Algorithm-Aided Design and Analysis for the Comparative Models Study of Heinz Isler’s Shells

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Abstract. Heinz Isler, known as the most famous contemporary shell designer, has employed physical modelling techniques for studying and constructing concrete shell structures. The Swiss engineer's work has spread over 50 years of continuous activity (1954 to 2008/9). The innovation in Isler's work stands by the pioneering form-finding methods based on physical structural models (expansion, inflation and hanging) of thin membranes. The strategy was adopted for many of his experimental structures, like (i) the Wyss Garden Centre in Solothurn (1962); (ii) COOP Warehouse Wangen in Olten (1960) and (iii) Deitingen Slid Service Station (1968).
In this document, the study focuses on the assessment of Isler's Shells employing new technologies and strategies based on Algorithm - Aided Design. The design steps comprehend the reparameterization of Isler's shells samples using Parametric Design techniques (geometry development in Rhinceros3D © + Grasshopper© add-on); the generative approach (parametric design + simulation) is conducted and achieved thanks to Alpaca4D©. The structural analysis relies on a Finite Element Analysis (FEA) carried on through the plug-in for Grasshopper© in Rhinoceros3D©. The results are retrieved to develop and validate the achieved results employing Alpaca4D© with a comparative model developed with the Karamba 3D© add-on and FEM-Design©, an advanced and intuitive structural analysis software.

Keywords: Generative Design, OpenSees, Alpaca4D, Benchmark Test, Parametric Development, Finite Element Analysis, Reverse Engineering.

1 Introduction

Heinz Isler was a Swiss structural engineer and architect known for his innovative work in the field of shell structures. Born on June 19, 1926, in Zurich, Switzerland, Isler gave significant contributions to developing lightweight and efficient shell structures that challenged traditional architectural and engineering norms.

Isler's approach to design was influenced by nature, specifically, the shapes and forms found in natural structures like shells, leaves, and flowers [**1**]. Isler's work builds upon the principles governing natural forms applied to create efficient and elegant structural designs [**2**].

One of Isler's notable achievements was his exploration of the double-curvature concrete shell structures. He developed a technique [**3**] involving the use of thin, reinforced concrete shells supported by a minimal number of slender columns or supports [**4**][**5**]. This approach allowed for large-span structures that were both visually striking and structurally efficient. His work earned him international recognition and numerous awards throughout his career, including the Auguste Perret Prize in 1976 and the IASS (International Association for Shell and Spatial Structures) Gold Medal in 1993 [**6**].

Heinz Isler's innovative approach to shell structures revolutionized the field of architecture and engineering, and his designs continue to inspire and influence architects and engineers worldwide, showcasing the possibilities of creating elegant and efficient structures using natural principles.

Isler's portfolio includes a variety of projects such as roofs, shells, and pavilions. Some of his most renowned works include (i) The Wyss Garden Centre in Solothurn (1962); (ii) COOP Warehouse Wangen in Olten (1960) and (iii) Deitingen Slid Service Station (1968).

In this study, the attention will be focused on the latter three structures ((i), (ii), (iii)), validating Isler's model exploiting the Generative Design Approach. The models initially developed through the innovative parametric modelling techniques in Grasshopper 3D for Rhinoceros 3D will then be analyzed and validated in three different FEM solvers: (a) Karamba 3D, (b) Alpaca 4D and (c) FEM Design. The results obtained show good accordance between the employed software((a), (b), (c)), validating not only the structural strength of the shells modelled based on Isler's geometries but also the performance and computing power of Alpaca 4D© and FEM - Design©.

2 Isler’s Models Development

The exceptional performance of Isler’s shells within the four decades, and the importance of his approach to modelling, has encouraged many designers to re-evaluate his shells and get inspired by Isler’s work [**7**]. Given the resonance of Isler's work concerning the shell structures and the studies produced in this field, three significant examples of Isler's design are considered. The following images (**Figure 1**) describe the geometry of (from the top): (**a**) Wyss Garden Center (1961, Zuchwil, Solothurn, Switzerland); (**b**) Deitingen Service Station (1968, Deitingen, Solothurn, Switzerland); (**c**) Bürgi Garden Center (1973, Camorino, Switzerland).

