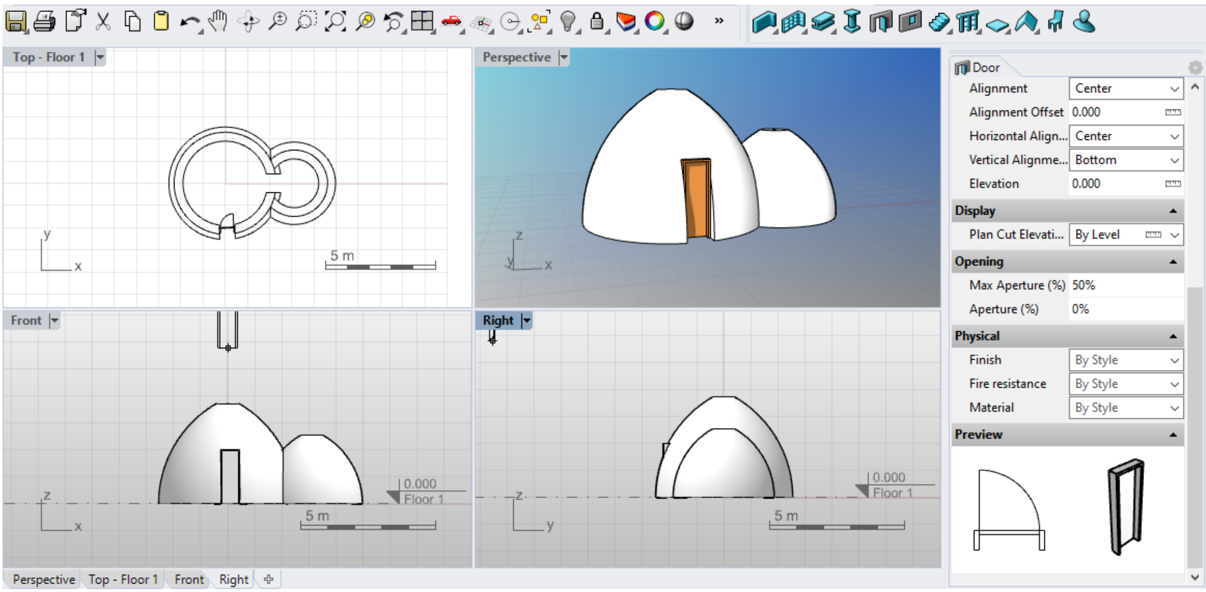


Figure 100. Inserting BIM standard door.

