Structurally Efficient Timber Grid-shells
Simultaneous Optimization of Topology and Geometry

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Introduction

To mitigate the effects of the climate emergency, there is an urgent need to vastly reduce the embodied carbon in buildings and other structures. Through changing to a material such as timber and utilising optimization techniques, the CO2 produced during production and construction can be greatly reduced. One such example of a structure that can utilise this to its advantage is a grid-shell. The design of grid-shells and vault structures employs the use of form-finding approaches to obtain suitable geometries which consequently excludes bending stresses. Therefore, a compression only structure is achieved and further material reduction is possible. The project's aim was to outline and evaluate the applicability and performance of the basic vault optimization approach for design of timber grid-shells.

Methodology

Through adapting an existing python script from He et al (2019) [1], we were able to create a numerical layout optimization script that generated optimal structures given certain criteria:

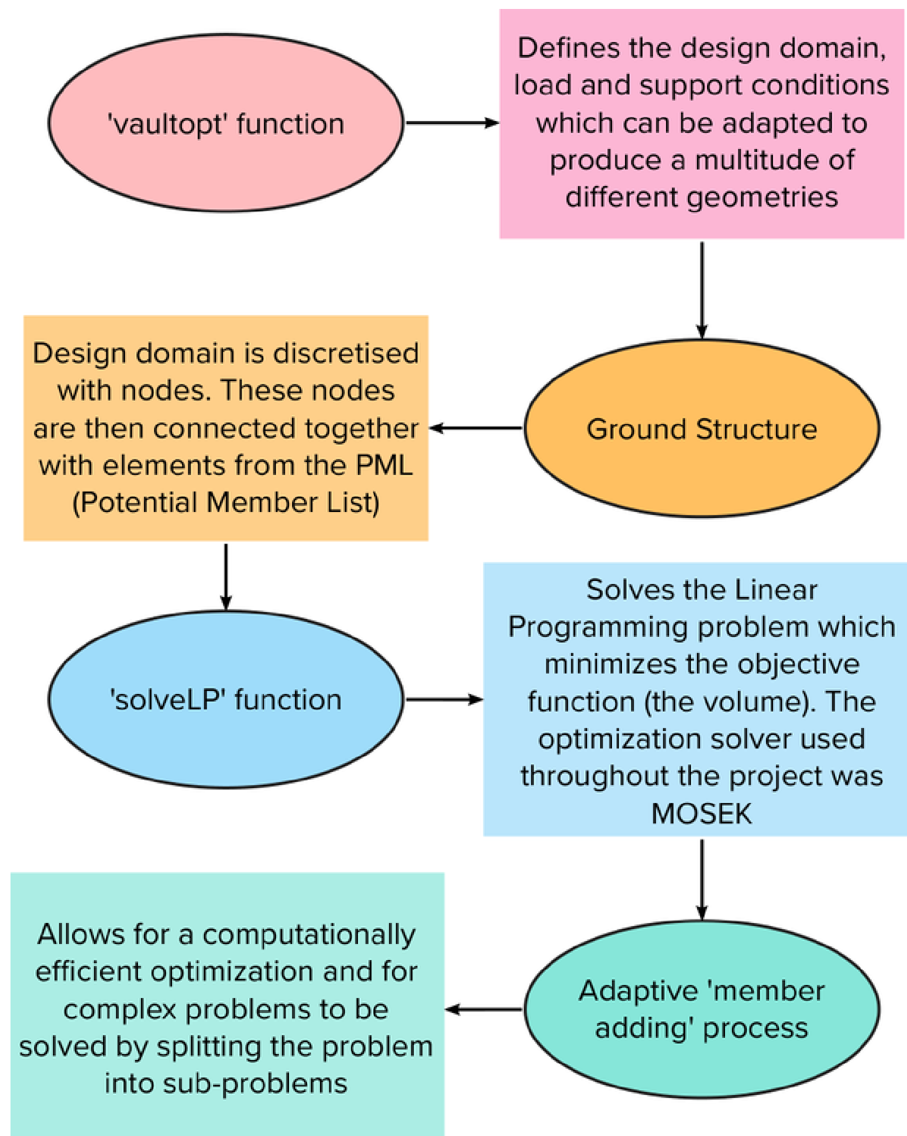


Figure 1 - Flowchart describing the python scripts process

Case Studies

To test just how effective the code was in producing the most optimal grid-shell structure, a few case studies were modelled and compared. In the case studies shown, lifting construction was adopted where the grid is assembled on the ground and then is uplifted and elastically deformed, creating the vault structure.

It can be seen from these results that, compared to the actual structures, that the models have shorter spanning elements and a reduced volume overall.