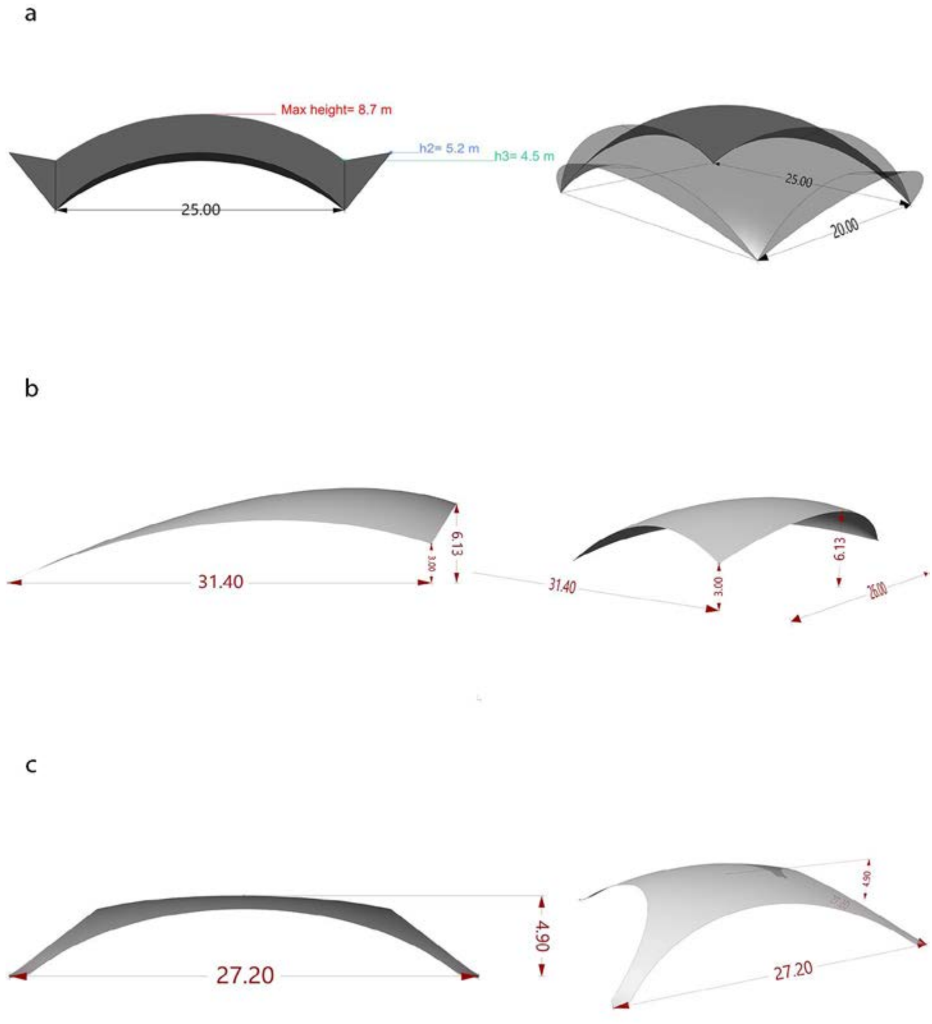

Figure 1 (**a**) Wyss Garden Center (1961, Zuchwil, Solothurn, Switzerland); (**b**) Deitingen Service Station (1968, Deitingen, Solothurn, Switzerland); (**c**) Bürgi Garden Center (1973, Camorino, Switzerland).

The development of the geometries illustrated in the previous image (**Figure 1**), was implemented in the Grasshopper environment. Grasshopper employs a visual programming paradigm, where users create and manipulate components called "nodes" within a canvas interface [**8**]. These nodes represent various operations, algorithms, and mathematical functions. For each geometry, the parameters have been set through design variables using the appropriate *number sliders* that allow the variation of the geometry and the consequent analysis in real-time (**Figure 2**).

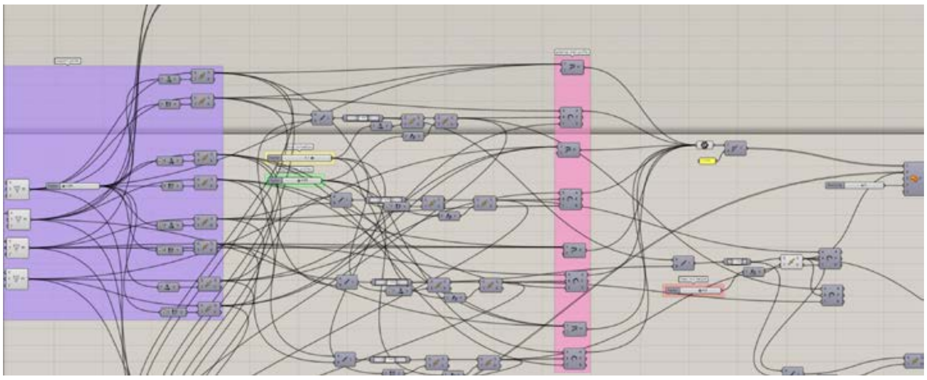

Figure 2 Geometry development in Visual Language of the case study (**c**) Bürgi Garden Center

Through the geometry definition, it was possible to obtain from the Boundary Representations (*BRep*) the mesh belonging to the three geometries to transform the structural object into Shell (*Mesh to Shell*).
Since the goal of the document is to study three of Isler's shells to achieve the software's comparison and benchmark, the next step is characterized by the geometry definitions using different finite element software.
To sum up, the work workflow for software testing through the definition of case studies is distributed as follows:

1. Grasshopper development for parametric definition (Geometry)
2. FEM using Karamba - 3D plugin
3. Data transfer from Grasshopper to Alpaca 4D
4. Benchmark test using FEM - Design.

