IASS 2020/21
SURREY 7
International Conference on
Spatial Structures 2020/21

Proceedings of the IASS Annual Symposium 2020/21 and
the 7th International Conference on Spatial Structures
Inspiring the Next Generation
23 – 27 August 2021, Guildford, UK
S.A. Behnejad, G.A.R. Parke and O.A. Samavati (eds.)

Structure and fabrication-driven conceptual design of space-frame structures

Antiopi KORONAKI*, Paul SHEPHERD[a], Mark EVERNDEN[a]

* Centre for Natural Material Innovation, Department of Architecture, Cambridge University
ak2260@cam.ac.uk

[a] Department of Architecture & Civil Engineering, University of Bath, Bath BA2 7AY, UK

Abstract

The challenge in designing efficient space-frame structures lies in optimising the configuration of their members to reduce material volume, as well as in minimising geometrical variability in their members to reduce construction complexity of joints. Advanced computational tools have been developed to address these challenges; however, they address them either individually or sequentially. This paper proposes a novel method for a multi-objective optimisation of space-frame structures to minimise material volume and geometrical variability in the joints. A computational framework is developed that performs a structural analysis of the starting geometry, while at the same time assesses the geometrical variability between its members and clusters the joints into the number of fabrication batches required for its construction. The optimisation process is then carried out and the impact that the relative weighting of the two objectives has on the generated configurations is explored. The efficiency of the proposed methodology is validated through its application on a series of realistic examples and the design space of optimised structures is explored. Developed in a computationally efficient and user-intuitive environment, it enables designers to comparatively evaluate a library of materially efficient design solutions of low construction complexity and take informed design decisions that respond to the specific requirements of each project.

Keywords: geometry optimisation, space-frame structures, fabrication, structural optimisation, conceptual design.

1. Introduction

The lightweight configuration of space-frame structures and their ability to approximate doubly-curved surfaces has led to their wide application in projects of complex geometry. Optimizing the design and construction process of such structures is necessary to ensure their effective and sustainable design. When applied in flat or singly curved designs, the standardisation of the structural elements makes layout optimisation for material volume the main driver for efficiency. When applied to doubly-curved designs, however, the geometrical variability introduced to the members and joints makes fabrication the key consideration [1]. An exploration of the relationship between the geometry of space-frame structures and its impact on the material volume and fabrication process can unlock the potential of materially efficient and robust doubly-curved space-frame structure designs.

The challenge in designing efficient space-frame structures lies in the layout and geometry of their members. Layout optimisation has been extensively studied as a method to minimise material volume [2-4]. Research in this field has led to the development of highly advanced computational analysis tools that can optimise structural configurations of large-scale space-frame structures [5]. Geometry optimisation, on the other hand, has been studied as a method of introducing fabrication requirements to rationalize complex layouts. The techniques applied include the introduction of a penalty function for joints, the merging of nodes, the deletion of bars and the updating of their spatial coordinates [6,7]. Research applying multi-objective optimization of space-frame structures, that links material volume reduction to fabrication requirements, remains limited. Precedent studies are either restricted to small-scale applications [8], or apply geometry optimisation as an alternating- or post-process to layout optimisation [9-11].

This paper proposes a novel method for the design and construction of space-frame structures through the multi-objective optimization of their material volume and fabrication requirements. A series of illustrative case-studies are analysed, that explore the relationship between the geometry of space-frame structures and their respective structural and fabrication requirements. This workflow lends itself well to early stages of a project development, for the performance-based assessment of diverse and efficient design solutions.

