Digital tools in the architectural design of a geodesic dome

The case-study of the bearing structure of an artificial sky lighting installation

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Abstract. This article discusses the use of digital technology in the design and construction of a geodesic dome built in a student workshop as the bearing structure for an artificial sky lighting installation. Digital tools were used for the whole process from preliminary to detailed design, fabrication and assembly, in order to allow the investigation and precise representation of the geodesic geometry. However, limited possibilities, in combination with the intrinsic nature of the geometry, which allowed segregation of tasks, did not permit a full exploration of the potential of the digital continuum at that time; even though taking advantage of digital technologies, the process maintained some of its linear characteristics. A couple of years after the successful completion of the installation, the project is ‘revisited’ in retrospect, and the design process is ‘reengineered’ considering the design potential of recent advances in digital technology. In this work in progress, an attempt is made to work with an inclusive model that contains geometric, structural, material and manufacturing input and constraints and can inform design, fabrication and assembly processes, allowing for dynamic manipulation and control of parameters at any given time; thus, reconfiguring in real time the design, as well as the related processes.

Keywords. digital tools; parametric design; geodesic dome; artificial sky.

DESIGN OBJECTIVE: DESIGN PROGRAM, CONSTRAINTS AND CHALLENGES

The project was initiated at the Department of Architecture at the University of Thessaly in spring 2008, as a response to the school’s decision to enhance daylighting studies and incorporate them in the architectural design sequence.

Since a geodesic structure seemed a relevant paradigm, as evidenced in numerous artificial sky installations (Mansy et al 2005), the goal served as a motivation for a student workshop, exploring geodesic geometries and technologies, as well as lighting performance. The actual designing team was narrowed down to a group of senior students of the Team [K]-onstruction [1] of the school, assisted by professional specialists and supervised by the professor in charge. Available means, tools and knowledge background of the students were defining parameters of the process. Real constraints, budget and purpose
related, defined decisions, while the time-frame was not restraining. Demand for easy and safe mounting by an inexperienced student crew was of key importance, while the lighting installation demanded a high level of precision, yet a considerable amount of flexibility, allowing low tolerances for displacement.

A brief feasibility study revealed the possibilities and challenges of a custom designed hybrid structure consisting of a primary bearing hemispheric geodesic dome with pin-joined custom elements (struts and joints) carrying a secondary inner ring-dome structure for the lighting installation. (Fig. 1)

The final installation is a 4.0m diameter free-standing dome structure raised on a 0.90m high base. The primary structure is a modified class-I three-frequency icosahedric hemispherical geodesic dome; that is, the geodesic polyhedron is generated by the icosahedron by subdividing into three parts each edge of its original faces. (Kenner 1976)

For the final dome configuration, 165 struts (of eight different lengths) and 61 node joints (of nine types, in four-, five- or six-strut arrangements) were fabricated; typical strut consisting of a circular steel tube (26.9dia.x1.5mm) and typical node joint produced of steel plates (4mm thick). The secondary inner structure outlines a hemispherical frame for the 145 luminaires, arranged after Tregenza (1987)'s model for sky luminance distribution.

This article refers in detail to the primary bearing geodesic dome of the installation; the secondary system and lighting system are not addressed.

THE PROJECT AS REALIZED: AN EFFECTIVE, YET INEFFICIENT, PROCESS

In the actual project (Vrontissi 2009), digital technology was used to:

- Provide diagrammatic sketches on possible alternatives at the conceptual phase
- Define exact geodesic configuration and extract geometric data
- Design the dome elements (design of node joints and definition of strut lengths)
- Share the design output with the manufacturer
- Decide on the assembly sequence

**Preliminary design**

While a geodesic dome seemed the apparent solution for the bearing structure, preliminary studies proved difficult the task of directly relating the lighting pattern with a geodesic one. Alternatives were considered and discussed based on diagrammatic digital models, generated with conventional 3d-modeling software, open source (Blender) or proprietary (AutoCAD and 3ds Max), to finally support the decision for a hybrid structure consisting of a bearing geodesic dome combined with a secondary inner structure for the lighting installation.

**Design development - defining the geometric configuration**

Initial studies focused on geodesic principles (Fuller 1975; Tarnai 1996; Wong 1999) and constructional complexities through physical models, while design development was based on digital models.

*Figure 1*

Plan, elevation and section of the artificial sky lighting installation
Application specific software tools (namely Cadre Geo [2]) was tried out to define the geometric configuration of the geodesic dome and extract the related geometric data. (Fig. 2) Input included selection of base polyhedron, sphere radius, geodesic class and frequency, as well as definition of zenith and cutting plane. Output, in the form of tables or 2d-drawings and diagrams (in .dxf format), contained information about overall quantities and identity (absolute and type related) of vertices and edges, as well as specific data for each edge (‘strut’: type, length) and vertex (‘hub’: type, amount and identity of neighboring vertices, as well as angles in section and relative angles between neighboring vertices in plan). (Fig. 3)

**Design development - design of node joints**
Several alternatives for the joint configurations were studied on full-scale mock-ups before the digital 3d-modeling of the node elements was finalized.

