Designing and building a geodesic dome as a bearing structure for an 'artificial sky' lighting installation

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Abstract

This article presents the design and construction process of a geodesic dome built in a student workshop as the bearing structure for an artificial sky lighting installation. The applied methods and tools are discussed as a case-study of an educational module providing not only significant input for the specific type of structures and related technologies, but, furthermore, giving valuable feedback to future practicing engineers.

Keywords: geodesic dome, artificial sky, Tregenza sky hemisphere subdivision, custom-design, space-frame joint, multi-disciplinarity, design-built workshop, experimentation.

1. Introduction

Daylighting is a key element of all architectural projects. Next to traditional daylighting design tools, including rules of thumb, simple formulas, nomographs and graphical methods, daylighting simulation tools add degrees of flexibility and accuracy to the process. Two different approaches can be noted for daylighting simulations: the use of computer simulations and simulations using scale models analyzed under real sun and sky conditions or under an artificial sun and sky. Scale models under real sky have been used for projects evaluation for centuries. The development of artificial skies has made the studies less dependent on factors such as the weather, the location and the time of year. An artificial sky facility allows researchers and designers to simulate, using scale models, the lighting conditions within, and around buildings, i.e. those emanating from the sun, the sky and clouds, and the reflections from the ground and nearby structures. (Aghemo *et al*. [1])

Several configurations of artificial skies have been produced in the past five decades investigating sky luminance distribution patterns and control systems and seeking to reduce construction and maintenance costs, calibration problems and energy consumption: mirror skies, dome skies, spotlight sky simulators or scanning skies. (figure 1)
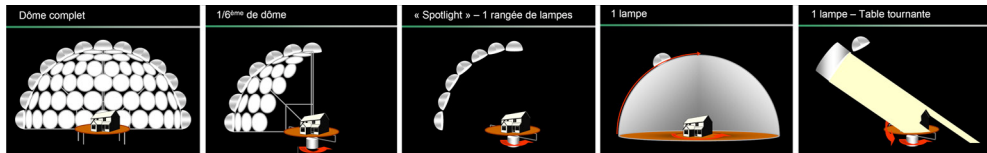
Figure 1: Artificial sky configurations (adapted from Bodart *et al*. [6])
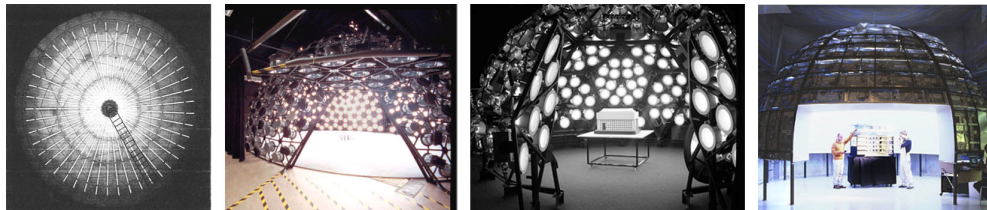

Figure 2: Artificial sky facilities:
Cambridge University, Cardiff University, Bartlett, Bartenbach Lichtlabor

According to Croghan [8], the Cambridge artificial sky, completed in 1962, 'is believed to be the first artificial sky that combines the luminance efficiency of diffused direct lighting employed by rectilinear skies with the versatility of domed types'. (figure 2) Currently, artificial sky facilities of various configurations exist in several academic and research institutions, namely the Welsh School of Architecture (Cardiff University) [5], the Bartlett (Faculty of the Built Environment, UCL) [3], Bartenbach LichtLabor [2], the Belgian Building Research Institute (BBRI) (Bodart *et al*. [6]), the Greek Center of Renewable Energy Sources (CRES) [4]. (figure 2)

2. The design program: constraints and challenges

In an effort to enhance daylighting studies and incorporate them in the architectural design sequence, the Department of Architecture of the University of Thessaly decided to add an artificial full dome sky facility to the school's resources in spring 2008. (figure 3) Primarily proposed for academic and research purposes, the facility would serve as an accurate and user-friendly tool to complement traditional methods and computer simulations; in addition, it could be used by professionals (architects, engineers, lighting designers).