Figure 2 - Numerical model depicting the optimization of the Trondheim Pavilion grid-shell

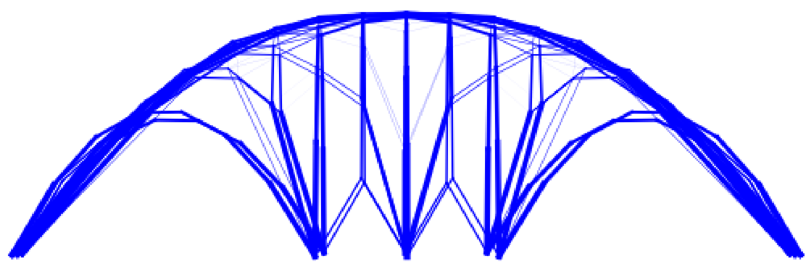


Figure 3 - Numerical model of the Chiddingstone Orangery grid-shell

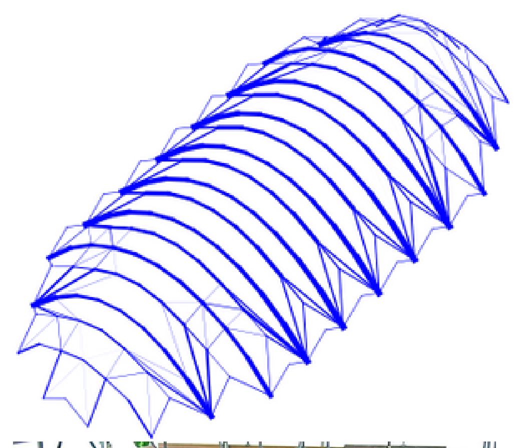


Figure 4 - Numerical model of the Weald and Downland Museum grid-shell

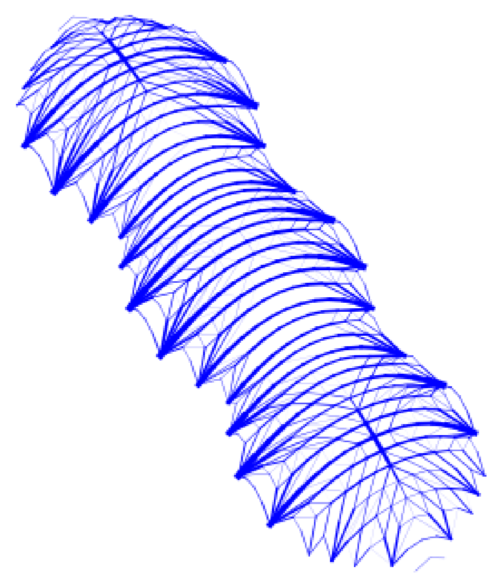
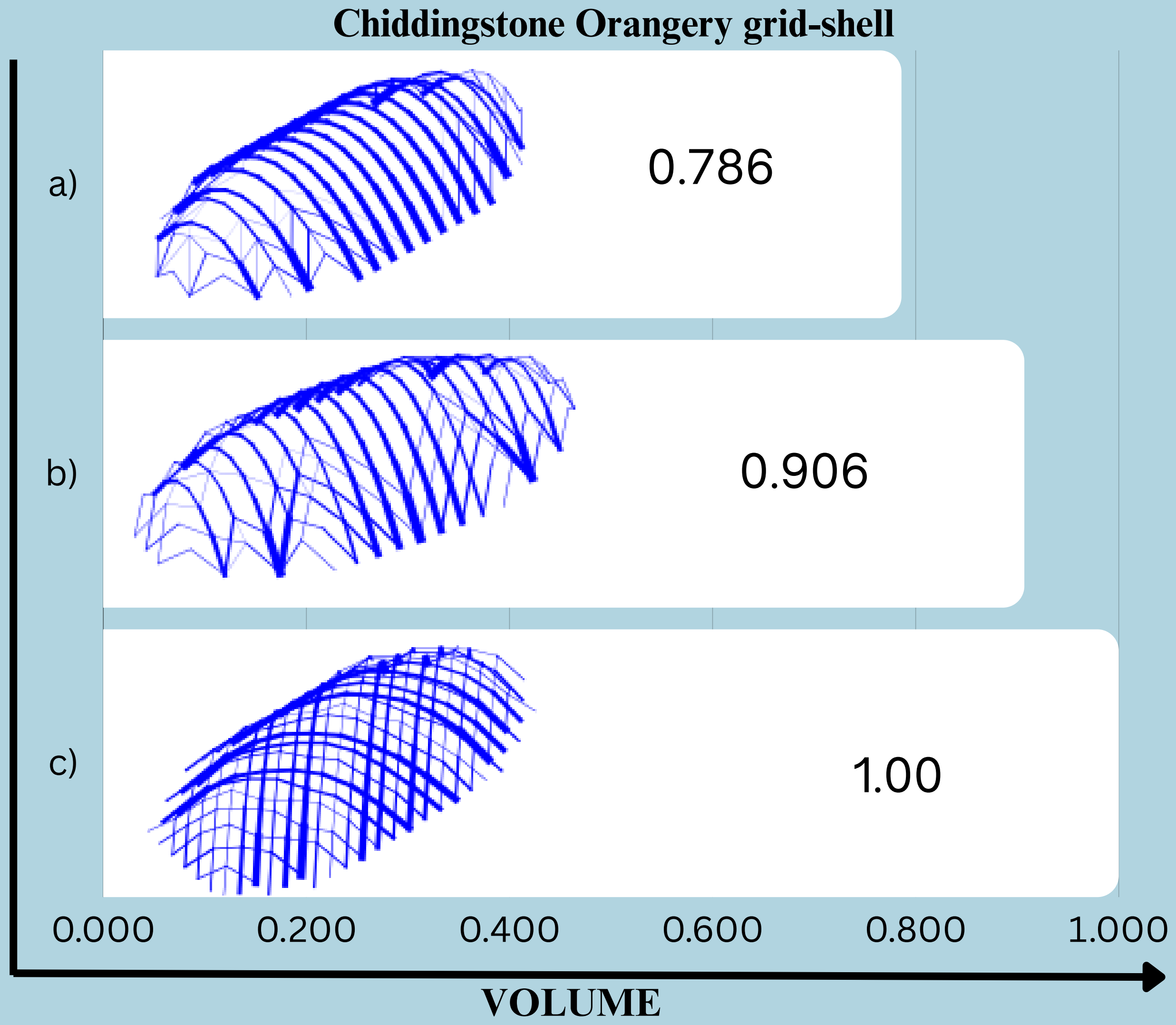


