FUZZY LOGIC IN BENDING-ACTIVE GRIDSHELL DESIGN

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Abstract. Performance-based design is encouraging designers to carry out quantitative-oriented research, sometimes indifferent to qualitative matters that concern social, cultural, and even psychological aspects. Design requirements related to humans' subjective value and decision-making ought to be properly addressed. This paper begins with the discussion of architectural complexity about its ill-defined design problems. Human's linguistic variables contain the ambiguous yet uncertain value that seemingly unfit for today's precise digital design approaches. Hence, this paper involves the idea of fuzzy logic and its inference system, presents a soft computing method using membership functions to describe qualitative parameters. It then uses MATLAB Fuzzy Logic Toolbox, as an auxiliary design tool apart from Rhinoceros Grasshopper, to grade design options of a bending-active gridshell from an undergraduate design studio.

Keywords. Fuzzy logic; digital architecture; linguistic variable; bending-active gridshell.

1. Introduction

This presented work selects a bending-active gridshell project from an undergraduate design studio where students were asked to work with NURBS modelling tool and physics simulation engine in long-space architecture design. Performance-based design approaches already came to the forefront of architectural discourse, so that pioneering architects, designers, and researchers are keen on carrying out quantitative form-finding designs based on data extracted from such as environment, material behaviour, and fabrication capacity. However, this emerging trend of digital paradigm may jeopardise a designer's conscious decisions made to his/her projects. Matters like spatial experience, cultural reflections, and aesthetical pursuits etc. are impossible to measure using conventional data strings. The very nature of architectural design must include complex design problems insofar as it urges today's architects to consider multi-variate factors when they are looking for design solutions. Hence, this reveals necessity to investigate potential means of transforming humans' ambiguous expression to measurable outcomes so that both quantitative and qualitative design variables can be rationally integrated.

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2. Architectural complexity

Peter Rowe (1987) categorised two types of design problems: well-defined and ill-defined. The former ones normally prescribe articulate goals and work towards expected results. Its problem-solving trajectory is relatively linear with few uncertainties. For example, the modern architectural industry used to pursue a Fordian mode of design and production by standardising building forms, component details, and implementing techniques. By doing so, one may evade latent risks caused by intricate design requirements but, at the same time, weaken a project's persona. Ill-defined design problems, on the other hand, can never be comprehensively described at the beginning of a project (Lawson, 2005). Lawson believes most of today's architectural and urban design practices belong to the latter one. This is because, firstly, new design requirements may emerge anytime without formulations; secondly, the problem-solving process may last more than expected; and thirdly, the problem-solution may be diverse from case to case.

2.1. FLEXIBLE DESIGN PROBLEMS

Lawson created a 'completed model of design problem' to describe the intricacy of an architectural project, which contains the problem's generator, nature, and category. From these three dimensions, the model illustrates design problems of their contained variables and corresponding rigidity. For example, practical requirements from legislator ought to be rigid since they often refer to strict matters such as building codes and site-specific restrictions. Comparatively speaking, questions about building forms and geometries usually play a less decisive role in architectural practice therefore are more flexible. These design requirements always involve qualitative variables from designer, stakeholder, and user.

However, there is no clear boundary between 'rigid' and 'flexible' design problems. What architects are pursuing within a design space is so-called 'trade-offs', while it is well acknowledged that there is never an optimal outcome without compromise made over certain aspects. Given this, architects usually rely on their pervious project experience and expertise to make the judgment call on the best design solution. With emerging digital advances, we may now be able to integrate both quantitative and qualitative needs until discovering a feasible design solution space.

2.2. LINGUISTIC VARIABLES IN ARCHITECTURAL DESIGN

Some qualitative design problems are not defined with articulate rules but are verbally described based on human experience. For example, a client may ask for 'proper colour', 'sufficient lighting', or a 'large room'; and an architect may also respond with an 'asymmetrical shape' or 'positive space'. Here, neither 'proper', 'sufficient' and 'larger' nor 'asymmetrical' and 'positive' encompass precise meaning that can be mathematically programmed with design tools. Conventional hard computing approach may appear short-handed since a 'high degree of precision is usually incompatible with a high degree of complexity,' says Oguntade and Gero (1983).