Figure 3: Artificial sky facility, Department of Architecture, University of Thessaly, 2008

This article describes in detail the process from conceptual design to realization of the bearing structure of the artificial sky installation; the lighting system and relevant technical issues are only briefly addressed.

Preliminary considerations had to do with the overall geometry of the structure, the combination of proposed structural and adopted sky luminance distribution patterns, the decision to buy or design the structure and, in the second case, the use of an industrial proprietary or custom designed system and the use of fixed or pin-joined connections. Real constraints, budget and purpose related, defined decisions, while the time-frame was not restraining. The lighting installation demanded a high level of precision (exact light sources coordinates), yet a considerable amount of flexibility (for installation and calibration purposes) allowing low tolerances for displacement.

While a geodesic dome seemed the obvious solution for the structure, as evidenced in numerous artificial sky installations, preliminary studies for the hemispherical structure proved difficult the task of directly relating the lighting pattern with a geodesic one. Alternatives included three possibilities: i) a non-geodesic structure consisting of horizontal rings and vertical semi-circular ribs tailor-made to carry the lighting installation, ii) a sole geodesic structure directly carrying the luminaires by a variable hanging element or iii) a hybrid system. Concerning construction methods, prefabricated systems proved to be too expensive, while industrial systems (see Chilton [7] for an overview) weren't flexible enough or posed proprietary issues; additionally, they couldn't easily provide a solution for the lighting installation. As in most cases of one-off modest-span projects (according to Makowski [12]), a brief feasibility study, in terms of cost, time, means, geodesic design and construction know-how, 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) combined with a secondary inner ring-dome structure for the lighting installation.

The goal served as a motivation for the study of geodesic structures, in terms of geometry and, especially, construction matters. A semester-long workshop on geodesic structures was organized and conducted in multiple steps, with varied work intensity, time-frame and number of people involved. (figure 4) The workshop was performed by [K]onstruction Team, a voluntary student workgroup experimenting with small-scale structures, emphasizing on the material and structural characteristics of the architectural artifact and the complexities of the design process. The actual designing team was narrowed down to a group of senior students assisted by professional specialists and supervised by the professor in charge. Time schedule was not fixed, allowing for design and construction interaction and experimentation. The assembly of the structure was expected to be performed by the students, adding one more parameter to design considerations. Demand for safe and easy mounting by an inexperienced student crew was a parameter of key importance, calling for clear and comprehensible assembly instructions and imposing a systematic organization of the construction process, which in turn pushed for a deeper understanding of geometric and technical characteristics.
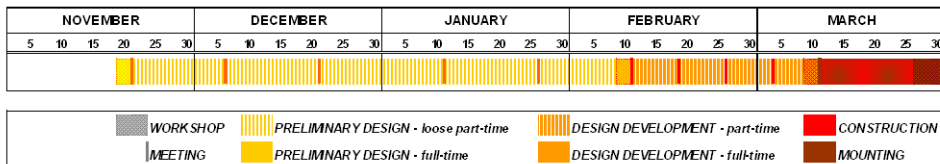
Figure 4: Schedule of the multiple-step workshop

3. Project description

The artificial sky dome installation comprises of several elements: i) the geodesic primary dome structure, ii) the secondary ring-dome structure and iii) an inner fabric dome. An artificial sun is mounted to an interior rotating arch structure, while a table located at the center of the hemisphere serves as a stand for the models. The lighting installation includes the luminaires and auxiliary electrical equipment, as well as a central control unit for the sunlight and daylight simulation. A photometric data acquisition system and a device for recording digital images are to supplement the facility. (figure 5)
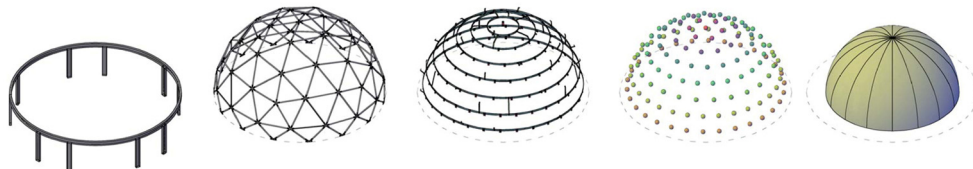