Chart 1 - Comparison of the volumes of the different variations of the Chiddingstone Orangery grid-shell



Analysis

- In *Chart 1,* numerical model c) represents the actual Chiddingstone Orangery grid-shell with its ellipsoidal shape and members at 45° and parallel to each other. It has a volume of 1 to easily compare to the other two models a) and b)
- Through looking at the other numerical models produced by the optimization code, it is abundantly clear to say that the optimization code significantly reduces the volume of timber needed to construct these grid-shells. For example, in *Chart 1,* model a) has a material reduction of almost a quarter (23.9%) compared to model c).
- As for the materiality of grid-shells, timber is a very applicable due to its low torsional resistance thus allowing it to be able to bend and deform into non-linear forms [2]. Timber also allows for a lighter structure overall which is especially useful when considering grid-shells normally go on top of a pre-existing structure i.e. *Figure 3* - Chiddingstone Orangery grid-shell sits upon a pre-existing masonry wall.

Conclusion

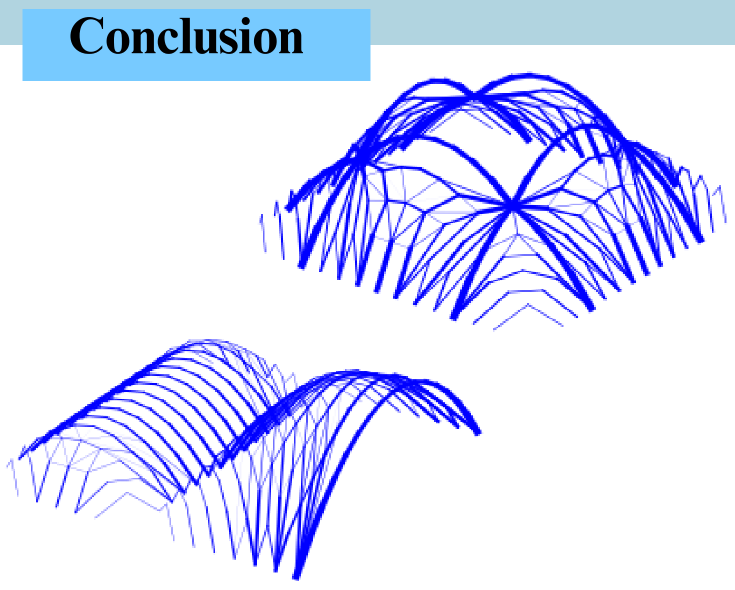


Figure 5 & 6 - Numerical models of other hypothetical grid-shell structure highlighting the usefulness of applying this optimization approach

Through undertaking this research it is evident that:

- The numerical modelling method, whilst utilising the beneficial 'member adding' scheme, can have significant reductions in the material usage in grid-shells
- Embracing timber grid-shells as an alternative to conventional construction methods can significantly reduce the carbon footprint associated with structures [3]

Limitations or areas of further research:

- Doesn't consider the self-weight of the structure
- The smaller spanning elements would make the construction process more tedious and more joints being necessary
- Timber is weaker than other grid-shell materials so more research needs to be made on joints between timber elements

How the research has benefitted Civil and Structural Engineering:

- *Figure 5 & 6* shows structures that could be constructed using this method of optimization
- By slightly altering the script, it is possible to create pure tension, hanging structures

References

[1] He, L., Gilbert, M. & Song, X. A Python script for adaptive layout optimization of trusses. Struct Multidisc Optim 60, 835–847 (2019). https://doi.org/10.1007/s00158-019-02226-6
[2] Lara-Bocanegra, A.J. Majano-Majano, A. Ortiz, J. Guaita, M. Structural Analysis and Form-Finding of Triaxial Elastic Timber Gridshells Considering Interlayer Slips: Numerical Modelling and Full-Scale Test. Appl. Sci. 2022, 12, 5335. https://doi.org/10.3390/app12115335
[3] Naicu, Dragos & Harris, Richard & Williams, Chris. (2014). Timber gridshells: Design methods and their application to a temporary pavilion. WCTE 2014 - World Conference on Timber Engineering, Proceedings.