2. Geometry optimization of space-frame structures for fabrication

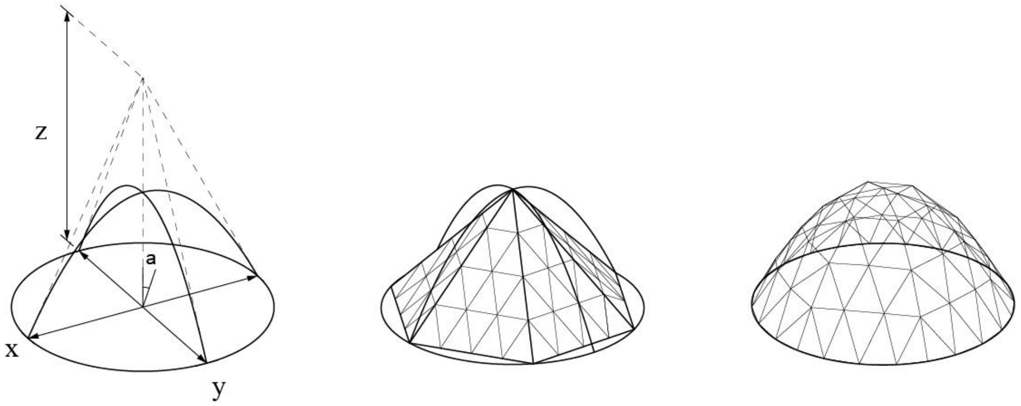
In the context of doubly curved space-frame structures, geometrical variability is expressed either in the member lengths or the angles of the joints, or both. The focus of this study is placed on joint angles, due to the high impact of joints on the overall fabrication and assembly process. In addition to representing up to 20-30% of the material required for construction [12], reducing geometrical variability of the joints can substantially accelerate the construction process, leading to savings in cost and time [1, 13]. Previous research by the lead author has linked the geometry of a space-frame structure and its fabrication complexity through the clustering of joints into fabrication batches, according to the angles of their members [14]. When combined with an assessment of the tolerance of different fabrication processes, this approach provides an insight into the construction complexity of a structure. A customised version of the *k*-means clustering algorithm has been developed, that considers parameters specific to space-frame joints and generates compact clusters. This approach has been applied to the assessment of different fabrication methods and the rationalization of truss structures.

3. Methodology

The methodology developed performs a multi-objective optimization of space-frames structures to minimize material volume and the construction complexity. The algorithm developed in [14] is applied here to assess the geometrical variability in the joints, while a structural analysis is simultaneously carried out to calculate the material volume required. The structural depth of the space-frame is optimized to generate a set of diverse and efficient configurations. This workflow is applied to space-frames of different surface curvatures to provide insightful information regarding the curvature of the starting geometry and the associated material and fabrication requirements.

A parabolic surface is initially produced for the generation of a doubly curved space-frame structure, as shown in Figure 1. A hexagonal pyramid is circumscribed about the bottom ellipse and its faces are subdivided into self-similar shapes. These are then projected on the parabolic surface to create the triangular top layer of the space-frame. Its hexagonal dual forms the bottom layer, which is offset normal to the surface and connected to the top through a web layer.

The parameters of the starting parabolic surface are then modified to generate a series of diverse space-frame configurations for this study. More precisely, the proportions of the base ellipse (x/y) and the angle (in degrees) of the vertical axis a of the parabolic surface are modified, as shown in Figure 2. The geometry of each of these space-frame configurations is optimized to minimize the material volume and the geometrical variability in the joints.



a) b) c)

Figure 1: a) A doubly curved surface is generated to guide the design of the space-frame structures. *P* represents the focus of the parabola b) A hexagonal pyramid is circumscribed in the basis of the surface and its faces are subdivided and projected on the surface to create the top layer c) The top layer of the space-frame structure.

