International Journal Of Engineering Research And Development
e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 19, Issue 4 (Jul.-Aug. 2023), PP. 01-09

The Architectural Design Process of Pneumatic Warehouses

Felipe Corres Melachos[1], Anália Maria Marinho de Carvalho Amorim[2]
[1]*Faculty of Civil Engineering, Architecture and Urban Design – Campinas State University, Campinas, BRAZIL.*
[2]*Faculty of Architecture and Urban Design – University of São Paulo, São Paulo, BRAZIL.*
Corresponding Author: Felipe Corres Melachos

ABSTRACT
The object of study of this paper is the body of four interconnected pneumatic warehouses, to be designed and built in a municipal food distribution and market in the city of Campinas, Brazil. The objective of this paper is the reflective and propositional analysis of the exploratory architectural design process of the aforementioned pneumatic warehouses with the use of manual and digital design tools. The architectural design steps comprised in this research include its early stages of formal-structural conception and ideation, that is, schematic design and design development. Pneumatic structures lack through research in Brazilian academic community, in a way that they have the potential of providing light structures with long spans, with quick and safe assembly procedures, all with reasonable economic construction costs. As the methodological procedures adopted in this research, it was adopted a reflection upon its design challenges and steps. As to the research's expected contributions, it is hoped that this paper could shed a light upon the challenges of architectural design of pneumatic structures, as well as the hybridization of analogical and high technology digital design tools in its design process as well.
KEYWORDS: *pneumatic structures; warehouses; shape-finding; form-finding; parametric modeling.*

Date of Submission: 20-06-2023 Date of Acceptance: 03-07-2023

I. INTRODUCTION

The state-of-the art classifies pneumatic structures as non-rigid structural surfaces (1), which could be either air-supported our air-inflated (2). Pneumatic non-rigid structural surfaces have seen an upsurge in the late twentieth and first decades of the twenty-first century because of new digital design tools and new construction materials (3). Amongst such digital new arisen design tools figure Rhinoceros 3d® associated to parametric tools such as Grasshopper 3d® alongside Kangaroo Physics® (4–9), whereas amongst the afore mentioned constructive novelties are the ETFE cushion façade systems (10–12), advances on pneumatic formwork processes for shell structures (13–16), or air-inflated tensairity® beams or arches (17–19).

Brazil maintains an economy based on the exportation of commodities (20), which in turn presents the nation with a growing infrastructure demand regarding warehouses in both a public and private specter. Thus, the agricultural industry in Brazil needs constructive spaces for storage and exportation, giving way for the exploration of pneumatic structures as in storages silos (21,22). The COVID-19 pandemic has accentuated the demand for warehouses, this time linked to *e-commerce* demands (23). Nonetheless, recent research in academic databases indicates a rather lack of academic explorations regarding the theme associated to pneumatic structures.

Hence, the object of study of this paper is the body of four pneumatic warehouses, to be designed and built in a municipal food distribution and market in the city of Campinas, Brazil. The city of Campinas was chosen for one of the authors of the papers teaches at the State University of Campinas, making the access to the design site more feasible. Thus, the main objective of this article is to reflect upon the analysis of the exploratory architectural design process of the aforementioned pneumatic warehouses, which was conducted with the use of both manual, analogical, and digital, high-end, design tools.

As aforementioned, pneumatic structures lack through research in Brazilian academic community (3), in a way that they have the potential of providing light structures with long spans (2), with quick and safe assembly procedures, all with reasonable economic construction costs (18). The construction industry in Brazil has a long-standing tradition of reinforced concreted and structural masonry (24), as opposed to industrialized construction systems, as well as light and dry structural systems, which could render a de facto economy (25–28).

The object of study of this article is the experimental architectural design of four interconnected pneumatic warehouses, to be designed in a public food distribution center in the city of Campinas, Brazil. Therefore, the objective of this research, is the reflective and propositional analysis of the exploratory architectural design process of the aforementioned pneumatic warehouses with the use of manual and digital design tools, specially so when it comes to state-of-the-art visual programming design tools.

The proposed methodological steps for this research comprised the screening of potential design sites for the exercise and potentializing of pneumatic structures strengths within Brazil' national demands (agriculture and/ or *e-commerce*); the gathering of design inputs to command the architectural ideation; the architectural design process itself; and an analysis and reflection upon the design process per se. The architectural design process within this research was guided by a mixture of shape finding (29) and form finding processes (30), where both architectural form and space, as well as structural stability where sought for.

Hence, it is hoped that this research contributes not only to the furthering of architectural design processes of pneumatic structures in Brazil, but the fostering of design processes which are industrialized, light and dry, aiming for economy, safety and sustainable development as a constructive process (31). For such purposes, the methodological procedures adopted in this research were a reflection upon its design challenges and steps. As to the research's expected contributions, it is hoped that this paper could shed a light upon the challenges of architectural design of pneumatic structures as well as the hybridization of analogical and high technology digital design tools in its design process as well.