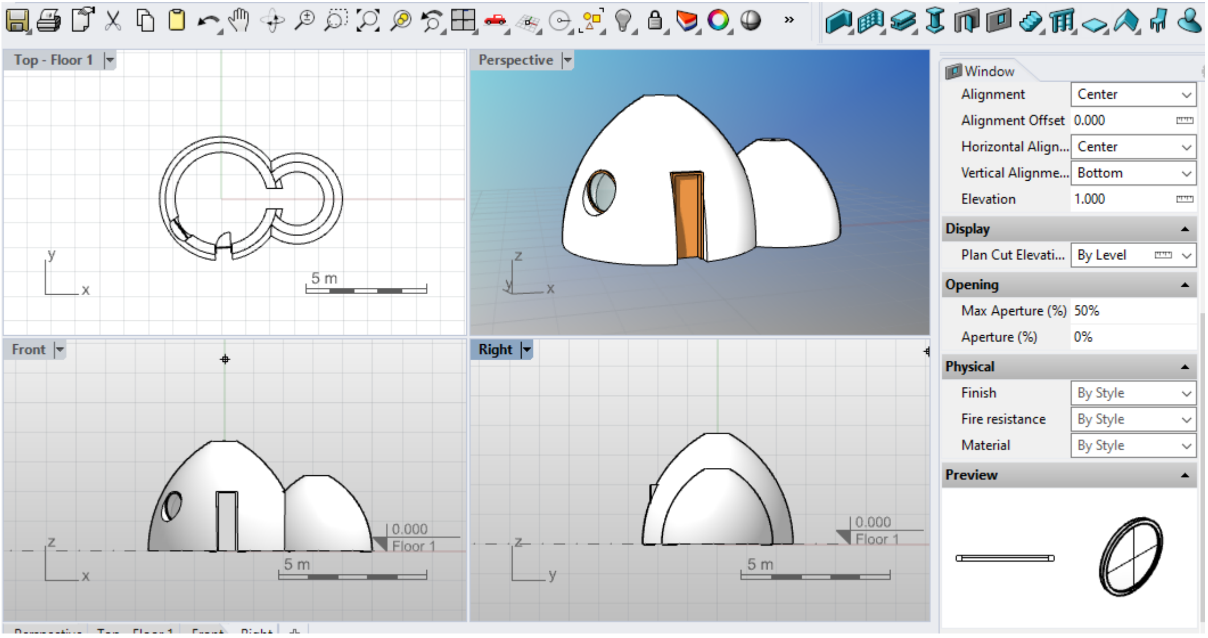


Figure 101. Inserting BIM standard window

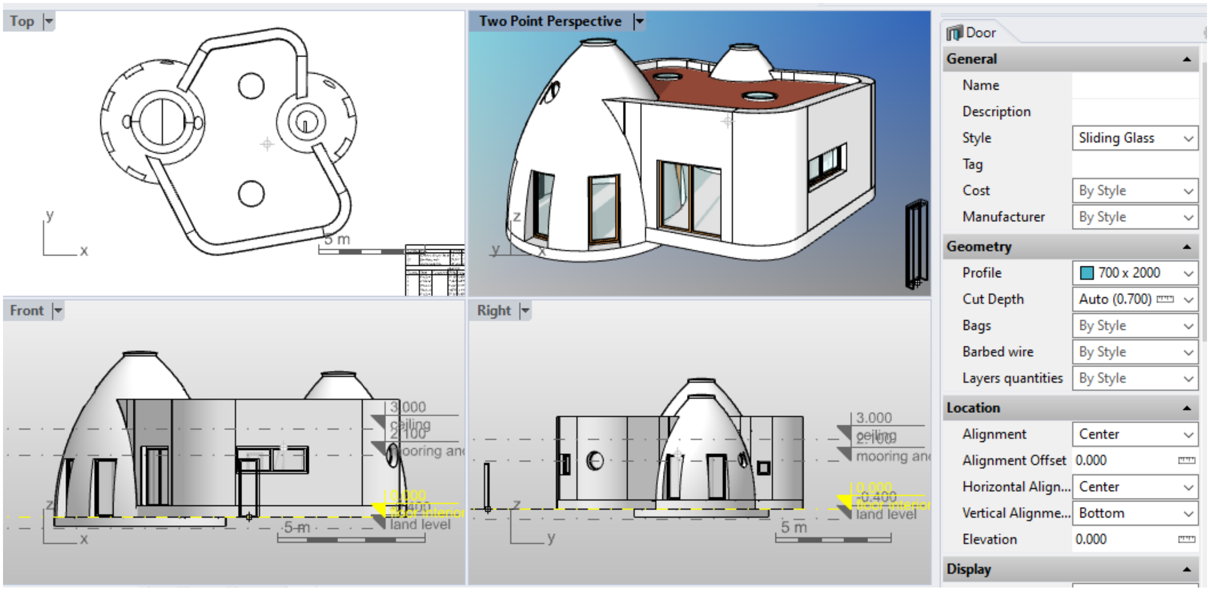


Figure 102. Inserting doors and windows. Example of Casa Vergara modelling

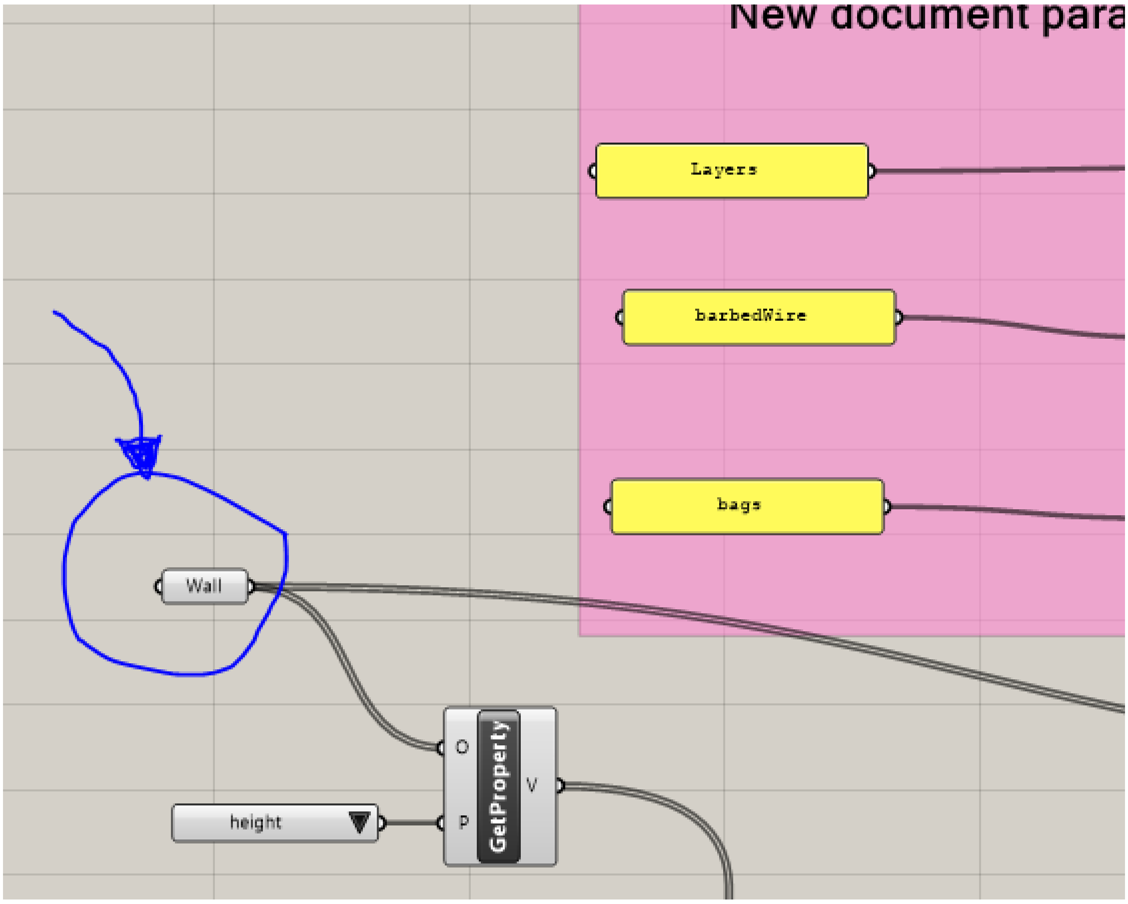


Figure 103. CICERO file 2 - Set walls to calculate the technical data

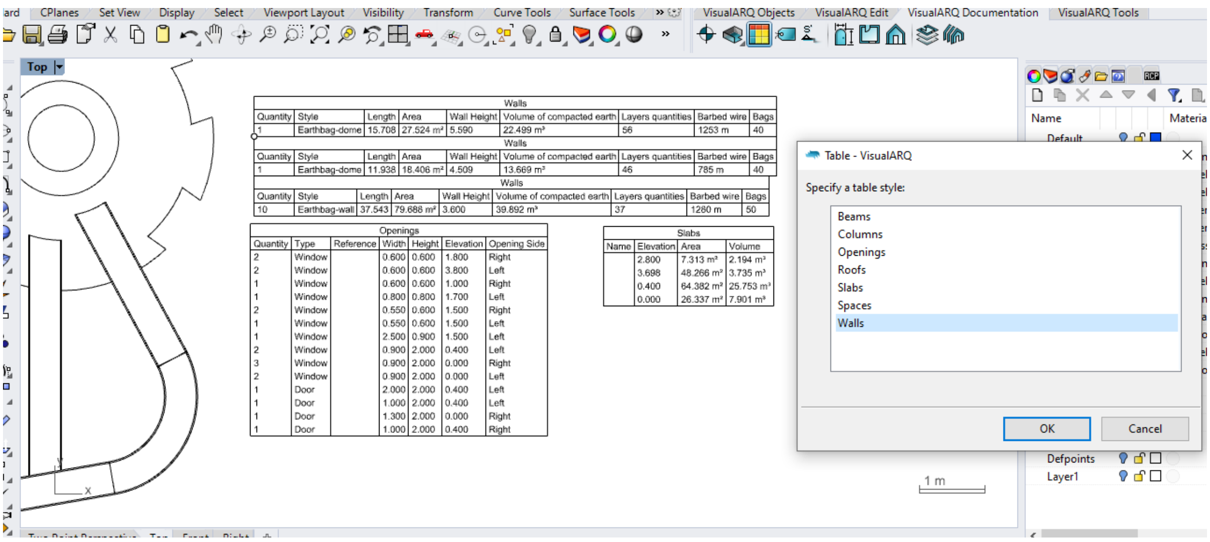


Figure 104. Inserting documentation tables

Appendix 3: CICERO validation, additional data

This appendix presents additional data regarding CICERO tool first phase validation. Namely (1) inquiries layout of the first phase and (2) inquiries' results.

The goal of this appendix is to present the data used to validate the first phase tool.

TOOL EVALUATION: Users characterization

Users characterization inquiries: 1st part results

Users	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Time stamp	7/13/2017 3:20:52	7/13/2017 10:24:10	7/13/2017 11:28:52	7/13/2017 13:38:55	7/13/2017 14:44:41	7/13/2017 16:45:41	7/14/2017 12:43:51	7/14/2017 22:26:07
Chosen Language	English	Português	English	English	Português	Português	Português	Português
Age	36 - 45	36 - 45	26 - 35	26 – 35	36 - 45	36 – 45	36 - 45	26 - 35