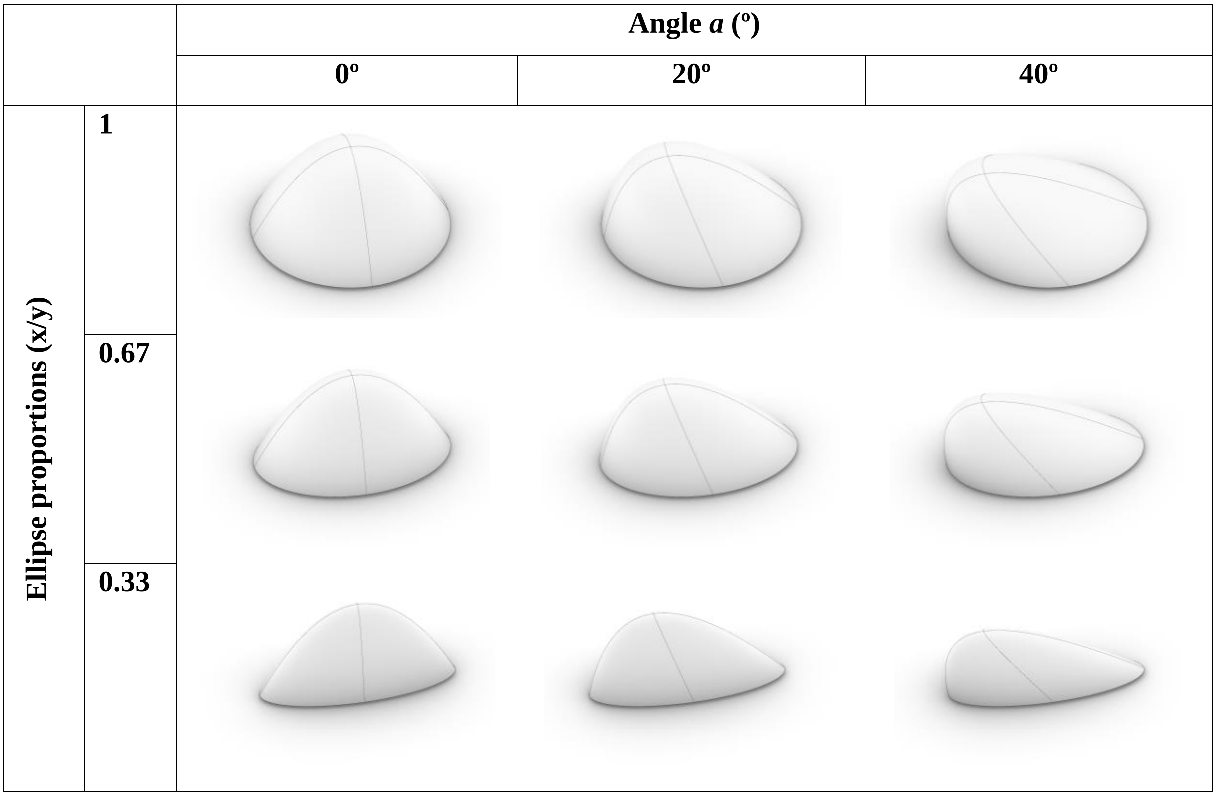


Figure 2: The set of space-frame geometries studied.

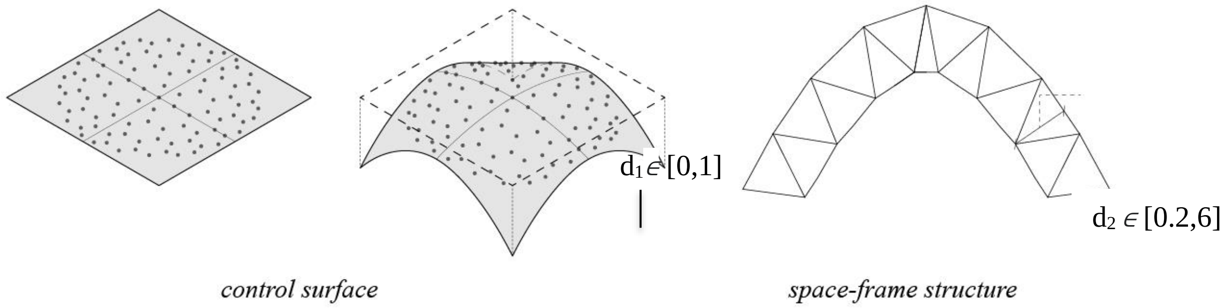


Figure 3: Configuration and application of the control surface to define the structural depth of the space-frame structure.

3.1. Optimization process

The multi-objective optimisation integrates a structural analysis with an analysis on fabrication requirements and is carried out in the parametric modelling environment of Grasshopper/Rhino3D [15]. The structural analysis assumes that the structure is fully restrained at the bottom and that a combined load consisting of the structure's self-weight and a combination of dead and live loads of 1kN/m^2, is applied. It is performed in Karamba3D [16] assuming timber circular solid sections with a constant cross-section for all members (Young's modulus= 9,600,000kN/m^2, density=4.9kN/m^3, Modulus of rupture= 53,000kN/m^2). A maximum utilisation of 1 and a maximum displacement of 0.1m (l_{max} /200) are allowed.

