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Research

Parametric Development of Variable Roof Structures with Central Supports (Tulips)

Presented at Nexus 2012: Relationships Between
Architecture and Mathematics, Milan, 11-14 June 2012

Abstract. This work describes the exploration of a parametric system to generate variable designs of low-cost roof units with central support (called “tulips”). The units aim to cover out-door areas and are composed of commercial wood struts, digitally manufactured plates and a fabric cover to enable mass production and variations according to different structural, functional and climatic conditions. The development has combined topological analysis, genetic algorithms, parametric programming and digital fabrication to produce models and full-scale prototypes. This process suggests an approach to rationalizing design through mathematical analysis and digital implementation that supports flexible and quick elaboration. That example illustrates new methods of architectural design with early integration of technical studies and industrial production.

Keywords: parametric design, genetic algorithm, digital fabrication, topological optimization, roofs, structures

1 Introduction

Due to the diverse conditions and complexity of today's buildings, architectural design usually develops unique solutions for each commission, thus generating long and burdensome processes for each specific project. However, new design, analysis and fabrication technologies make it possible to establish work strategies for groups of building parts [Kieran and Timberlake 2004], and some experiences have demonstrated the possibility of applying these capacities to produce variable construction components [Stacey 2004; Gramazio and Kohler 2008; Meredith et al. 2008; Figueiredo and Duarte 2009], such as the usually sophisticated elements of large-scale building projects, to absorb the cost of the advanced technologies used. This paper presents an exploration of the potential of these systems to generate a variety of low-cost roofing modules with central supports (called “tulips”) to cover outdoor places. It develops a parametric programming for roofing units with digitally fabricated timber plates, regular struts, and a covering fabric. The system is aimed at large-scale production of solutions that can be adapted to suit different structural, functional and climatic conditions.

The development first involved the use of topology optimization software to determine the general shape of the roofed module. This was then interpreted as a structure of struts and plate connectors. Next, analyses of functionality and daylighting were then carried out for different structural designs, which were studied in parallel to assess their load-bearing capacities. In this way, numerical tables were obtained, listing the angles of the upper and lower struts in different conditions, which were integrated

with genetic algorithms to determine more appropriate solutions. This procedure was implemented in a parametric design system with two strategies of genetic algorithm (an installed component and open programming) to compare their results with different population regulations and mutations. The parametric elaboration of the construction design is then developed, generating a visualization of the different modules with mapping of the connecting boards and design of the covering fabric for digital fabrication. The execution stage involves the assembly of the timber struts with manufactured plates, smaller pieces and the corresponding fabric. The process deals with analysis, design and general planning as well as the creation of physical models and full-scale prototypes.

Fig. 1. Alternative designs of the units. Rendering: authors

2 Design and analysis

The shape of the units initially came about through an analysis with structural topology optimization, using CALFEM, ANSYS and TOPOPT software in a collective exercise with students. A one-day collaborative workshop with architecture, civil engineering and computer science students from different universities was developed in order to explore design possibilities. After that, some students then went on to carry out further specific tests of specific alternatives. The structural topology optimization method enables the definition of the most resistant configuration for a quantified space through finite element analysis with continuous isotropic materials [Bensoe and Sigmund 2003; Allaire 2004; Huang and Xie 2010]. In this case a covering area per module was defined with a central support area at the base, which was translated into volumetric and planar section discretization. This data was processed by commercial software with optimisation functions or independent experimental programmes to compare processes and results. Iterations were carried out with different densities and penalization values, generating maximum resistance silhouettes which were then converted into spline profiles in CAD software either by direct drawing or archive conversion. These layouts were prepared for cutting with digital fabrication on scale models, using laser cutters on 3mm MDF sheets with pieces of fabric and in some cases with the incorporation of struts. Different

assembly strategies were developed, mostly concerning the connections between plates. The models were reviewed according to the architectural configurations generated, functional capacities (maximum coverage, efficient use of the base), structural solution and use of materials.