Figure 5: The elements of the artificial sky installation:
base, geodesic dome, ring-dome, lighting installation, inner fabric dome
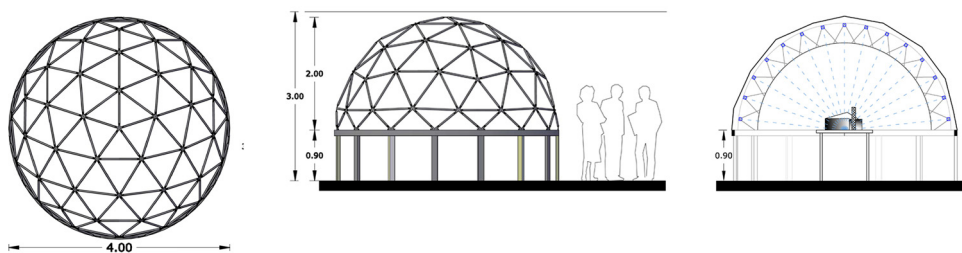

Figure 6: Plan, elevation and section of the artificial sky installation

The installation is a 4.0m diameter free-standing hemispheric structure raised on a 0.90m high base allowing for entering the dome from below without compromising its structural integrity. The overall height of the installation is 2.90m., defined by the height of the room (3.0m), while the level of the horizon is set at the base of the dome at 0.90m.(figure 6) The base excluded, overall weight of the installation is ~250kgr, the lighting installation weighing ~50kgr.

3.1. The primary structure – the geodesic dome

3.1.1. Geodesic structures

Geodesic domes are a category of lightweight spatial structures, their design applications ranging from children toys to mega-structures containing settlements. (Tarnai [14]) If one adheres to the technical definition of a geodesic as the shortest distance between two points on a given surface; then a geodesic dome would be constituted primarily of structures deployed along the geodesic lines of a sphere.

In the 1940s, R.B.Fuller widely explored the potential of spherical geodesic patterns for a new type of spatial structures, known as geodesic domes. According to Wong [16], the primary uniqueness of Fuller's patented version of the geodesic dome is in the geometrical alignment of the individual structural elements 'in a geodesic pattern of approximate great-circle arcs intersecting to form a three-way grid.' The 'geodesic problem' being a practical quest to approximate a particular type of spherical form, it entails a process for creating a polyhedral form that approximates a sphere. Though Fuller's initial geodesic geometry was based on the spherical projection of a cube-octahedron, he eventually chose the icosahedron as the preferred base polyhedron, motivated primarily by production and assembly considerations in his quest for a maximum standardization of parts. [9]

In practical terms however, especially in a large dome, more tesselations of the spherical triangles are needed. The extent of the tesselation is measured as the frequency of the spherical icosahedral, while the class refers to the actual tesselation grid. Thus, a class-I, three-frequency icosahedral spherical geodesic means that the edges of its base icosahedral face are tesselated into three equal segments, presenting a total of nine spherical triangles.

3.1.2. The geodesic dome

Several geometries and frequencies were studied (Kenner [11]) in physical and digital models (figure 7), especially in relation to the resulting amount of different strut lengths and node types, as well as to the complexity of resulting node configurations. The final configuration was selected as the optimum solution, economic and technical issues considered, yet for providing a structure dense enough to carry the secondary structure, i.e. with a sufficient amount of nodes to act as suspension points.

The final geodesic dome is a modified class-I three-frequency icosahedric hemispherical geodesic; that is, the geodesic polyhedron is generated by the icosahedron by subdividing into three parts each edge of its original faces. (figure 8)

The principal polyhedron, the platonic icosahedron, has 20 identical triangular faces, 12 vertices and 30 edges. The selected derivative has 180 faces, 92 vertices (3 types) and 270 edges (3 types) for the full dome configuration, or 105 faces, 61 vertices (3+2 types) and 165 edges (3 types) for the 3/5 dome configuration. A further modification was needed, for the 3/5 3V dome configuration to be converted to a hemispherical dome. However, this modification resulted in an increase of the amount of different strut lengths and node types.