II. MATERIAL AND METHODS

The scheme below is a synthesis of the methodological procedures to be adopted in this paper, to be divided into three major sections: a "screening" phase, an "inputs" phase, a "design" phase, and a "analysis" phase. The "screening" phase took into consideration the teaching place of the authors of this paper, and hence, the city of Campinas was the chosen ground for experimentation. Given the weight of the agricultural industry in the nearby and/or *e-commerce* inherited demand for pneumatic structures in Brazil, the "input" research phase yielded a local food distribution and market center as the chosen design site for this research's design experimentations. This market was founded in the late 80s, and in an on-going expansion since the mid-90s, situated in a northern district of Campinas.

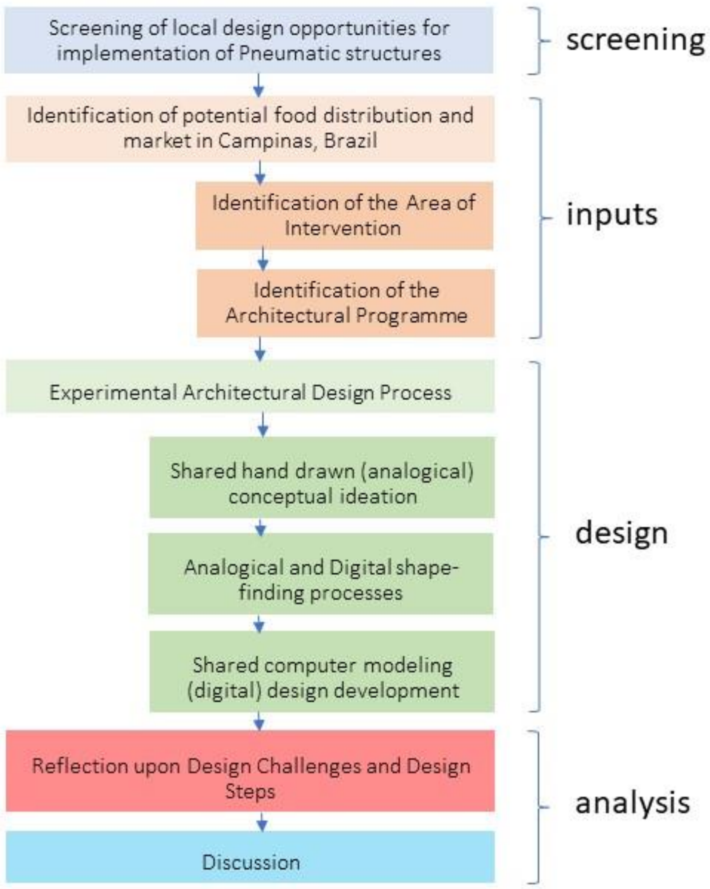


Figure 1: The flow of the methodology

Within this particular local food and distribution market, there were prospected different potential demands for the location of the pneumatic warehouse, whereas an open area between existing warehouses A and B was the recommended by management, as long as public bathroom C was to be maintained (Fig. 2). Fig. 2 also illustrates the presence of existing trees in the recommended design area, culminating in two potential blocks for implementation of nearly 63 meters by nearly 36 meters and nearly 37 meters respectively. The "input" phase also resulted in the obtention of the architectural programme of the proposed designs, consisting of mainly 4 great storage areas of 600 m² each, and 4 management areas of 100 m² (Table 1). The presence of eventual bathrooms for the management areas was posteriorly suppressed due to the presence of the large bathroom in the center of the design area ("C" in Fig. 2).

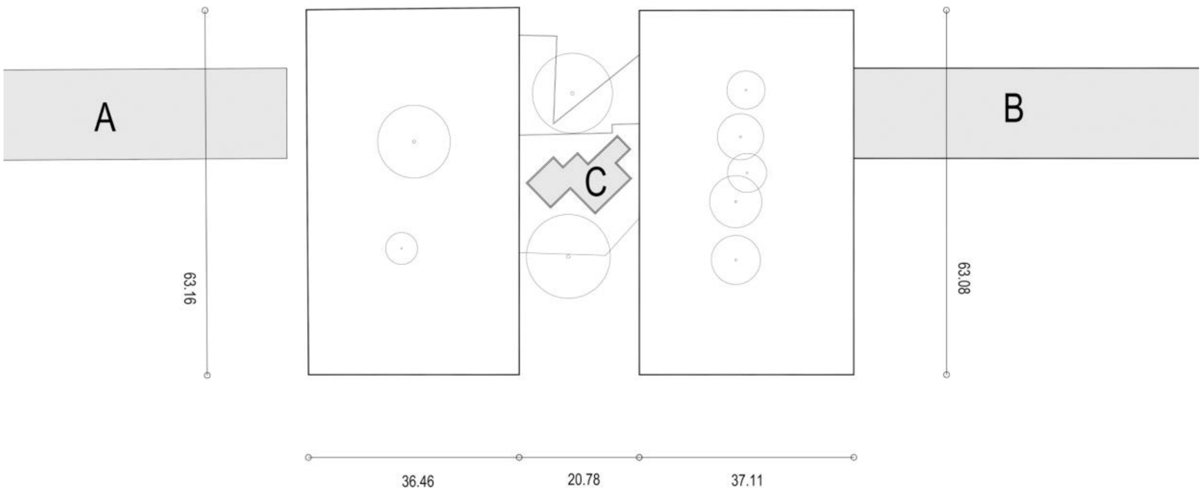


Figure 2: The existing design area (without scale).