Once determined, the geometric output was imported in conventional 3d-modeling software (Autocad) and a set of the actual 3d-models of all node joints was produced, informed by structural and material input (strut diameter, bolt types, thickness of steel for plate connectors and strut end parts), as well as manufacturing and assembly constraints (cutting, folding, piercing and processing capacities of available machinery). (Fig. 4)

This proved to be a rather laborious task, tedious, yet exceptionally demanding, as the 3d-modeling of each node joint, though following the same routine, was performed separately, while additional cross-checks had to be performed periodically to ensure consistency of the design of all elements and optimization of the construction process (i.e. to identify the ‘critical node’ from which the design of all nodes was to be derived, to readjust the geometries of node joints, to calibrate positioning of holes and strut lengths in order to ease strut fabrication).

**Fabrication process**
While a file-to-factory approach was envisioned, directly using the set of 3d-models of the node joints for production, further modifications were needed in order to translate the design output to fabrication data. Given the specifications of the available facilities, tables (for strut lengths), 2d-drawings (of the node joints and strut end elements) and accompanying diagrams (with folding directions) were necessary for fabrication.
The 3d-model of each node joint was unfolded to a 2d-drawing to be sent to the fabricator for the final pieces to be cut, pierced and marked (with type and orientation) as indicated on the 2d-drawing and, then, folded as instructed by the accompanying diagram. At the final stage, all pieces were meticulously hand-tagged and arranged by type, based on the explicit inventory of the initial geometric output. (Fig. 5)

Assembly
The assembly of the geodesic dome - extensively tested on physical models at first - was cautiously designed, based on the recurring geometric patterns; the geodesic dome being basically composed of five identical sectors.

Further editing of the digital material was needed in order to explore the geometric patterns of the geodesic structure and decide upon the assembly sequence. Three elements (Fig. 6) were of crucial importance for the assembly process:

- the overall 3d-model of the dome, composed out of the, so far, individual 3d-models of the node joints, mapping (by color indexing) different types of struts and nodes within the overall figure, in order to display in a self-explanatory way the geometric patterns
- the catalog and individual 2d-diagrams for every type of node joint, containing information about node type, quantities, orientation and type of neighboring struts
- the actual marking of node type and orientation on the node pieces

The actual mounting of the geodesic structure, the highlight of the workshop, was smoothly performed in a day (five working hours!) by a crew of fifteen students. Starting from the base, mounting was performed by level, adding five identical pieces or geometric entities in each step. (Fig. 7)
Comments
In this first approach, digital tools allowed the investigation and precise representation of geodesic geometries, otherwise difficult, if not impossible, through mathematic constructs, or of low precision through physical models.

Although the design approach was universal and similar process was used for the design of all pieces, each element had to be modeled individually from scratch, locally defined and then globally transferred, in an effective, yet inefficient, process, requiring an enormous amount of effort and time for a large series of, otherwise, repetitive tasks and control-checks.

Furthermore, the approach was quite fragmented, for different parts of the design development, as well as for different steps of the whole process. Five discrete tasks, each one using a different set of digital tools, could be identified: overall geometric configuration, design of dome elements, overall dome design, fabrication, assembly; some of them progressing simultaneously, some requiring a fixed input from a prior stage and some partly overlapping. It was a laborious, not to mention problematic, task.
to transfer information across different tasks and software applications; the Cadre Geo tables or 2d-diagrams (containing geometric data), the Autocad catalog of (construction aware) 3d-models or (fabrication ready) 2d-drawings, the Autocad and 3ds Max overall 3d-model of the dome structure (for assembly purposes).

Finally, while the intrinsic characteristics of the geodesic structure allowed separation of tasks, this method forced to finalize certain decisions at a certain point of the process, which in turn allowed for limited changes, interactions or explorations during the design process.

**THE PROJECT ‘REVISITED’: PROPOSING A DYNAMIC INCLUSIVE MODEL**

**Design development**
The design development, for the geometric configuration as well as for the individual design of the elements and the overall design of the dome, is based on a sole 3d-model. This inclusive model contains geometric, structural, material and manufacturing input and constraints and can inform design, fabrication and assembly processes, allowing for dynamic manipulation and control of parameters at any given time; thus, reconfiguring in real time the design, as well as the related processes.

In a work in progress employing contemporary tools and techniques, generative modeling software (namely Rhino 3d) using a graphic algorithmic editor (Grasshopper 3d) is tried out in an effort to ‘re-engineer’ the design process and allow for a parametric approach. Theoretical studies [3] and existing tools, such as the StructDrawRhino [4] [5] [6] plug-in (from Geometry Gym) were considered in order to come up with a relevant definition. The final definition, generating a controllable geodesic topology is derived from the Geodesic Sphere definition [7] by D.Piker (which generates geodesic curves, therefore, not suitable as it is). All intersections of a tesselated face of the icosahedron are projected on a sphere, generating at first the equivalent set, and then, by revolution, the whole of the vertices of the geodesic dome. (Fig. 8) Further modifications are set up to extract the edges and introduce a cutting plane. Input includes sphere radius and geodesic frequency (the base polyhedron and the geodesic class are predefined), while output is generated in the form of a 3d-model of the geodesic geometries. (Fig. 9)