Hence, the vague messages from one human being to another need to be interpreted before they become intelligible to a computer. Design requirements like 'large' and 'asymmetrical' are linguistic variables which possess uncertain qualities (Talašová and Achten, 2009). These 'soft' forms of data, according to Ottchen (2009), reveal aesthetical, socio-cultural, historical, and even political dimensions that should not be left out by architects while making design decisions. He suggests architects to look at a bigger picture where these qualitative variables are parameterised, constrained with domains, assigned with weight and integrated in order via building information models. Soft computing is capable of handling the architectural complexity of its inexactness and imperfection, which therefore suits architecture's ill-defined characteristic.

3. Fuzzy logic

Introduced by Lotfi Zadeh in 1965, fuzzy logic is one of the soft computing methods providing alternatives to classic bivalent hard computing. In order to describe linguistic variables or human mind per se, fuzzy logic reveals an inference system that models nonlinear functions of vagueness and complexity then transforms into a desired degree of precision. In a traditional crisp set, there are only two types of relationships exist between a variable x and a universe A: membership ($x \in A, A(x) = 1$) or no membership ($x \notin A, A(x) = 0$). Contrary to a traditional crisp set that builds on two-valued logic, a fuzzy set adopts partial membership to accommodate imprecise expressions. Its mathematical expression can be illustrated as $\mu A(x)=[0,1]$ (Cox, 1992).

3.1. FUZZY LOGIC IN ARCHITECTURE

This multi-valued expression allows designers to deal with qualitative design problems, which allows them to map an input space to an output space. Fuzzy logic was initially used for boiler design, in which the valve status has been determined by a range of temperature from 'cold' to 'hot'. Likewise, such soft data operation may also be applied to the architectural and urban domain so that multi-variate requirements are appropriately addressed. Within the realm of the fuzzy set, the problem-solving trajectory is no longer linear. For instance, if one divides the domain of a ceiling height into three subsets: 'tall', 'medium', and 'low', value h=3.2 m may belong to the 'low' and 'medium' subset at the same time.

In architecture, fuzzy logic is mainly used for design analysis and post-design interpretation. Talašová and Achten (2009) utilised fuzzy logic to evaluate the spatial composition of a villa design by Adolf Loos; Koutamanis (2001) has noticed the capacity of fuzzy logic representing human's vague expression, so he applied it in transforming architect's hand sketch into a digital model; Çekmiş (2016) created an evaluation method for the planning project of a residential community. However, only a few examples illustrated fuzzy logic's contribution to design generation: Wierzbicki-Neagu and Wilfred de Silva (2012) applied the idea to a folding structure design where they combined the soft-computing operation with genetic algorithm.

3.2. FUZZY LOGIC TOOLBOX AND DIGITAL DESIGN

Commonly used fuzzy logic control systems include Mamdani, Tsukamoto, Sugeno and Larsen. This project chose MATLAB Fuzzy Logic Toolbox with Mamdani inference system as an auxiliary design tool apart from Rhinoceros Grasshopper. It includes three general steps: 1) 'fuzzification' translates linguistic yet inexact variables into membership sets; 2) 'inference' creates a series of 'if-then' rules to integrate multi-dimensional design problems and to set their relative weights; and 3) 'defuzzification' adopts a centroid (centre of gravity) approach to extract a final solution from the output space.

The combination of Fuzzy Logic Toolbox and Grasshopper aimed to explore a pragmatic method addressing qualitative matters. A project's digital model reveals a fundamental design logic, in which its composition is secured with a series of parametric parent-children relations. By defining input parameters, an architect also articulates the boundary for fuzzy inference. In the gridshell design discussed below, this project regards Fuzzy Logic Toolbox as an analytical tool that grades project variations. By adopting Fuzzy Logic Toolbox, the student was able to transform her linguistic demands into computationally intelligible meanings, then combine with other measurable criteria in order to finalise the shape of a bending-active gridshell.