Programme Item	Quantity	Area
Storage Area	4	600 m²
Management Area	4	100 m²

Table 1: Proposed Architectural Programme.

The "design" phase of the methodological process started with experimental design enterprises which intertwined shape finding (29) form-finding (30) processes, which started from an intense exchange of hand-drawn ideations (Fig. 3). Such shape finding processes (29) in this research had a biomimetic phase (32) which sought to emulate tortoise shells from the northeastern coastal Brazilian fauna (Fig. 4A), which were translated into abstract patterns (Fig. 4B) as to emulate Native Brazilian peoples Kayapó-Xilkrin drawings (33). These patterns were then attempted to be translated onto Grasshopper 3D® (Fig. 4C) Voronoi patterns (Fig. 4D) and then applied to experimental warehouses surfaces (Fig. 3E), corroborating with the "analogical and digital shape-finding processess" stage in the "design" phase of the methodological procedures. Despite of proven formwork adaptations (citations), the shape-finding and form-finding processes of the research opted for a rather rational path.

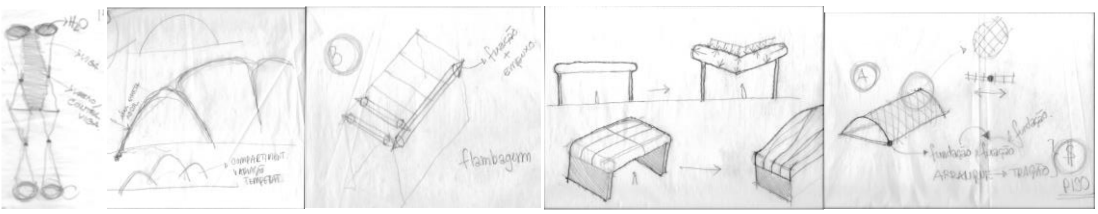


Figure 3: Samples of Croquis Ideation exchanged during the design process.

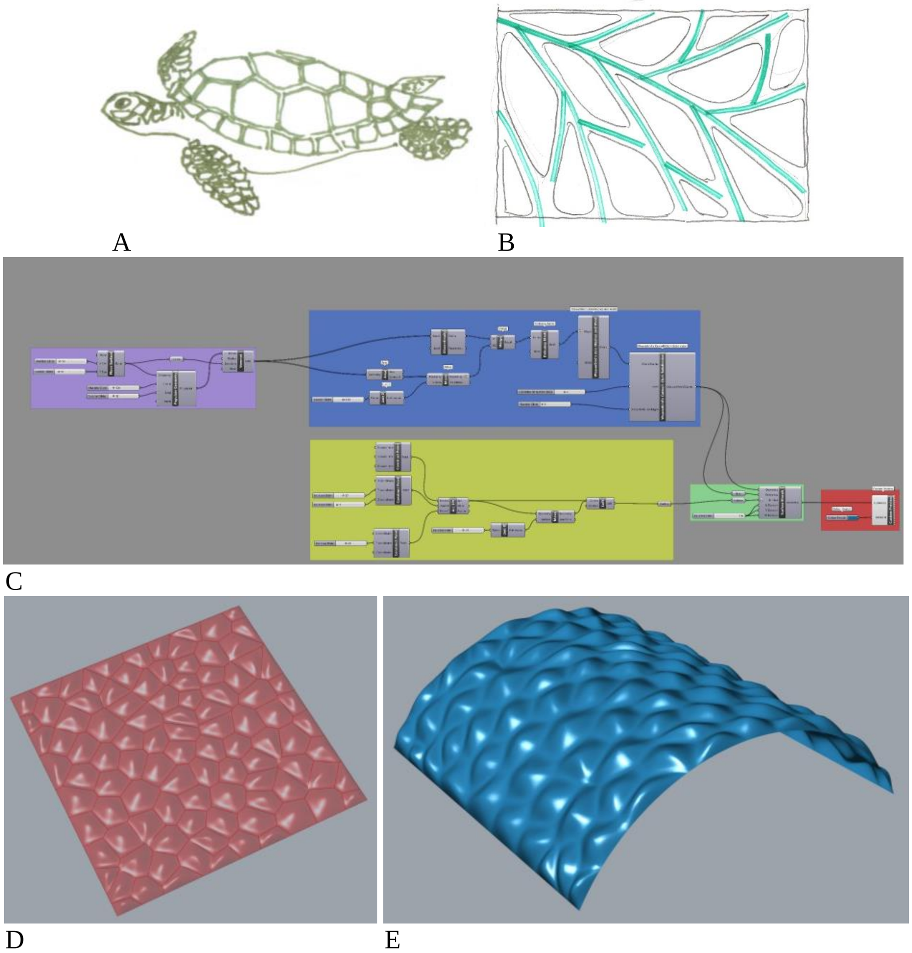
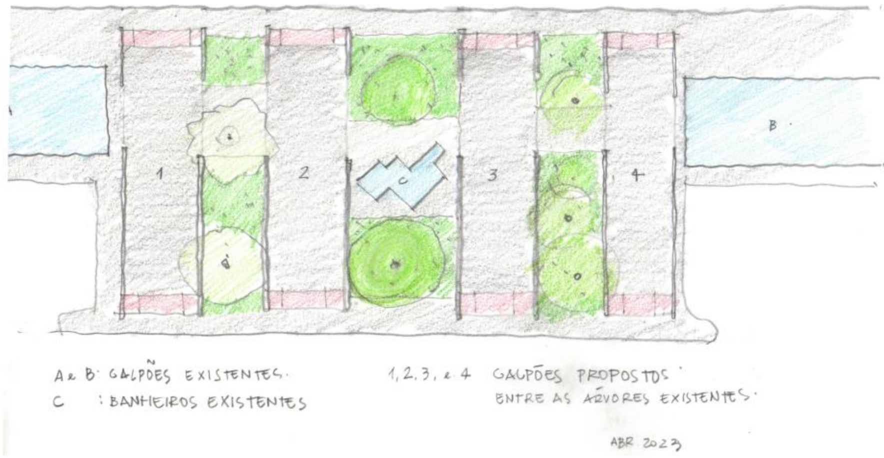