Proposed materials for the struts included wood rods, aluminum, copper or steel circular tubes or plastic pipes; steel was finally chosen for both the strut and node elements in

relation to cost, fabrication, high temperatures and fire precaution limitations. Preliminary studies showed that, if steel tubes were to be used, the lightest type in the market would be sufficient for this span and load conditions. Therefore, final choices were to be based on aesthetic and construction considerations, since strut elements were to be oversized in all cases. As in most cases of modest span one-off projects using purpose-made joints (see also Makowski [12]), the case was the same for the node elements, which in turn allowed for experimentation.
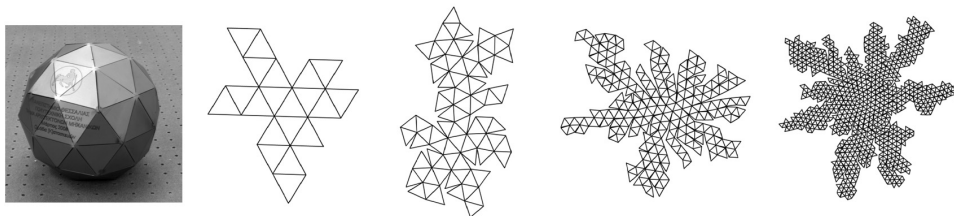
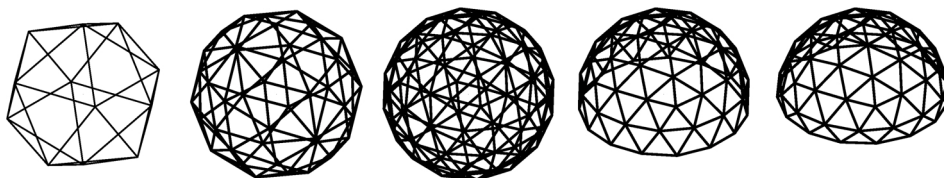Figure7: Studies on geodesic geometries and frequencies

Figure 8: 1V, 2V, 3V, 3/5 3V, 1/2 modified 3V icosahedric geodesic dome configurations

The base of the geodesic structure consists of a ring element on ten poles directly located beneath a respective number of nodes. Triangulation was not considered necessary for the specific weight and use. Provision has been made for large models to be carried inside the dome.

3.2. The secondary structure – the ring-dome

3.2.1. The Tregenza subdivision of the sky hemisphere

Several models exist to divide up the sky into small segments for sky luminance measurements. According to the model of the sky hemisphere proposed by Tregenza [15], suggesting that the optimum diameter of a sky area is approximately 0.2 radians (11.5°), adopted by the International Commission on Illumination (CIE), the sky hemisphere is subdivided into 145 circular areas of equal-surface, each of which is considered of uniform luminance. The proposed subdivision is based on eight equal altitude bands, allowing each area to be approximately considered as a point source without noticeable error. (figure 9)

In an artificial sky, the 145 areas can be simulated by means of 145 circular luminaires arranged in eight parallel horizontal zones located on a hemispherical surface according to the angular coordinates established by Tregenza. The luminance distribution of the whole

sky is obtained by opportunely varying the luminance of each luminaire. In this way different sky conditions (overcast, clear and intermediate conditions) can be reproduced according to both standard models and real luminance values recorded at IDMP (International Daylight Measurement Program) measuring stations. (Aghemo *et al*. [1])
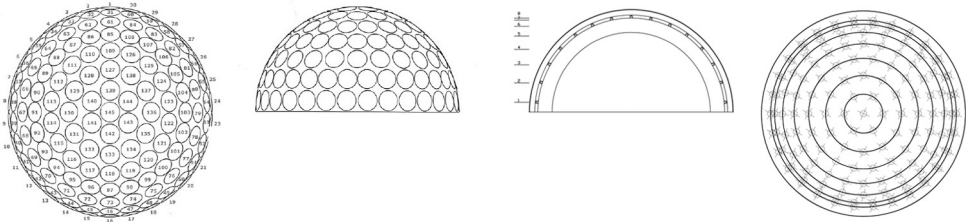