4. Fuzzy logic in gridshell design

The research of bending-active gridshell started from Frei Otto, a German structural engineer and architect who dedicated his life to designing lightweight flexible architectures. Gridshells are curved framework gains structural integrity from bending-active rod elements and rigid joints. 'Flatbed' is a typical gridshell construction method which gradually bends a planar grid that prefabricated on-site into shape (Crolla, 2018). Renowned built projects adopted this method include Mannheim Multihalle (1975) by Frei Otto, Japan Pavilion (2000) by Shigeru Ban, and Weald and Downland Gridshell (2002) by Cullinan Studio.

With emerging computational design and implementation technologies, people began to revisit gridshell practice and liberate this structure type from its typological cliché. Most importantly, off-the-peg simulation tools allow today's designers to quickly generate forms, offer them significant advances comparing to Otto's classic hanging-chain method. However, comparing to design data such as bending force and material properties, qualitative factors including space efficiency and construction difficulty remain unmeasurable. This project investigates the possibility of adopting Fuzzy Logic Toolbox to assist gridshell design.

4.1. A GRIDSHELL DESIGN STUDIO

This project chooses one student's design to illustrate the use of Fuzzy Logic Toolbox and design selection. The concept is a multi-purpose building with an equilateral gridshell that occupies an area of around 140 metres long and 90 metres wide, and the maximum structural height should be less than 30 metres. The building's program includes a theatre and several indoor basketball courts which demand a vertical space more than 10 to 15 metres. With the algorithmic modelling tool Rhinoceros Grasshopper and the real-time physics simulation engine Kangaroo, gridshell design concepts are created from a planner grid and anchored to several edge profiles. The project selects 6 different design options for evaluation via Fuzzy Logic Toolbox (Figure 1).

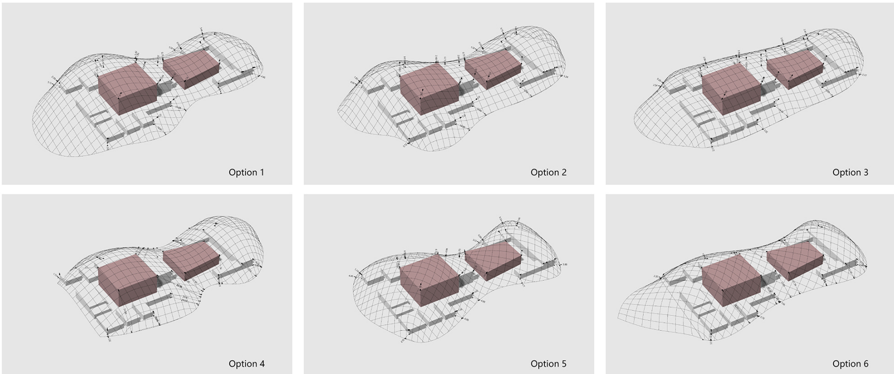

Figure 1. Gridshell design variations.

4.2. FUZZY LOGIC SETUP

Fuzzy Logic Toolbox is an individual plug-in of MATLAB, which uses data from a design's parametric model and transforms into fuzzy sets according to the inference rationale mentioned above. The project sets 4 types of data that concern structural integrity, space rationality and efficiency. Figure 2 shows several checking points that measure the distances between the roof structure and the programs inside. Coloured spheres are the indication of Gaussian curvatures at structure joints. For each gridshell design option, the programme boxes (in red) remain unchanged and whose corresponding 'Preference (P)' score is calculated from these variables below:

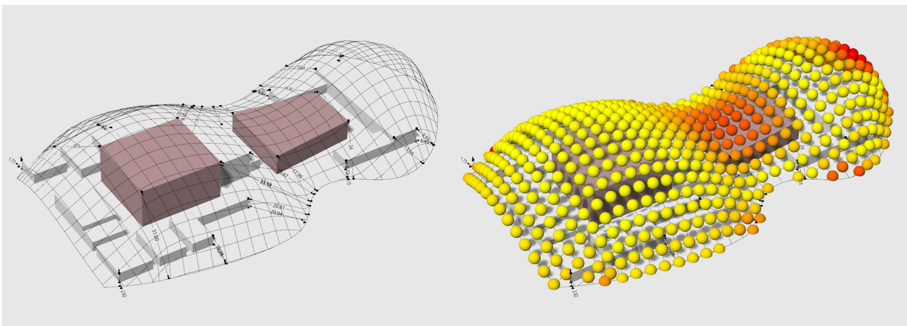

Figure 2. Gridshell checking points and Gaussian curvature indication.

1. The minimal (Hmin) and the maximum height (Hmax) of vertical space between a gridshell surface and the checking points. These distances (measured in metre) reveal the space efficiency inside a structure meanwhile evaluate if the overall structural height matches the requirement (neither too short nor too high). Both input variables are divided into 3 fuzzy sets based on designer's common knowledge: namely 'short', 'medium', and 'large'. For Hmin, these domains are [0, 2.5], [1, 3.5], and [2.5, 5]; and they are [0, 13], [10, 20], and [17, 30] for Hmax;
2. The horizontal space between internal walls and the gridshell surface, which is illustrated using minimal width (Wmin) and maximum width (Wmax). A proper distance shall neither be too narrow for a pedestrian walkway nor too tight for a public space. Thus, Wmin contains 3 fuzzy sets: [0, 1.5], [1, 3], and [2.5, 4], while Wmax's domains include [1, 8], [6, 14], and [12, 20], all units are in metres. The ranges of 'short', 'medium' and 'large' are defined according to human scale and common dimensions.
3. Structural and implementing rationality are represented using Gaussian curvatures. From the design's digital model, the study extracts three types of data including the tightest positive curvature (K+), the tightest negative curvature (K-), and the percentage of tightest curvatures to all (K%). Based on material test and gridshell construction experience, the study defines [-0.005, -0.003] and [0.003, 0.005] as 'high' curvature; [-0.0035, -0.0015] and [0.0015, 0.0035] as 'medium' curvature; and [-0.002, 0.002] as 'low' curvature. As shown in Figure 2, the range of curvatures is visualised with a colour gradient from red to yellow where red spheres represent 'high'.
4. A gridshell's total area (A) also influences the space efficiency. Thus, the project also categorises this parameter into 3 fuzzy sets: 'small', 'medium', and 'large' area (m2). The domain is appointed as [8000, 10000], [9000, 11000], and [10000, 12000] according to site conditions.

4.3. INFERENCE RULES AND EVALUATION

Fuzzy inference rules are the key to integrating these qualitative design requirements that are seemingly disconnected or even conflicting. All these input variables are influenced by the gridshell geometry. For example, an 'efficient' building plan layout may result in a high percentage of 'high' curvatures in the roof structure; or the vertical and horizontal space cannot be 'large' or 'small' at the same time. With the Mamdani fuzzy inference system, the project defined in total 16 rules (Figure 3) subject to the input values and the corresponding design problems the value represented. Design options are graded using 'preference (P)' where 'not preferred' range from 0 to 40, 'medium preferred' range from 30 to 70, and 'preferred' range from 60 to 100.

Each rule shares the same weight insofar as it equally affects the final score of a design option. More than half of the rules (rule No.1 to No.12) describe the designer's concern about spatial quality. For instance, rule No.1 says 'if Hmin is short while Hmax is large and A is small, then a gridshell is preferred.' On the contrary, rule No.8 indicates 'if Wmin is large and Wmax is short or A is large, then a gridshell is NOT preferred.' These are 2 rules that interpret a designer's demand for 'proper' space. Also, rule No.13 to No.16 follow rigid structural requirements. For example, rule No.13 clarifies 'if both K+ and K- are low and K% is low, then a gridshell is preferred,' but rule No.15 argues 'if either K+ or K- is high and K% remains medium, then a gridshell is 'medium preferred.'