Figure 4: Shape-finding trials attempts through biomimetics with the inspirations from nature (A), translation into patterns (B) and algorithmic definitions (C), and planar (D) and vaulted (E) geometric results.

Such rather rational pathways could be observed in the croquis below (Fig. 5A, *1-4*), where 4 warehouses initially occupied the terrain and were positioned as to preserve the original high vegetation and the access to the existing public bathroom (Fig. 5A, *c*). Initially it was thought to be possible to design a pathway amongst all warehouses to connect them to the central public bathroom amidst all green area and added and original green area. However, such intervention would take up much needed storage area, in a way that it was left only in a landscape design intention.

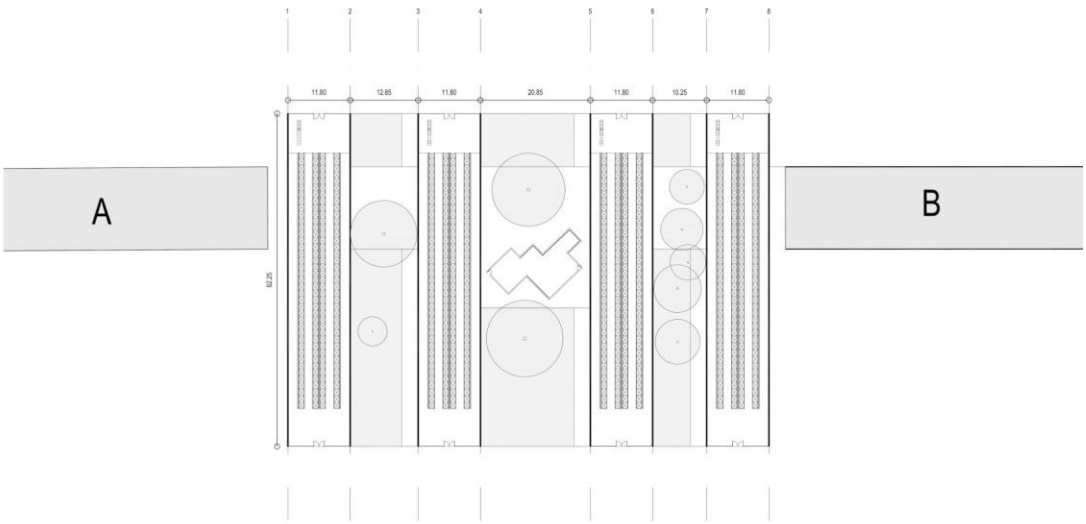
The transverse sections developed during the hand-drawing ideations (Fig. 5B) made sure that eventual amplitude differentiations did not contribute to storage capacity, making sure that all warehouses' designs were geared towards similar, and finally towards a same height. One of the ponderations within the height of the designs were its relationship with the existing trees, in the landscape that would be created in the existing food market, since it would be interesting for the slope of the rooftops not to interfere with the tree's canopies in the same sense that the canopies do not constitute a issue in the maintenance and cleaning of the construction themselves.

Such conclusions were transported onto Autodesk CAD® for a mor precise geometrization and resulted in four identical warehouses of 62.25 meters with a width of 11.80 meters. Their maximum height was 9.10 meters, resulting in a rational construction output such as can be seen in Fig. 5C.