Profession	Technical Director - Green New World	Arquiteto	Architect	Architect	Servidor público	Arquitecto	Permacultor	Designer em Permacultura
Country where you work most	USA, Guatemala	Portugal	Portugal	United States	Brasil	PT	Brasil	Brasil
Do you have CONSTRUCTIVE experience with earthbag/ SuperAdobe?	Sim	Não	Não	Não	Não	Não	Sim	Sim
How many years?	> 10						06/out	> 10
How many buildings?	06/out						06/out	> 10
Did you usually build without plans?	No						Yes	No
PLANNING experience with earthbag/SuperAdobe	Yes	No	No	No	No	No	Yes	Yes
How many years?	5 – 7						05/jul	> 10
How many buildings?	02/abr						05/jul	> 10
Which tool you use most to project?	CAD Software (eg. Autocad, Sketchup, Rinoceros, etc)						à mão	CAD Software (ex. Autocad, Sketchup, Rinoceros, etc)
How many time do you need to design a virtual model of one earthbag dome with correct data constructions?	Days						Nunca fiz	Minutos
Where did you learn about earthbags/SuperAdobe?	Cal-Earth	Ainda não aprendi	University, Manuals, Books, Websites	University, Books	Livros, Websites	Universidade/ faculdade, Livros	Workshop, Livros, Websites	Workshop, Livros, Websites

Users characterization inquiries: 2nd part results

	9	10	11	12	13	14	15	16	17