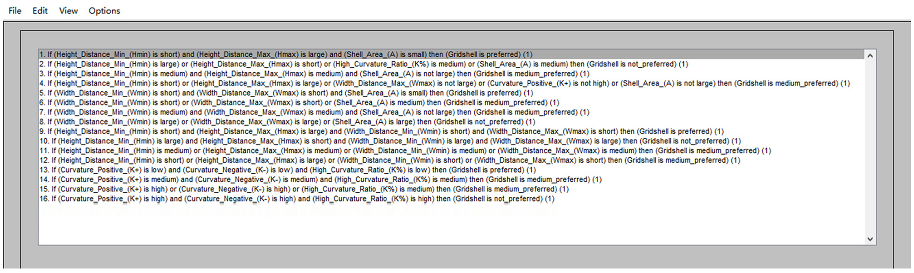

Figure 3. Inference rules created in Fuzzy Logic Toolbox.

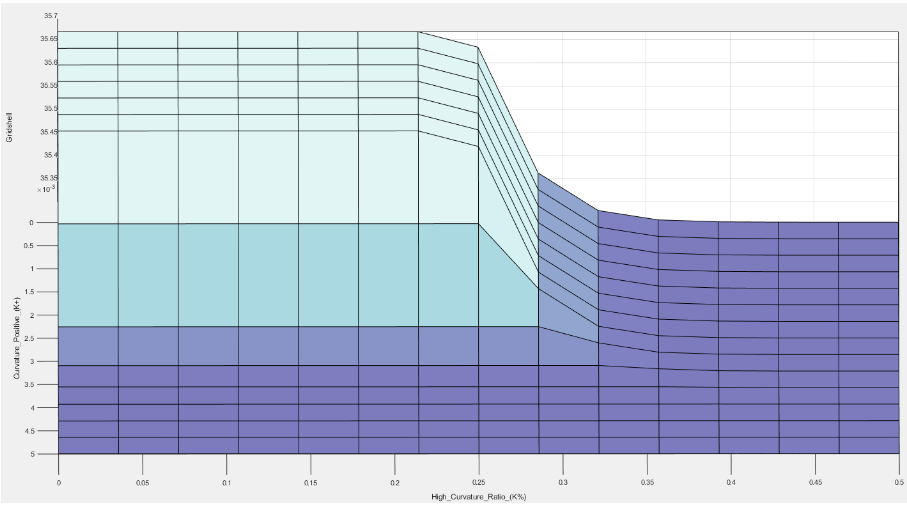

Figure 4. A 3-dimentioanl relation of 'K+' and 'K%'.

These 16 rules establish a non-linear analytical system that helps the designer to sort design options. Figure 4 illustrates the non-linear relation of 'K+' and 'K%' under rule No.13 to No. 16. For each design option, the project extracts 30 values from the gridshell's digital model and converts which into 8 types of fuzzy sets. Final grade 'P' is calculated through a centroid defuzzification method (Figure 5). In the end, Option 4 gets the lowest score (35.4 = 'not preferred') while Option 6 is relatively higher than the others (43.2 = 'medium preferred').