The definition is extended in order to generate the 3d-models of all geodesic elements (node joints and struts). Parameters include structural and material input (strut diameter, bolt types, thickness of steel for plate connectors and strut end parts), while manufacturing and assembly constraints are uniformly embedded and cross-checks are automatically performed. (Fig. 10) The structure is populated, as routines are automatically repeated for all elements; the progressive design of all node joints and struts is gradually performed, so is the characterization of elements by type. (Fig. 11)

**Fabrication**
The parametric approach doesn’t affect the fabrication process if the same facilities are to be used. An unfolding routine can be added to the definition in order to produce the necessary 2d-drawings for the fabricator; however, the model would still not contain all necessary information for fabrication.

**Assembly**
Regarding the assembly process, the proposed approach provides the basis for studies of geometric patterns and assembly sequence; however, in this case also, further editing is needed for adequately mapping, indexing and cataloging different types of elements.

**Comments**
The potential of parametric methods and tools was already evident from the initial process. A parametric approach, in the design development phase in particular, could effortlessly substitute for a series of tedious repetitive tasks (namely drafting and cross-checking) performed manually and individually for each element.
Figure 8
The Grasshopper definition- part I: generating the geometric configuration of the geodesic dome

Figure 9
Several geodesic configurations (5V, 4V, 3V, 5/8 3V, 4/8 modified 3V) generated from the initial definition

Figure 10
The Grasshopper definition- part II: design of typical node joint

Figure 11
The Grasshopper definition- part III: progressive design of all nodes and struts is performed automatically, so is the characterization of elements by type
However, the real advantage of this approach is the generation of a sole, yet inclusive, dynamic model (Fig. 12) that allows interaction between the top-down geometric exploration (related to programmatic requirements) and bottom-up construction investigations (in relation to structural, material, fabrication input and necessary output); therefore adding constant flexibility to the design and introducing a non-linear design process.

A more sophisticated process (in terms of mathematical knowledge of geodesic geometries) would be needed in order to effectively generate an efficient set of data equivalent to the explicit counterpart produced by the application specific (for geodesic structures) software, which proved vital to the logistics of the project and the assembly process. A further challenge would include the potential to embed such an input within the 3d-model in order to inform directly the assembly process (i.e. each piece carrying an individual identity and marked with data, such as type and orientation, necessary for the assembly process).

In regards to fabrication, the real potential of the tool could be explored if different facilities were available, in order to take full advantage of the digital workflow from design to manufacturing, using intermediary scripting methods to directly transfer the information from the 3d model to the cutting table.

**CONCLUSION - FURTHER DEVELOPMENT**

The successful implementation of this project, initially confirmed in the assembly process, and then demonstrated in the first trials of the artificial sky installation, provides positive evidence about the skills and competences that can be nurtured in an educational framework.

Digital tools proved to be crucial in the design and manufacturing of this project, by providing the means to study, design, construct and assemble a non-rectilinear geometry. Furthermore, the parametric approach provides the means not only to further facilitate the design process, but also to allow the exploration of variations of this geometry, by dynamically informing the design process with

*Figure 12*

*The Grasshopper definition: a dynamic inclusive tool*
topological, as well as material, structural, fabrication and assembly input.

While the use of digital fabrication methods and tools has been largely discussed in recent years, as renewed interest in material, structural and environmental performance has emerged (Oxman and Oxman 2010), examples that focus on the parametric generation of construction aware architectural geometries are still limited, especially in the case of structures with discrete connection components, even more in architecture education (Pottmann 2010).

In the design of non-rectilinear forms in particular, current discourse in professional and research practice addresses issues related to geometry and manufacturing (i.e. tessellation problems), as well as technological studies (i.e. design of nodes). The design of nodes in geodesic structures, or, more generally, in space-frames (Gerrits 1998; Chilton 2000; Makowski 2002), has been repeatedly discussed in the past and is still open to discussion, while the issue of solving a node universally defined, yet locally refined, remains of crucial importance. In this direction, this work in progress, addressing a structure that has discrete connection elements, and attempting to include their design within the parametric model, remains of relevance.

While no specific contribution is attempted as far as the digital fabrication process per se is concerned, interesting remarks are drawn in relation to the need to embed information related to the assembly process and the logistics of the process within the parametric model; parameters that are often left aside to be dealt at a later stage or through separate tasks and tools.

Furthermore, in the case of artificial skies in particular, associative geometry strategies and tools could be explored to investigate possibilities of combining geodesic patterns with patterns modeling sky luminance and resulting arrangements of luminaires (Yoshizawa et al 2008), in order to avoid the interfering secondary structure for the lighting installation.

REFERENCES
Fuller RB 1975, Synergetics: Explorations in the Geometry of Thinking, MacMillan.
Kenner H 1976, Geodesic Math and how to use it, University of California Press.
Structures, Proceedings of the International Association for Shell and Spatial Structures (IASS) 2009 Symposium, Universidad Politecnica de Valencia, Spain, pp. 1379-1390.