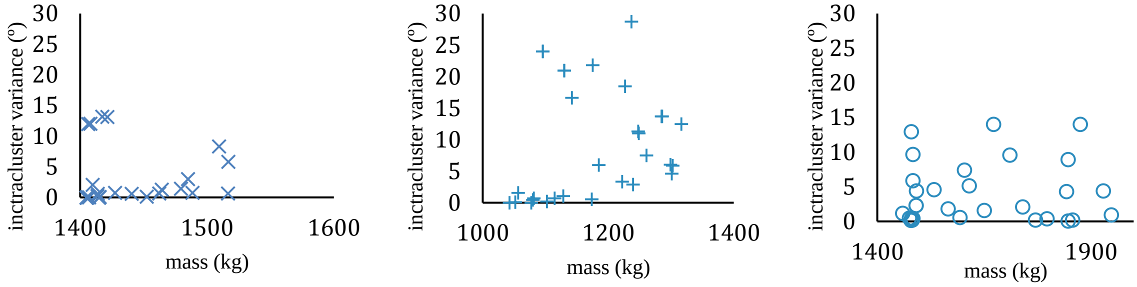
The algorithm developed in Koronaki [20] is applied to cluster the joints into fabrication batches. The formulation of the algorithm requires the number of clusters as an input to generates compact clusters. The intracluster variance of each cluster forms a measure of the geometrical variability in the structure. As a result, the identification of the minimum number of clusters required to meet the tolerance of a specific fabrication process, requires the iterative application of the algorithm for different numbers of clusters, until the minimum value is identified. For the scope of this study, the number of clusters is set to k=3 and it is considered fixed to accelerate the optimization process. The intracluster variance of each cluster is extracted and set as an objective to be minimized. If required, the generated configurations can then be further analysed to identify the minimum number of clusters required for a specific fabrication process.

The depth of the space-frame structure is defined as the variable of the optimisation process, with the top layer vertices remaining fixed in position and the bottom layer vertices moving along the surface normal. Considering every vertex of the bottom layer as an independent variable allows for an extensive exploration of the design space; however, this approach may render the method inappropriate for large-scale applications. A control surface is therefore defined to reduce the number of variables, following the method developed in [1] (Figure 4). The vertical displacement of the points on the surface (0-1m) is remapped for the offset of the bottom layer vertices (0.2-6.0m). The number and distribution of the control points, as well as the range of depth values can be defined by the designer, according to the scale and complexity of each project, as well as the time and computational resources available.

4. Results

Table 1 presents the results for the experiments carried out. An initial observation highlights the diversity in the performance of the optimized configurations. As far as the starting grid geometries are concerned, when both the angle of inclination and the x/y ratio are high, the pareto front solutions show a high diversity in their performance and are scattered (b, c, e, f). On the other hand, when the base of the starting geometry is longitudinal, the results tend to cluster in a very small are of the graph (g,h,i).

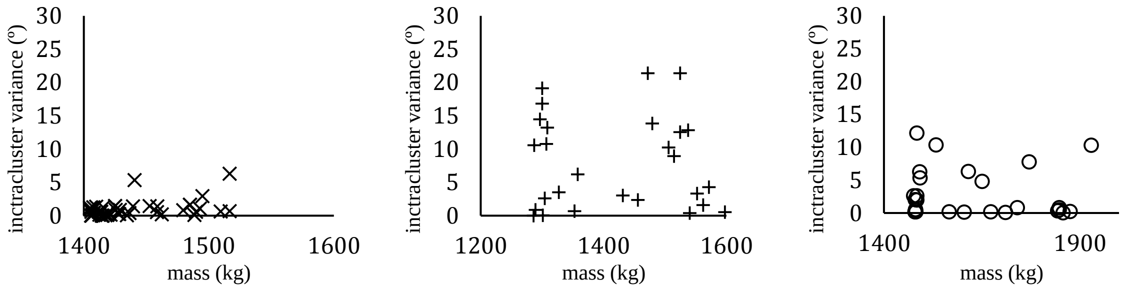
Table 1: Resulting pareto front solutions of the different grid configurations evaluated.