Figure 9: The Tregenza subdivison of the sky hemisphere

3.2.2. The secondary structure

Following Tregenza's model, the secondary structure would be the frame for 145 luminaires arranged in eight levels. The 145 luminaires are individually fixed in place on a respective number of plates attached to a set of rings. The set consists of seven horizontal rings (a sole luminaire is located at the top level), independent from each other, yet outlining a 3.80m diameter hemispherical surface. Each ring is hanged with vertically aligned brackets by the same adjacent family of nodes of the geodesic dome. Auxiliary electrical equipment (individual dimmable electrical transformers, cabling,...) runs along each ring. Initial solutions proposed all luminaires to be directly fixed on the rings either by tilting each ring in cross-section (basically each ring being a part of a different cone) or by providing individual tilting fixtures. Fabrication and cost considerations suggested the final design, i.e. individual angled plates fixed on the rings, ensuring easy manufacturing of the rings and precision in the positioning of the luminaires, yet allowing for the necessary flexibility. (figure 10)
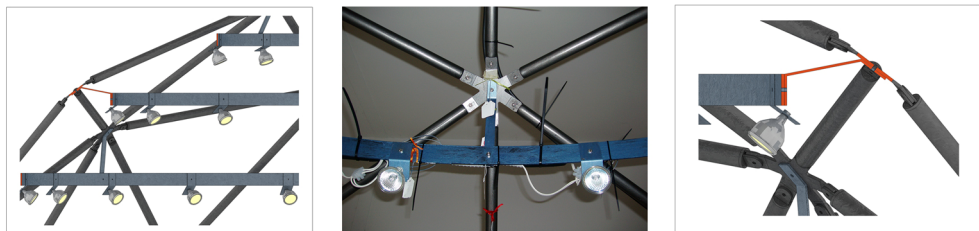

Figure 10: Typical detail of the secondary structure

3.3. The inner dome

The inner light-diffusing dome is made of semi-transparent fabric. The 3.10m diameter hemispherical dome consists of fifteen identical spherical sector pieces and is hanged by cords from the structure.

4. The process

4.1. Design process

Initial studies focused on geodesic principles and constructional complexities through physical models and full-scale mock-ups. (figure 11) Design development was based on digital models. While general use 3d modeling software, proprietary (AutoCAD and 3ds Max by Autodesk) or open source (Blender) allowed for modeling the overall structure or even the node elements, application specific software tools (namely Cadre Geo v5.0) were tried out to define the geometric characteristics of the geodesic dome, and the node elements in particular. Input included selection of base polyhedron, sphere radius, class, frequency and level of intersecting base plane. Output, in the form of tables or drawings, contained information about overall amount of nodes and struts, as well as specific data for each node ('hub'); type, relative position, quantities and identity of hubs/ type, quantities and identity of struts/ hub, (relative) angles in plan and in section. (figure 12)
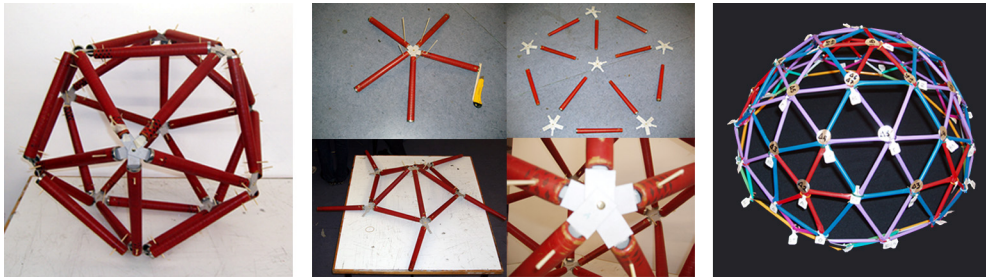

Figure 11: Immersion exercise on geodesic principles and constructional complexities
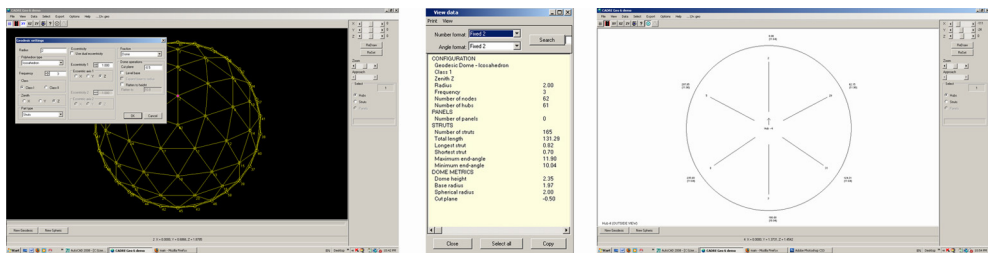