Time stamp	7/15/2017 19:09:51	7/15/2017 22:44:59	7/17/2017 11:00:14	7/17/2017 14:24:54	7/18/2017 1:09:46	7/20/2017 10:42:11	7/24/2017 12:11:41	7/26/2017 1:48:35	
Chosen Language	Português	Português	Português	Português	English	Português	English	English	English
Age	46-55	26 - 35	26 - 35	26 - 35	>= 66	36 - 45	26 - 35	56 – 65	26 - 35
Profession	prof. / arq. / des.	Arquiteta e Urbanista	Arquiteto e Urbanista	designer	writer and webmaster	Arquiteto e Urbanista	Earth Builder	Retired	Student
Country where you work most	brasil	Brasil	Brasil	Portugal	United States of America	Brasil	Europe	America	Istanbul, Turkey
Do you have CONSTRUCTIVE experience with earthbag/ SuperAdobe?	Não	Não	Não	Não	Sim	Não	Yes	No	No
How many years?					> 10		<= 5 years		
How many buildings?					06/out		<=5 units		
Did you usually build without plans?					No		No		
PLANNING experience with earthbag/SuperAdobe	No	No	No	No	Yes	No	Yes	No	No
How many years?					> 10		02/abr		
How many buildings?					05/jul		02/abr		
Which tool you use most to project?					By hand		CAD Software (eg. Autocad, Sketchup, Rinoceros, etc)		
How many time do you need to design a virtual model of one earthbag dome with correct data constructions?					Hours		Never did		