a) x/y = 1, a = 0º

b) x/y = 1, a = 20º

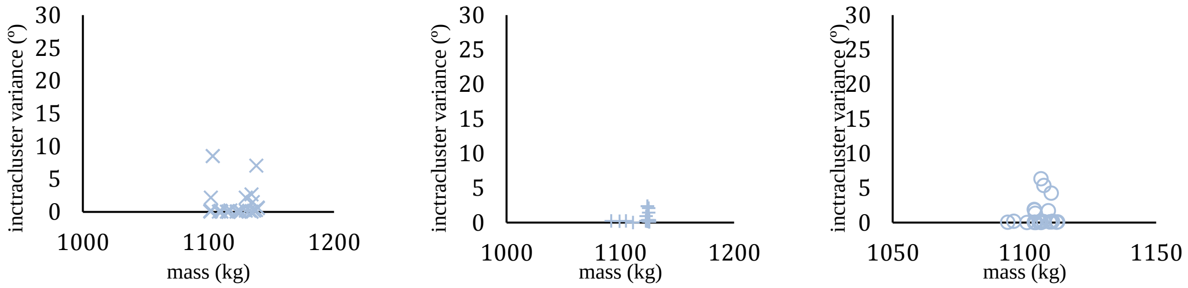
c) x/y = 1, a = 40º



d) x/y = 0.67, a = 0º

e) x/y = 0.67, a = 20º

f) x/y = 0.67, a = 40º



g) x/y = 0.33, a = 0º

h) x/y = 0.33, a = 20º

i) x/y = 0.33, a = 40º

Once the overall impact of the starting geometry has been evaluated, the results of two grid configurations are analysed in more depth. More precisely, the individuals *a) x/y = 1, a = 0º* and *e) x/y = 0.67, a = 20º* are studied and individuals of the grid configurations generated are studied, as shown in Figures 2 and 4. As far as the former is concerned, the constant depth of the generated configurations reflects the symmetry of the starting surface geometry, providing uniform structural properties throughout the surface. The optimum solutions of this study have a minimal depth, as shown in cross sections 1-3 in Figure 2. Even in less optimum configurations, the depth remains constant throughout the structure, with a uniform increase in its offset. As far as the analysis of the second grid configuration is concerned (*x/y = 0.67, a = 20º*), the results demonstrate that the analysis and optimization process followed depict the changes in the curvature of the starting geometry and generate grid configurations that can respond to them effectively. More precisely, the cross sections presented show a change in the