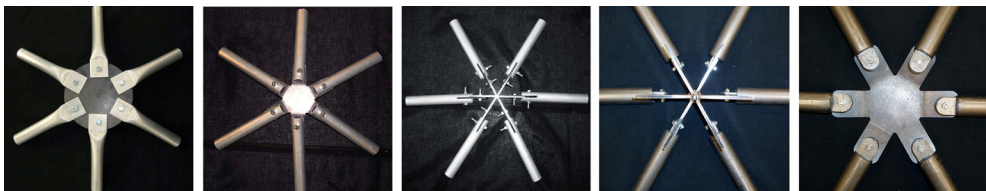Figure 12: Cadre Geo: input screen and output table (overall data) and drawing (node)

Figure 13: Alternatives for the custom-designed joint configuration

4.2. Construction process

Several alternatives were studied for the joint configurations regarding the end part of the strut and the node element. (Gerrits [10]) (figure 13) Cost, fabrication and mounting considerations, related to required workmanship and allowable tolerances, led to the final decisions.

Alternatives for the formation of the end part of the strut basically fall into two categories, either by forming the actual end part (pressing, pressing and folding, piercing, piercing and cutting through) or by adding an end piece (inserting and welding an intermediary connecting plate or welding a fork end piece). Priority was given in keeping the strut straight and providing the necessary angles at the plate connector. Alternatives for the node element included a flat circular plate connector, a conical plate connector, a 3d star connector, a 2d star plate connector with folded parts. The conical plate was rejected for possibly creating overall instability problems, while the star connector was excluded because of higher cost, mounting difficulties and concerns about welding quality and precision. The 2d star plate connector was finally chosen for guaranteeing maximum precision, while the fork end piece was selected for giving mass-production possibilities. Bolts and safety nuts completed the node assembly. For the final dome configuration, 165 struts (of eight different lengths) and 61 plate connectors (of nine types, in four, five or six-strut arrangements) were fabricated; typical strut consisting of circular steel tubes (26,9dia.x1.5mm) and typical plate connector produced of steel plates (4mm thick).
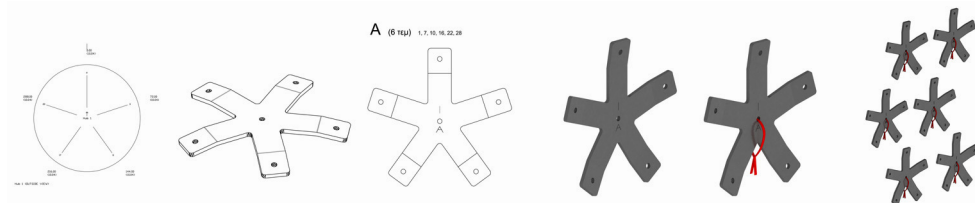

Figure 14: Typical design and construction process for a node plate connector

Figure 15: Typical design and construction process for a suspension bracket

Based on the software output, 3d models of each plate connector were drawn, then unfolded to be sent to the fabricator for the final pieces to be cut, pierced, marked and folded as indicated. At the final stage, all pieces were painted and meticulously tagged by type. (figure 14) Similar process was followed for the parts of the secondary structure. Seven different types of suspension brackets were designed, one type per ring. (figure 15) Rings

were designed and fabricated in one to three pieces, according sizes, and then assembled (bolted) in place. Marks were used to ensure relative position of different parts and guarantee right positioning of luminaires. The base ring element (steel 60x40x3mm rectangular hollow section) was also fabricated in three parts and then assembled (bolted) in place. A full trial assembly was performed at the shop, by mounting the base polygon of the dome along with the base ring and directly welding auxiliary base plates for the plate connectors of the base polygon on the ring.