Where did you learn about earthbags/SuperAdobe?	Universidade/ faculdade, Livros, Websites	Websites	Universidade/ faculdade, Livros, Websites, Programas de TV	Não aplicável	I have produced video programs, websites, plans, and written 2 books about earthbag building.	Universidade/ faculdade	Workshop	Manuals, Books, Websites	University, Workshop, Conferences

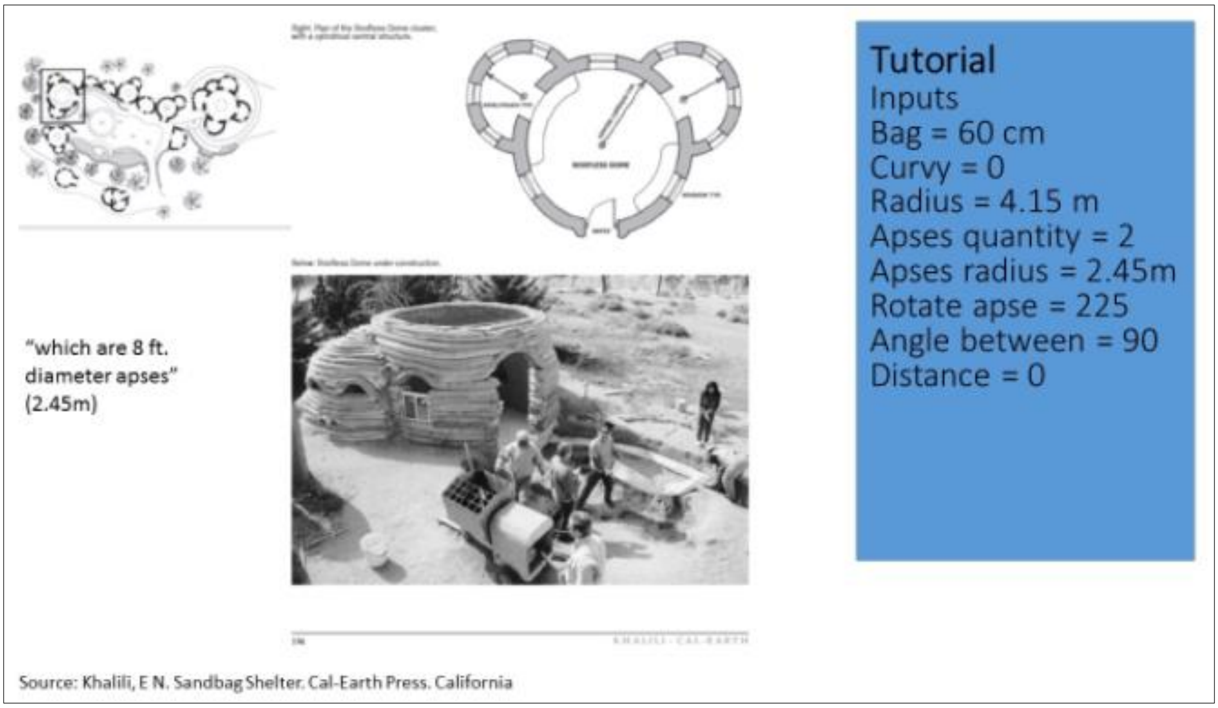
Numerical results of tool evaluation

Exercise 1: Try to recreate the dome of picture above using the "tutorial" information with CICERO. How long did you take to design a virtual model of one earthbag dome with correct data constructions?