Fig. 2. Structural topological analysis. Computer visualization: authors

Fig. 3. Examples of collaborative workshop to explore initial possibilities. Photo: authors

Some architecture students then continued the work, drawing up the construction strategy, replicating the profile with steam-bent timber pieces to create a large-scale prototype that including fabric, floor and fastening connectors on minor struts. Engineering students also carried out subsequent analyses to determine the structural development area and the underlying free space, identifying the main layouts that could be interpreted with industrialized elements to facilitate large-scale execution. The capacities of different materials and construction elements were reviewed, and a general shape was established and interpreted in construction terms with commercialized timber struts.

Fig. 4. Schematic design of the roof units (tulips). Renderings: authors

In this way the overall design for the subsequent development stages was defined by the standard lengths of the commercial timber struts with a radial distribution, forming a pyramidal base and a six-faced polyhedron above as the roof covering, both shapes converging to a point of union. This structural unit (called “tulip”) creates a stable central support with the minimum of three elements and an extensive roof covering made up of six similar elements forming a hexagon, facilitating the relationship between the base and the roof, as well as the combination between modules to obtain extensive coverings. The length of commercially available struts allows for a roof covering of about 30 square meters per module with a base that occupies some 3 to 5 square meters using very low cost and easy to assemble elements for the surface area covered. The horizontal relationship between the struts is kept constant (120° for the base and 60° at the roof covering) in order to maintain a regular load distribution. However, the vertical angles can vary at both the base and cover to adapt to different topographies and functions at the base, or environmental conditions such as solar radiation, wind or rainfall at the roof level. The relationship between base and roof can also vary (if the roof plane is inclined on one side this must be compensated by lower supporting struts). To this end, structural resistance studies were carried out with different angle conformations, first with regular (symmetrical) variations in the roof cover and base and then with irregular (asymmetrical) variations.

Some functional and environmental analyses were also undertaken at the initial design stage. First, the total horizontal surface covered was examined according to the different angles of the upper structure excluding the horizontal surface area occupied by the base in order to determine useable surface area and functional possibilities (as well as rainfall protection and accumulation, according climate data). Secondly, the sun angle was simulated for the site latitude at different times of the day and periods of the year. A summary of sun shading was then calculated for the summer equinox between 12:00 and 18:00, as the occupation period requiring the greatest sun protection. This generated different shade amounts according to coverage angles of the struts (with greater shading achieved with an asymmetrical layout), resulting in tables for shading and surface area covered. In the differing angles of asymmetric coverings, modifications in the angles were related to changes in the base pyramid necessary to maintain stability and the consequent reduction in useable ground space. Likewise, a numerical table was drawn up showing global resistance according to roof inclination angles and wind directions according to structural calculations. This series of tables was fed into in a genetic algorithm to select appropriate designs according to sun and wind orientation. Tables or values regarding the topographic variations of the site or the relationships between units for the connecting pieces (since any inclined unit must connect with the adjacent one to form a continuous roof) or other specific variations in the project can also be incorporated. However, in this present study the application was assessed according to the aforementioned functional, environmental and structural tables which provided relevant and partially contradictory

values (since the highest useable area and structural resistance coincided with symmetrical configurations but better environmental conditions arose from more asymmetrical designs). Genetic algorithm analysis makes it possible to find suitable solutions (though not necessarily the optimum ones) to complex problems with multiple requirements. This is achieved by generating sets of possibilities (populations), reviewing some of these (individuals) in relation to a function of features and producing a number of mutations following rules similar to those of genetic growth [Goldberg 1998]. The technique has already been applied in some architectural problems, demonstrating the application of this technique to find more proper design alternatives [Nahra and Terzidis 2006; Marin et al. 2008; Papapavlou and Turner 2009].