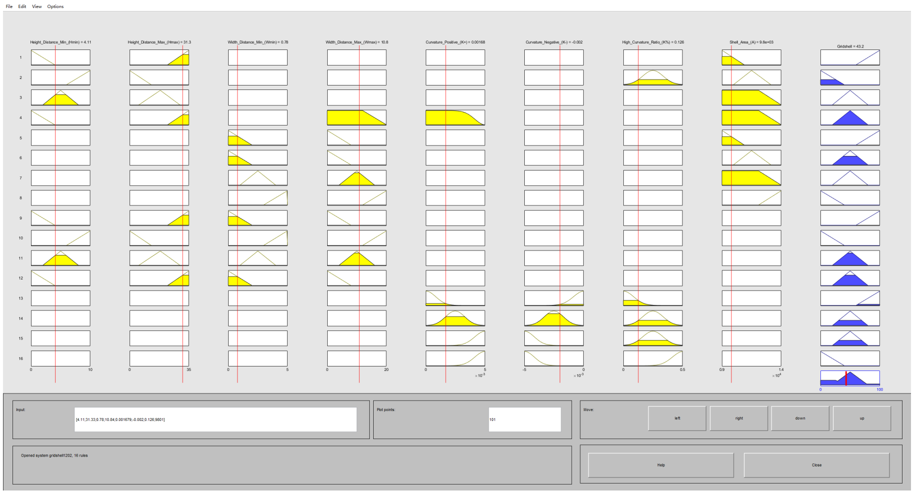

Figure 5. Option 6 fuzzy inference and defuzzification.

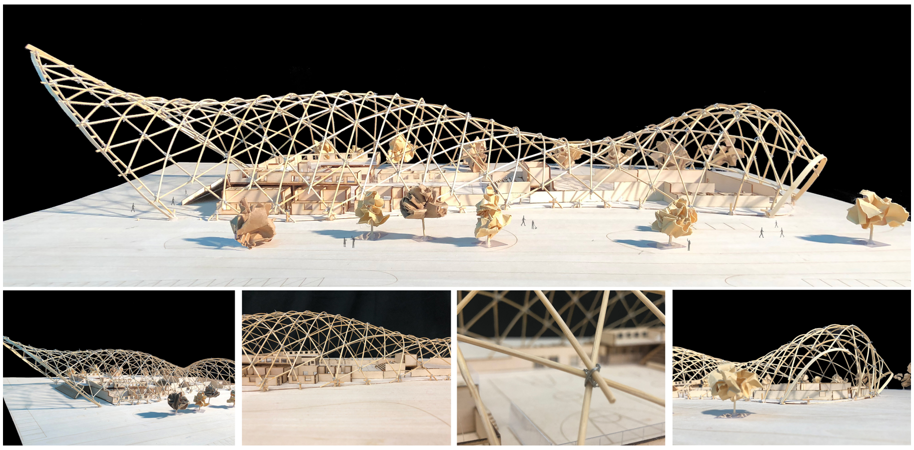

Figure 6. Physical model of option 6.

Just by visually comparing Option 4 and 6, the designer will not be able to tell the reason why one gridshell is better than the other. This makes Fuzzy Logic Toolbox interesting media for architects and engineers to approach complex design problems. In this case, the project helps the student to choose the best yet pragmatic shape out of 6 bending-active gridshells. The chosen outcome is tested through physical modelling (Figure 6).

5. Conclusion

This project uses a bending-active gridshell design to demonstrate the feasibility of fuzzy logic in assisting design decisions. The introduction of fuzzy logic may reduce the negative impact of traditional hard computing since, in this project, the chosen parameters for soft computing combine common design knowledge, human scale, material properties, and designers' conscious demands. The author believes that fuzzy logic is not only suitable for post-design evaluation, but also can be used for design generation as an optimisation tool.

Integrating soft computing into architectural decision-making aims to reduce architects' bias and increase design rationality. Fuzzy logic provides a mathematical approach for describing linguistic variables as these qualitative design requirements often play an essential role in shaping a design trajectory. With the rapid development of computational intelligence, questions emerge: how to address 'humanity', or the uncertainties, ambiguities, and comprehensiveness in other words, in today's digital workflow? What is the appropriate collaboration mode between human and machine? Through a preliminary experiment, this project postulates fuzzy logic as one way to help architects resolve ill-defined design problems, to sort multi-variate variables, and eventually to mathematically transform qualitative needs into a design-solution space. Its further applications may appear in urban-scale analysis and design as well.

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