19‘ (5.79m) interior diameter, 283 sq. ft. interior main floor, 169 sq. ft. (16' diameter) bedroom loft, total = 452 sq. ft. interior, 1 bath; footprint: 22' diameter.
Source: http://www.dreamgreenhomes.com/plans/peace.htm

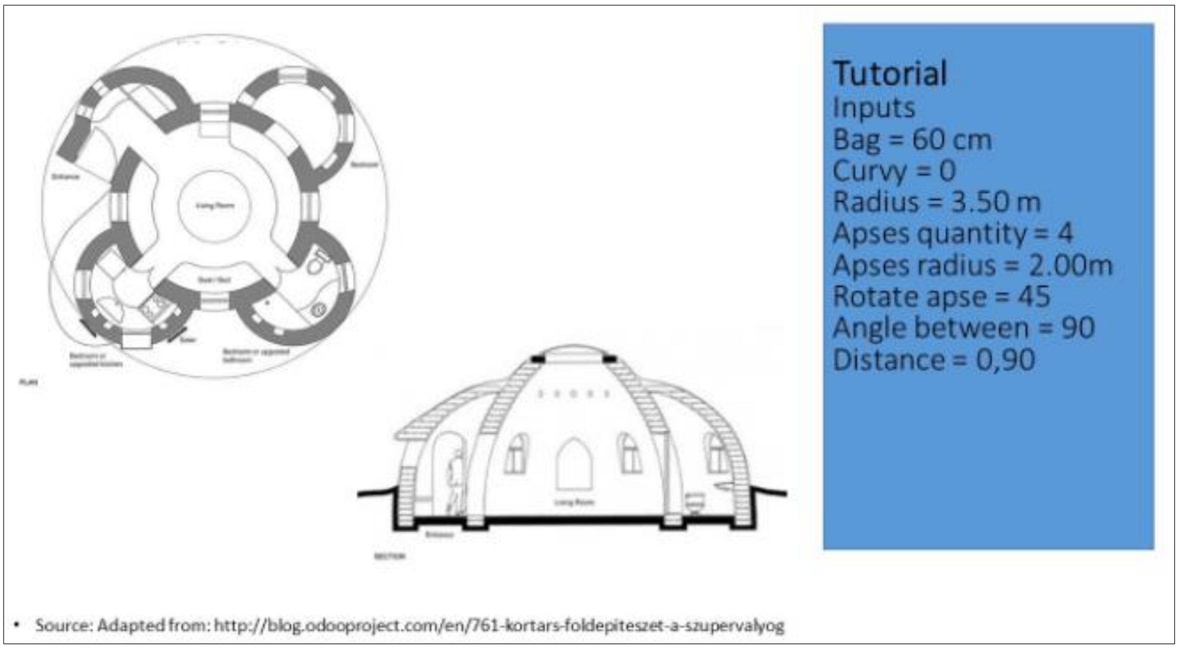
Less than 10 min	15
11 - 30min	1
31min - 1h	1

Exercise 2: Try to recreate the project of picture above using the "tutorial" information with CICERO. How long did you take to design a virtual model of one earthbag dome with correct data constructions?



Less than 10 min	15
11 - 30min	1
31min - 1h	1

Exercise 3: Try to recreate the project of picture above using the "tutorial" information with CICERO. How long did you take to design a virtual model of one earthbag dome with correct data constructions?



Less than 10 min	15
11 - 30min	1
31min - 1h	1

During the exercises, did the system informed you in real time what was changing?

Yes	12
No	2

Are the parameters names related with real world?

Yes	12
No	2

Would you say that using CICERO you are able to design different dome compositions?

Yes	13
No	1

Is the sliders visual pattern easy to manipulate?

Yes	14

No	0

Would you say that by using CICERO you could prevent project errors?

Yes	11
No	3

Would you say that you can recognize and manipulate CICERO with no need to memorize it?

Yes	13
No	1

Would you say that a beginner user can manipulate CICERO?

Yes	13
No	1

CICERO is an objective and simple program?

Yes	12
No	2

Did you receive any error message?

Yes	3
No	11

The FAQ was enough to help your understanding of CICERO?

Yes	12
No	5