Fig. 5. Genetic algorithm with Galapagos (top) and Visual Basic (bottom). Screen shot: authors

For the genetic algorithm analysis a basic layout was implemented in Grasshopper's parametric programming within Rhinoceros three-dimensional modelling software using the Galapagos component, as well as a specific utility developed in Visual Basic in order to compare results [Namoncura and Vásquez 2011]. In both cases variations in upper and lower strut angles of the basic structure were established with an optimization

formula using the data tables sequentially, starting with random values generation and a determined solar/wind orientation. The Galapagos component has the advantage of enabling modifications to be visualized since it shows all the angle alternatives evaluated as well as a graph of the progression of evaluations and convergence with function, although crossing patterns cannot be modified. Visualization was not implemented in the programming developed, but rather alterations of populations and mutations could be defined. A significant difference was noticed in the results between software, with the Galapagos component presenting a high level of convergence in each generation, hence requiring many populations and generations to test more optimal alternatives that became progressively more similar. In contrast, the programming developed with Visual Basic achieved more optimal results with a smaller number of populations in each generation (and hence less time and computing resources were needed) while finding a greater variety of solutions. This was mainly the result of a greater variety of strut crossing patterns, thus creating mutations for a broader range of configuration possibilities, as shown in other similar experiences [De la Barrera 2010]. This is relevant architecturally speaking, since more diverse but sufficiently optimal possibilities can arise, combining configurations or making them compatible with other non-quantifiable requirements (circulation, views, etc.).

Fig. 6. Parametric programming (top) and models developed (bottom). Renderings: authors

Subsequently, based on the general layout, the complete parametric design of each structure unit (tulip) was created. This started with the main timber struts, defining volumes for the different pieces according to the structural calculations and developing the connector plates by means of intersection operations and define connections between pieces, according the thicknesses of commercial boards. A final visualization process was included in the programming to permit further elaboration (integrating structure with general modeling of the surroundings to obtain renderings of the places covered). In a further programming sequence the plate profiles were developed in preparation for the cutting process by digital manufacturing (and also the distribution routines in commercial boards were calculated). The fabric also has a programmed design process, based on the disposition of the points of support in each upper piece (the lower pieces are always fixed to the base ring). Variations in fabric development were mainly related to the asymmetry or extensions of the pieces. In each case an unfolding process is used to

establish cutting lines with overlaps required for the edges and unions, thus favoring a radial layout for the final assembly on-site. Regular construction detail plans were used for the concrete foundations, minor connectors and special pieces as well as a list of materials per unit. These data completed the documentation used for the production and installation.

Fig. 7. Programming of fabric cover. Renderings: authors

Fig. 8. Arrangements of units. Rendering: authors

3 Fabrication

The construction of the tulips involves standardized supporting elements and components created by digital fabrication procedures, which are easily modifiable with parametric design [Seely 2004]. The supporting struts are made of natural re-forested timber pieces commercialized at low cost throughout the country (about \$5-\$10 US per piece), although the quality is irregular (in terms of moisture content and knots, which can lead to subsequent deformations or reduced loading-bearing capacities). However, a visual selection can be used to adequately identify such problems without a major increase in costs. These timber pieces are sold in different rectangular sections measured in inches with a general length of 3.20m due to the limits imposed by commercial sawing machines. The ends of these timber pieces must be refinished since they may need to be regularized and perforated and, in the case of the main struts (of the central pyramid), also slimmed along their sides to reduce their weight at the far end (and hence provide a larger and lower base). Generally, three main struts are used, then a further six upper ones for the roof and six lower ones for upper stress at mid-height of the covering structure. If the design includes an extension to the bases or roof cover due to special topographic or environmental conditions, then more struts may be used or longer pieces of timber sourced (available to purchase, though usually in a smaller selection of thicknesses). The timber struts are cut with hand-held electric saws using aids also made by manufactured plates where the pieces and saw are placed in slots to hold the timber in place and direct the saw cuts according to the required angles and lengths of the design.