A

B

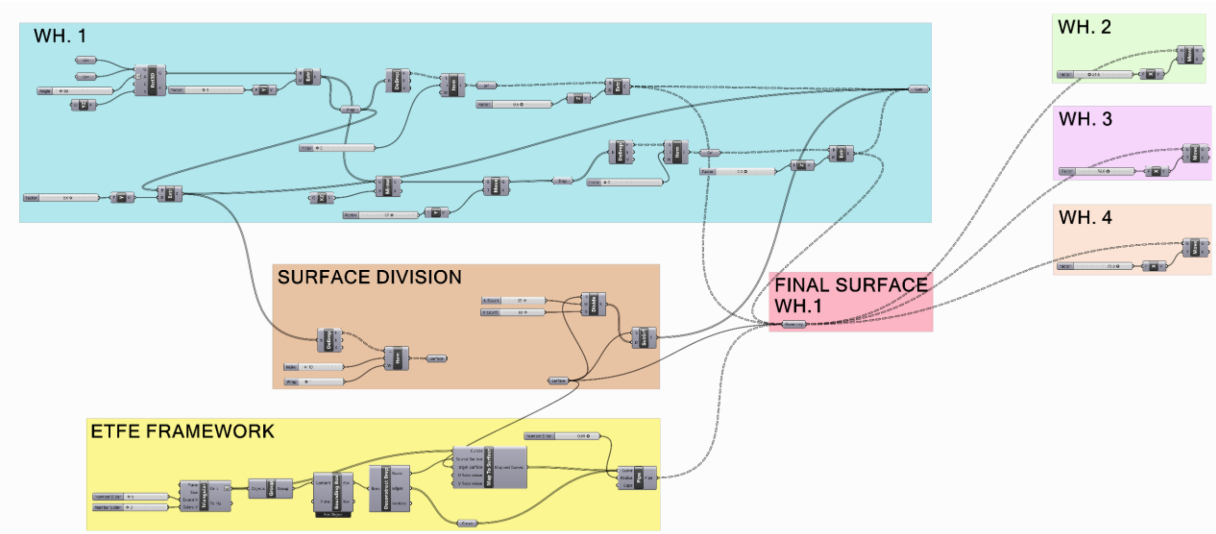


C

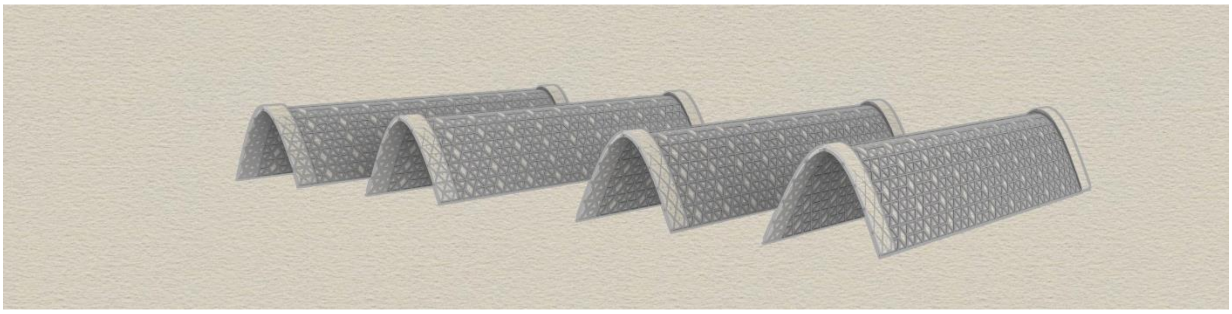
Figure 5: Analogical (A-B) and Digital (C) Design Ideations as the Conceptions Evolved (without scale).

III. RESULTS

The results of the experiment are demonstrated by the following definition (Fig. 6) designed in Rhinoceros 3D® in association with its plugin Grasshopper 3D®, in association with the plugin Parakeet®, used for the mapping of the ETFE frames onto the designed architectural surface. The resulting architectural surface is in its essence a gridshell – "a shell with large openings in it in a manner that allow the remaining strips or grids to behave, structurally, as a shell" (34). The developed algorithmic definition is essentially comprised of the design of the transverse cross-section and its extrusion onto a surface in group "WH.1" (Warehouse 1) (Fig. 6a), whose surface was isolated in "surface division". The ETFE frames where the pneumatic moduli are to be fixed were designed in the corresponding grouping, Finally the resulting surface in group "FINAL SURFACE WH.1" was replicated into "WH2", "WH3", and "WH4" (Fig. 6b) as according to the designed architectural distances, and thus producing the remaining warehouses respectively.



A.



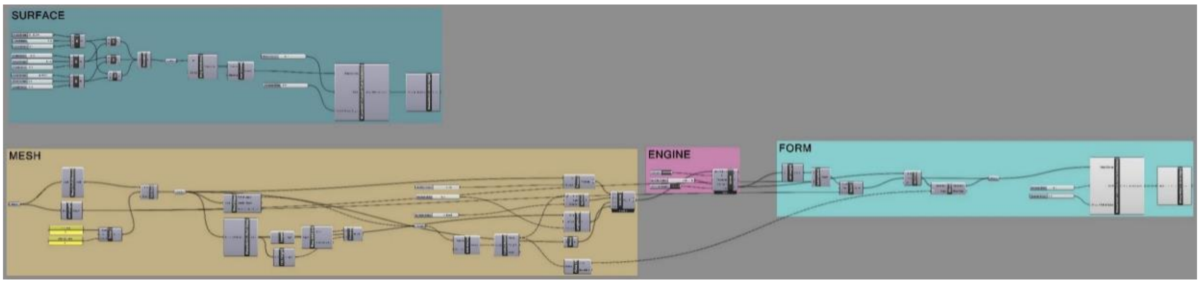
B.