4.3. Assembly process

The assembly of the geodesic dome, first tested in physical models, was carefully designed, based on the recurring geometric patterns; the geodesic dome being basically composed of five identical sectors. Starting from the base, mounting was to be performed by level, adding five identical pieces or geometric entities in each step. (figure 16) Subsequent tasks included the mounting of brackets, rings and luminaire plates. The actual mounting of the structure, the highlight of the workshop, was smoothly completed in four consecutive days, one day per task; fifteen students (working for approximately 5 hours/ phase) accomplished respectively the assembly of the base, the geodesic dome, the secondary structure and, finally, the luminaire plates. The electrical equipment and inner fabric dome were put into place at a later time by a second group of students responsible for designing and putting up the lighting installation.

It should be noted here, that the use of pin-joined connections allowed for fine-tuning of elements position during and after the assembly without compromising overall stability of the final configuration.
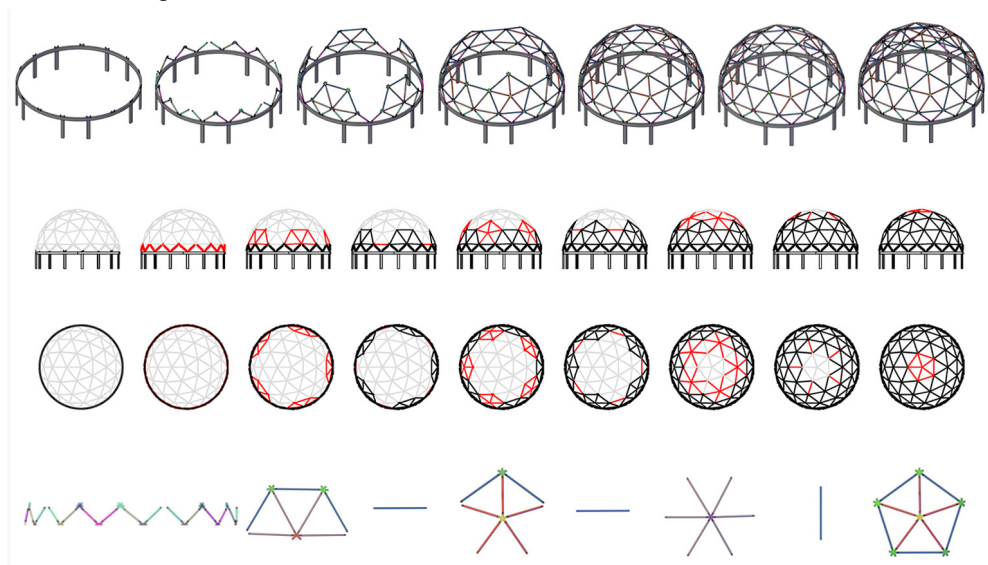

Figure 16: Assembly sequence of the geodesic dome, performed in sets of five

5. Conclusions

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 a positive evidence about the skills and competences that can be nurtured in an educational framework. Besides, the completion of a full-scale project comes to endorse initial decisions to undertake the challenge of a custom designed structure and proceed to such an endeavor with a student team.

From an educational standpoint, the design-built workshop is a module providing expertise by training and giving students the unique opportunity to participate in the whole design process from concept to realization, dealing with real constraints and enjoying the delight of the final result. The applied methods and tools are discussed as a case-study of an educational module providing not only significant input for the specific type of structures and related technologies, but, furthermore, giving valuable feedback to future practicing engineers about the interaction between design and construction, the complexities of the process and significance of inter-disciplinarity and the importance of meticulous construction management especially in the case of spatial structures.

In a research framework, this work could be used as a base for further investigations. Inclusive studies on prefabricated space-frame systems would provide significant input for the design and manufacturing of custom designed joints for modest-span geodesic structures and space-frame systems. Parametric approach and development of resulting tools would be suggested for the design of the node elements, as well as for the definition of strut lengths, to substitute for repetitive tasks performed individually in each case. Particularly for the case of artificial skies, additional work would be needed to explore possibilities of combining geodesic patterns with patterns modeling sky luminance and resulting arrangements of luminaires, in order to avoid the interfering secondary structure for the lighting installation. (Mansy *et al*. [13], Yoshizawa *et al*. [17]).

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