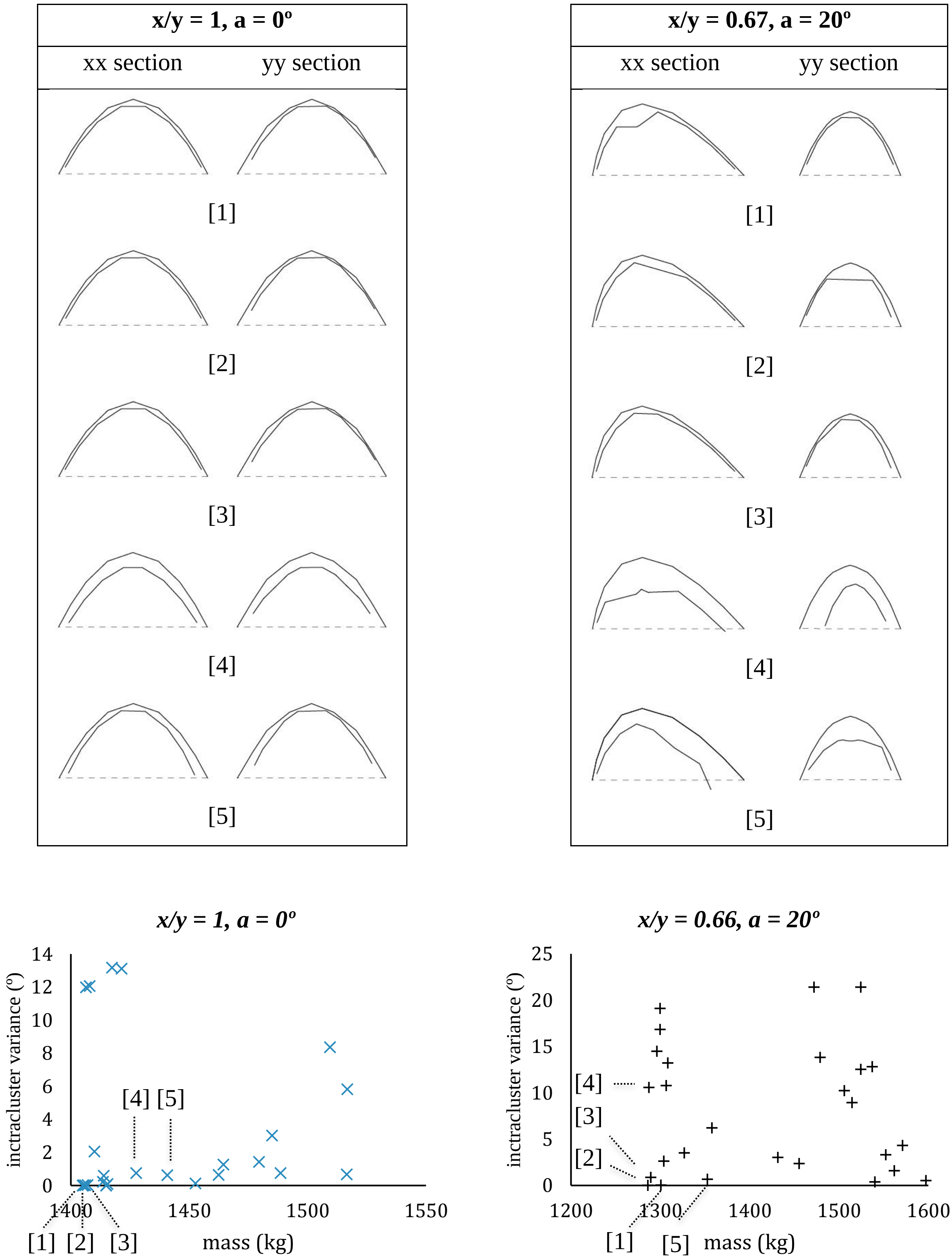


Figure 4: Performance of the *x/y = 1, a =0º* and the *x/y = 0.67, a =20º* starting geometry and geometrical configuration of selected configurations.

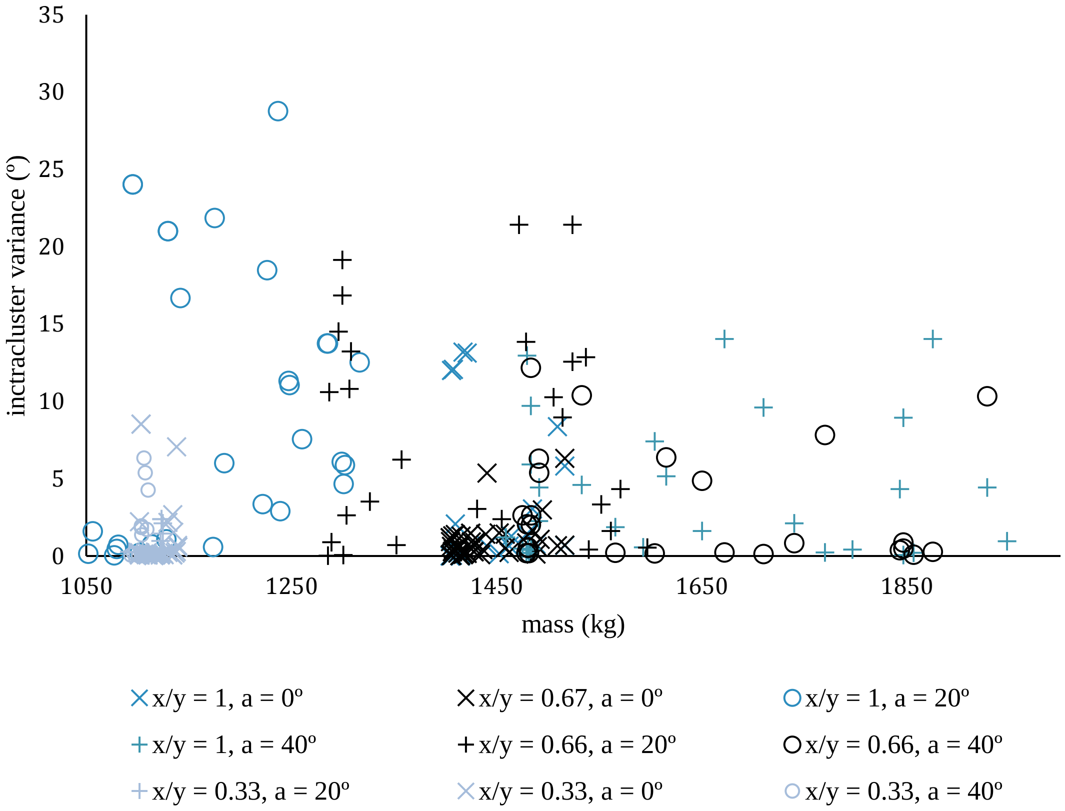


Figure 5: Results of all the analyses carried out.

structural depth either in areas of higher curvature (1, 2, 4, 5-yy) or a gradual change in the structural depth, as the curvature changes (5-xx). These observations validate the efficiency of the analysis method deployed and its ability to generate design solutions that respond to the curvature of the input geometry in an efficient manner.