C.

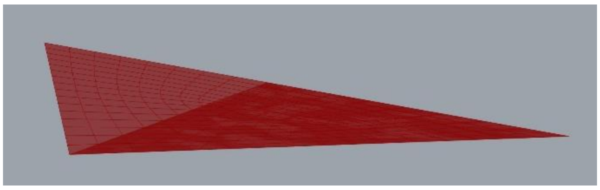
Figure 6: (A) Pneumatic Warehouse Definition; (B) the Warehouses in perspective and in detail (C), showing their ETFE moduli.

It is important to note in Fig. 6c that both extremes of the warehouses are hardened by rigid arches in order to tackle buckling and to withhold stairs to a administrative second floor to the storage warehouse main ground floor. Fig. 6c also illustrates a zoom in the ETFE frame moduli, whose specific algorithms can be shown in Fig. 7a. This definition was developed in Rhinoceros 3D® in association with Grasshopper 3D® alongside other plugins such as Weaverbird® and Kangaroo Physics®.

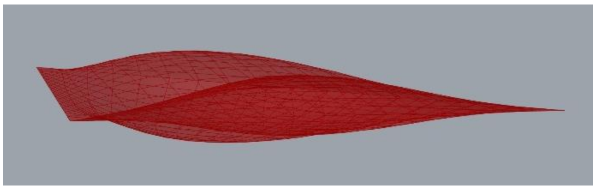
The first portion of the definition grouping, "Surface", uses Weaverbird® to extract meshes from the triangular surface framework moduli from the warehouse itself. The "Mesh" grouping prepares the mesh for the unified applying of pressure by means of Kangaroo Physics®, the most widely used plugin for form-finding of pneumatic structures in parametric design (3), whereas the grouping "engine" highlights Kangaroo Physics´s® engine itself. Finally, the grouping "form" mirrors the inflating producing in the earlier groupings in order to properly assemble the desired ETFE pillow. Fig. 3B and 3C illustrate the ETFE pillow deflated (Fig. 7b) and inflated (Fig. 7c) by means of the Kangaroo Physics® plugin.



A.



B.



C.

Figure 7: (A) ETFE Moduli Definition; (B) Deflated Module; Inflated Module.

IV. DISCUSSION AND CONCLUSION

The challenges in this academic endeavor were initially marked the shape-finding processes, which initially geared towards a biomimetic approach and then leaned more rationally, as a means to tread more carefully in the then unexplored waters of ETFE formwork associated with gridshell surface structures. Such shape-finding processes, was then associated with form-finding procedures aided with computational tools in order to determine an architectural forms compatible to pneumatic constructive systems.

The analogical-digital interaction was conducted in a non-spectacular fashion, not using technology as a mere adornment (35) or competing instrument, but as complementary tool to hand-drawing instruments. Shape-finding processes were conducted both on paper and computational tools, whereas form-finding and verification procedures were usually conducted computationally because of the necessity of precise data.

A difficulty aroused in the design process of the proposed warehouses coming the use of state-of-the-art computational tools was the option for rather complex shapes or rather rationalized designed solutions. The literature review (3) regarding the subject demonstrated that it was feasible to go either way in the design process, making such decisions a matter of landscape and contextual adaptation, computational tools proficiency, as well as structural design proficiency. Those variables affected directly the geometric complexity of ETFE moduli and framework, in the case of a gridshell structure accommodating a pneumatic skin such as the designed proposition, as well as the management of preexisting man-made and natural structures such as neighboring warehouses and the public bathroom in the center of the lot as well as the myriad of trees in the terrain.

Another challenge that arose in the process of designing such propositions was convincing the potential clients to invest their time onto non-conventional constructive technologies, as opposed to structural masonry warehouses with roofs structured with metallic trusses, conspicuous in the whole of the food and distribution market. As the design process and propositions evolved, it became clear that certain arguments such as lightness, rapid assembly, construction site hygiene, predictability of cost and tectonics, winded up convincing the final clients.

REFERENCES

[1]. Bechthold M. Innovative Surface Structures: Technologies and Applications. 1ª edição. Abingdon England ; New York: Taylor & Francis; 2008.

[2]. Schodek D, Bechthold M. Structures: Pearson New International Edition. 7ª edição. Pearson; 2013. 524 p.

[3]. Melachos F, Amorim A. The dissemination of visual programming parametrical digital design tools in the form-finding of pneumatic structures: a systematic literature review. Em: Proceedings of the IASS 2022 Symposium affiliated with APCS 2022 conference. Beijing; 2022. p. 800–10.