Fig. 9. Constructive details of execution. Image: authors

Sheets of structural plywood may also be used for the manufactured plates (made of thin laminas of timber from native hardwood trees glued together to form a thicker sheet with high stress resistance), with profiles defined by the parametric design and cut with a CNC router machine. An optimization routine is used to determine distribution in the board, particularly when a large number must be cut. These make up the central node with two horizontal plates and six vertical ones to bear the upper struts and receive the lower ones, with various securing methods for different angles. An intermediary bracing plate can further strengthen the configuration (and also serve to carry or channel the accumulation of rainwater on the roof) as well as a base plate to guide initial assembly (removed once construction is complete). Other plates can also be added for additional functions, particularly regarding the central pyramid (seats, tables, space divisions, etc.). Diverse minor metal parts are also included but attempts have been made to minimize and simplify these by using simple connectors readily available from any supplier, including nuts and bolts and folded metal bands.

There are different options for the roofing material depending on the function and maintenance care involved. These vary mainly in terms of their technical quality and cost. They range from simple linen to highly resistant and durable fabrics, such as Précontraint® 402 from Ferrari with a tear resistance of 250/250daN/5cm (according to ISO 1421) and a weight of 490g/m², requiring a design process (dimensioning) in accordance with the lengths of commercially available fabric for layout, cuts and seams (or heat sealed edges). This includes the use of barrette and wire-reinforced edges. Prefabricated concrete cubes can also be used for the foundations on site and to compensate for lower loads, bolted to the struts of the pyramid.

Fig. 10. Prototypes built. Photos: authors

Therefore, for the elaboration of each module, parametric design is used to define the main struts (verifying if regular commercial or special lengths are needed) and determine the necessary accessories and bases (which do not usually vary per unit). After this the layout of the plates and roofing fabric is obtained, taking into account specific variations. The layouts of the different modules are then grouped together into a whole (or a series of parts to be constructed) to make the best use of materials, optimizing use of timber boards and roofing fabric lengths. Following this, the cutting of plates and fabric is programmed and carried out with regular-sized CNC machines. The base plate to guide assembly and a labeling system for the pieces in each module are included.

Installation starts out from a determined ground level and reference point, where the base plate is positioned, thus enabling the concrete bases and supports for the main struts to be put in place. The pyramid is then assembled on its side with its intermediate plate and upper node, then lifted and placed onto the concrete bases. The upper struts and ties (already braced) are then built on with the use of scaffolding and lastly the roof fabric is added and a final coat of sealant applied.

4 Conclusion

This experience in working on a centrally-supported variable roof module has led to the development of a complete production strategy, including design, planning and creation of models and prototypes using advanced digital resources. Final fabrication, installation and widespread use are still needed in order to fully prove the potential of this approach, enhanced by the expected adaptability and low cost per unit.

Topology optimization techniques were applied to explore structural configurations that were then interpreted with industrialized elements, in a novel design strategy. An

analysis of geometric alternatives was developed according to functional, environmental and structural factors through the use of genetic algorithms, thus identifying the incidence of population regulations and mutations in the variety of resulting solutions. Parametric programming for the main configuration of the design was devised, including the connector plates and fabric cover, thus demonstrating the geometric relationship between the components and variations visualized and determining the automatic fabrication of design layouts. Digitally fabricated scale models were also created with a laser cutter and real size prototypes produced with CNC routers, combining commercial timber struts, manufactured plates and textile, as well as other minor pieces. A procedure was established for execution and verification of aspects of construction, use, spatial conformation and appearance.

This initiative to date has permitted the testing of diverse advanced design and fabrication technologies, aimed at creating variable units that are both economic and fast to produce. It has served to identify diverse conditions through the use of numerical ranges and analysis procedures to define optimum characteristics in different situations while also integrating regular design and construction processes. Although this proposal has yet to be built on a mass scale and distributed in order to fully refine the processes involved, it points to a combined strategy of design rationalization with mathematical studies and digital implementation that could lead to large-scale and efficient development. This example suggests new methods of architectural production with the early integration of technical analysis and industrialized production with the potential to contribute to a wide variety of construction possibilities.

Fig.11. Model of a group of tulips. Rendering: authors

Acknowledgments

Research project Fondecyt 1100374, students Omar Rivera, Eduardo Saez and Manuel Vasquez.

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