Figure 7 summarizes the results of all the studies carried out. A comparative evaluation of the outcomes highlights the significant impact that the curvature of the starting geometry can have on the structural performance and fabrication requirements of a space-frame structure. This is highlighted by the fact that the results of each starting surface are clustered in a different area of the graph.

5. Conclusion

This paper developed a novel method for the design and construction of efficient space-frame structures. A multi-objective optimization enabled the simultaneous consideration of both material and fabrication considerations. The experiments carried out demonstrated the direct impact of the surface curvature on the performance of the generated designs and highlighted diverse and efficient designs. This workflow lends itself well to early stages of a project development, for the performance-based assessment of diverse and efficient design solutions.

Acknowledgements

The author(s) disclosed receipt of the following financial support for the research, authorship and/or publication of this article: This study was supported by the EPSRC Centre for Decarbonisation of the

Built Environment (dCarb; Grant Ref. EP/L016869/1) and the Engineering & Physical Sciences Research Council [Grant Ref: EP/N023269/1].

References

[1] Koronaki, A., Shepherd, P., Evernden, M., 2020. Rationalization of freeform space-frame structures: Reducing variability in the joints. International Journal of Architectural Computing 18, 84–99. https://doi.org/10.1177/1478077119894881

[2] A.G.M. Michell. The Limits of Economy of material in frame-structures. Phil.Mag., 8(47):589–597, 1904.

[3] M.P Bendedsoe and O. Sigmund. Topology Optimization Theory, Methods andApplications. Springer, 2004.

[4] W.S. Hemp. Optimum structures. Oxford University Press, Oxford, 1973.

[5] Linwei He, Thomas Pritchard, Matthew Gilbert, and Hongjia Lu. Peregrine User Manual Technology Preview. Technical report, LimitState3D, 2019.

[6] E. W. Parkes. Joints in optimum frameworks. International Journal of Solids and Structures, 11(9):1017–1022, 1975.

[7] Helen Fairclough, Matthew Gilbert, Clement Thirion, Andy Tyas, and Pete Winslow. Optimisation-driven conceptual design: case study of a large transfer truss. The Structural Engineer, 2019.

[8] Wolfgang Achtziger. On simultaneous optimization of truss geometry and topology. Structural and Multidisciplinary Optimization, 33(4-5):285–304, 2007.

[9] M W Dobbs and L P Fleton. Optimization of truss geometry. ASCE J Struct Div, (95):2105–2118, 1969.

[10] Qingpeng Li, Paul Shepherd, Matthew Gilbert, and Linwei He. Rationalization of layout optimization result by updating discretization of the design domain. In C. Lazaro, K.-U. Bletzinger, and E. Onate, editors, Proceedings of the IASS Annual Symposium 2019 - Structural Membranes 2019. Form and Force, Barcelona, 2019.

[11] L He and M Gilbert. Rationalization of trusses generated via layout optimization. 52:677–694, 2015.

[12] Tien T Lan. Space Frame Structures. In Chen Wai-Fah, editor, Structural Engineering Handbook, number 1999, chapter Space Fram, pages 1–50. LLC, CRC Press, Boca Raton, 2005.

[13] Koronaki, A., Shepherd, P., Evernden, M., 2018. Geometry optimization of space frame structures for joint modularity. In C. Lazaro, K.-U. Bletzinger, and E. Onate, editors, Proceedings of the IASS Annual Symposium 2019 - Structural Membranes 2019. Form and Force, Barcelona, 2019.

[14] Koronaki, A. (2020). Optimising space-frames for construction. (Doctoral thesis). Department of Architecture & Civil Engineering, University of Bath, UK.

[15] Robert Mc Neel. Rhino3D. https://www.rhino3d.com/, 2019. Online. Accessed on 01/06/2019.

[16] Clemens Preisinger. Parametric Structural Modeling - Karamba, 2016.