[4]. Agirbas A. Pneumatic Structure with Kinetic Sub-system: A Proposal for Extraterrestrial Life. Em: SIGraDi 2020 [Proceedings of the 24th Conference of the Iberoamerican Society of Digital Graphics - ISSN: 2318-6968] Online Conference 18 - 20 November 2020, pp 400-405 [Internet]. CUMINCAD; 2020 [citado 23 de maio de 2023]. Disponível em: http://papers.cumincad.org/cgi-bin/works/paper/sigradi2020_400

[5]. Chia HY, Hsien HP. The fabrication and application of parametric inflatable structure. Em: 22th conference of the iberoamerican society of digital graphics [Internet]. São Carlos; 2018 [citado 23 de maio de 2023]. Disponível em: http://papers.cumincad.org/data/works/att/sigradi2018_1609.pdf

[6]. Liuti A, Liew K, Ng L. In(flatable) Mod(uli) - Air-buoyant, form-resistant, temporary structures. Em: Proceedings of the 21st International Conference of the Association for Computer-Aided Architectural Design Research in Asia CAADRIA 2016. Hong Kong: S. Chien, S. Choo, M. A. Schnabel, W. Nakapan, M. J. Kim, S. Roudavski; 2016.

[7]. Melachos FC, Florio W, Rossato L, Balzani M. PARAMETRICAL ANALYSIS AND DIGITAL FABRICATION OF THIN SHELL STRUCTURES: THE IMPACT OF CONSTRUCTION TECHNIQUE ON THE RESULTING GEOMETRY OF THE GAUSSIAN VAULTS OF ELADIO DIESTE. Int Arch Photogramm Remote Sens Spat Inf Sci. 31 de janeiro de 2019;XLII-2-W9:479–85.

[8]. Tedeschi A. AAD Algorithms-Aided Design. 14ª edição. Brienza: Le Penseur; 2014.

[9]. Wahbeh W. Building skins, parametric design tools and BIM platforms. Em: Conference Proceedings of the 12th Conference of Advanced Building Skins. 2017. p. 1101–11.

[10]. Flor JF, Sun Y, Beccarelli P, Wu Y, Chilton JC. Switchable ETFE cushion: designing and building a model for experimental testing. Em: Proceedings of the IASS Annual Symposium 2019 – Structural Membranes 2019. Barcelona; 2019.

[11]. Velikov KT, Thun G, O'Malley M. PneuSystems: cellular pneumatic envelope assemblies. Em: ACADIA 14: Design Agency [Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) ISBN 9781926724478]Los Angeles 23-25 October, 2014), pp 435-444 [Internet]. Los Angeles: CUMINCAD; 2014 [citado 23 de maio de 2023]. Disponível em: http://papers.cumincad.org/cgi-bin/works/paper/acadia14_435

[12]. Wit AJ. Towards an Intelligent Architecture: Creating Adaptive Building Systems for Inhabitation. Em: Blucher Design Proceedings [Internet]. 2014 [citado 23 de maio de 2023]. p. 328–32. Disponível em: https://www.proceedings.blucher.com.br/article-details/towards-an-intelligent-architecture-creating-adaptive-building-systems-for-inhabitation-14282

[13]. Kromoser B, Pachner T, Tang C, Kollegger J, Pottmann H. Form Finding of Shell Bridges Using the *Pneumatic Forming of Hardened Concrete* Construction Principle. Adv Civ Eng. 29 de novembro de 2018;2018:e6309460.

[14]. Kromoser B, Kollegger J. Efficient construction of concrete shells by Pneumatic Forming of Hardened Concrete: Construction of a concrete shell bridge in Austria by inflation. Struct Concr. 2020;21(1):4–14.

[15]. Poinet P, Baharlou E, Schwinn T, Menges A. Adaptive Pneumatic Shell Structures - Feedback-driven robotic stiffening of inflated extensible membranes and further rigidification for architectural applications. Em: Herneoja, Aulikki; Toni Österlund and Piia Markkanen (eds), Complexity & Simplicity - Proceedings of the 34th eCAADe Conference - Volume 1, University of Oulu, Oulu, Finland, 22-26 August 2016, pp 549-558 [Internet]. CUMINCAD; 2016 [citado 23 de maio de 2023]. Disponível em: http://papers.cumincad.org/cgi-bin/works/paper/ecaade2016_113

[16]. Quinn G. Structural analysis for the pneumatic erection of elastic gridshells. Structures. 1º de dezembro de 2020;28:2276–90.

[17]. Lv L, Fan Z, Sun H. Experimental study on bearing capacity of a Tensairity arch. J Phys Conf Ser. 1º de junho de 2022;2285:012026.

[18]. Tensairity Solutions. Tensairity Solutions [Internet]. 2023 [citado 23 de maio de 2023]. Disponível em: https://www.tensairitysolutions.com/

[19]. Tung NQ. Experimental Characterization of Tensairity Beams. Int J Recent Technol Eng IJRTE [Internet]. 2019 [citado 23 de maio de 2023]; Disponível em: https://www.ijrte.org/portfolio-item/c5399098319/

[20]. Assis M. Brasil mantém posição no comércio mundial | Mundo | Valor Econômico [Internet]. Valir Econômico. 2020 [citado 23 de maio de 2023]. Disponível em: https://valor.globo.com/mundo/noticia/2020/04/08/brasil-mantm-posio-no-comrcio-mundial.ghtml

[21]. João A, Rocha F, Henrique V, Caixeta-Filho J. VIABILIDADE DO INVESTIMENTO EM INFRAESTRUTURA DE ARMAZENAGEM: COMPARATIVO ENTRE ARMAZENAGEM CONVENCIONAL E SILO BOLSA. 2019.

[22]. Paturca E. CARACTERIZAÇÃO DAS ESTRUTURAS DE ARMAZENAGEM DE GRÃOS: UM ESTUDO DE CASO NO MATO GROSSO [Internet]. Piracicaba: UNIVERSIDADE DE SÃO PAULO; 2014 [citado 24 de maio de 2023]. Disponível em: https://esalqlog.esalq.usp.br/upload/kceditor/files/2015/05/Caracteriza%E2%94%9C%C2%BA%E2%94%9C%C3%BAo-das-estruturas-de-armazenagem-de-gr%E2%94%9C%C3%BAos-um-estudo-de-caso-no-Mato-Grosso-PATURCA-E.-Y..pdf

[23]. Diniz N, Gonçalves PP. Nelson Diniz As cidades dos galpões: dinâmicas e contradições da urbanização. Rev E-Metropolis. 13 de março de 2023;49:6.

[24]. Bauer LAF. Materiais de Construção - Vol. 1. 6ª edição. LTC; 2022. 563 p.

[25]. Gallo F. Nonetheless, recent research indicates a rather lack of academic explorations regarding the theme. [Internet]. [São Paulo]: Universidade de São Paulo; 2015 [citado 24 de maio de 2023]. Disponível em: https://teses.usp.br/teses/disponiveis/16/16138/tde-25042016-142830/publico/fabiogallo.pdf

[26]. Latorraca G. A Arquitetura De Lele. Fabricação E Invenção. São Paulo, SP, Brasil: Imprensa Oficial; 2011.

[27]. Latorraca G. Joao Filgueiras Lima Lele. Lisboa, Portugal : São Paulo, SP, Brasil: Editorial Blau,Portugal; 2000.

[28]. Mosaner FFL. O desenho e o processo de produção da arquitetura: João Filgueiras Lima (Lelé) e o Centro de Tecnologia da Rede Sarah (CTRS) [Internet] [text]. Universidade de São Paulo; 2021 [citado 24 de maio de 2023]. Disponível em: https://www.teses.usp.br/teses/disponiveis/16/16138/tde-01122021-184015/

[29]. Goldsmith NH. Shape Finding or Form Finding? Em: Proceedings of the IASS-SLTE 2014 Symposium "Shells, Membranes and Spatial Structures: Footprints" [Internet]. Brasilia, Brazil: Reyolando M.L.R.F. BRASIL; Ruy M.O. PAULETT; 2014 [citado 22 de maio de 2023]. Disponível em: https://ftlstudio.com/wp-content/uploads/2016/04Form%20Finding%20vs%20Shape%20Making.pdf

[30]. Coenders J, Bosia D. Computational tools for design and engineering of complex geometrical structures: From a theoretical and a practical point of view. Game Set Match II Comput Games Adv Geom Digit Technol. 1º de janeiro de 2006;

[31]. Roaf S, Crichton D, Fergus N. A Adaptação de Edificações e Cidades às mudanças: Um Guia de Sobrevivência para o Século XXI [Internet]. Porto Alegre; 2009 [citado 24 de maio de 2023]. Disponível em: https://www.amazon.com.br/Adapta%C3%A7%C3%A3o-Edifica%C3%A7%C3%B5es-Cidades-Mudan%C3%A7as-Clim%C3%A1ticas-

ebook/dp/B019HM0HB8/ref=sr_1_1?__mk_pt_BR=%C3%85M%C3%85%C5%BD%C3%95%C3%91&crid=108ZYHKQTMQN3&keywords=sue+roaf&qid=1684899488&sprefix=sue+roa%2Caps%2C261&sr=8-1

[32]. Thompson DW, Thompson K. On Growth and Form: The Complete Revised Edition. Revised ed. edição. New York: Dover Publications; 1992.

[33]. Vidal L. Grafismo Indígena. Estudos de Antropologia Estética | Amazon.com.br [Internet]. São Paulo: Studio Nobel; [citado 26 de maio de 2023]. Disponível em: https://www.amazon.com.br/Grafismo-Ind%C3%ADgena-Estudos-Antropologia-Est%C3%A9tica/dp/853140066X

[34]. Charest P, Potvin andré, Demers C, Ménard S. Assessing the Complexity of Timber Gridshells in Architecture through Shape, Structure, and Material Classification. Bioresources. 7 de janeiro de 2019;14:1364–78.

[35]. Gleiter JH, Kronbichler T, Kerschbaumer M. Ornament Today: Digital Material Structural. 1st edition. Bolzano: Bozen University Press; 2012.