Karamba3D is a parametric structural engineering tool which provides accurate analysis of spatial trusses, frames, and shells. Karamba3D is fully embedded in the parametric environment of Grasshopper which is a plug-in for the 3d modelling tool Rhinoceros (Rhino3d) [**9**]. In parallel to the Karamba 3D model, also Alpaca4d was used for the benchmark test. Alpaca 4D is a Grasshopper plugin which has been developed on top of OpenSees. It lets you analyse beam, shell, and brick elements through Static, Modal and Ground Motion Analysis. Alpaca4D is currently being developed by Marco Pellegrino and Domenico Gaudioso. Alpaca4d facilitates the interaction with OpenSees making it possible to model complex geometries within your parametric workflow and reducing the time spent in the modelling. The main idea of Alpaca4d is to provide an efficient and easy way to use OpenSees without writing any line of code. The library is mostly used by researchers and academia because of the not user-friendly interface even if the math at the core library is highly sophisticated [**10**].
To perform the analysis, the models have been evaluated under their self-weight with a structural uniformly distributed overload equal to 4 kN/m^2 for the simulation of the snow load, due to the location of the structural artefact. For all the parallel analyses was used the same linear material properties and definitions. The mechanical properties of

the concrete material of Isler's shell constructions are not identical and different references have mentioned different values for it.
The typical concrete mixture of Isler's shells constitutes of cement percentage of a maximum (325 kgm3), gravel stone with a maximum dimension of (15 mm) [**7**],[**11**] for the concrete of 28 MPa (C-28) compression strength. Since, the aim of this study is the comparison of the structural performance of different shells considering the benchmark test employing several finite element software, in all the shells, the same strength and material properties for concrete is assumed: C 45/55, E= 3600/3kN/cm^2, Specific weight (γ)=25kN/m^3, ν (**Figure 3**).

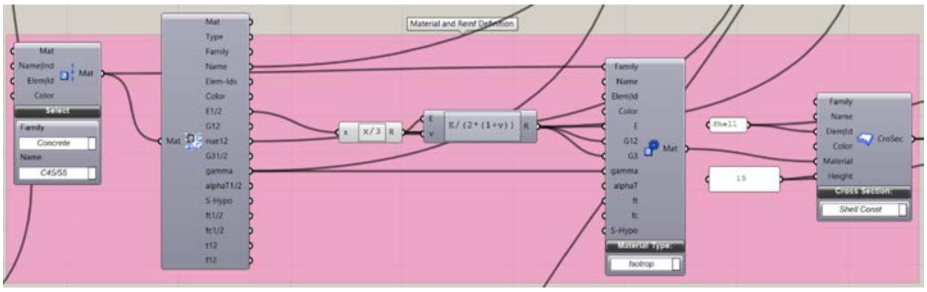

Figure 3 Material Development and Shell Constant Cross Section in Visual Language

The data include the thickness, the span, and the height dimensions of shells. For the shells (a), (b), and (c), different heights were mentioned in the references. The shells' thicknesses vary, and the assumed values are based on ranges found in the relevant references. Considering the shells (a), (b), (c), the thickness (t) varied in the range between $6 \leq t \leq 10$ cm. However, for the analysis, the thickness of all shells t = 15 cm is assumed to develop comparative models. A uniform thickness is considered to acquire general results of the force flow and stress distribution.

3 Models Evaluation

In this section the retrieved results are described and compared in the following Tables (1, 2, 3). The main indicators of comparison between finite element analysis software (i.e., Alpaca4D©, Karamba3D© and FEM-Design©) are represented by *mass and displacement*. The trend of the vertical displacement is described through the following images for each of the shells analyzed through the different FE software (**Figure 4.,5.,6.**)

Table 1. Results comparison of the Test Case (a) Wyss Garden Center (1961).

Solver	Displacement [mm]	Mass [kg]
Karamba 3D	13.98	326186.93
Alpaca 4D	14.89	332618.58
FEM - Design	14.16	332416.48

The vertical deformation of the shells can be considered low considering their span; this is a clear indication that the load transmission work as in the membrane rather than in flexural form.

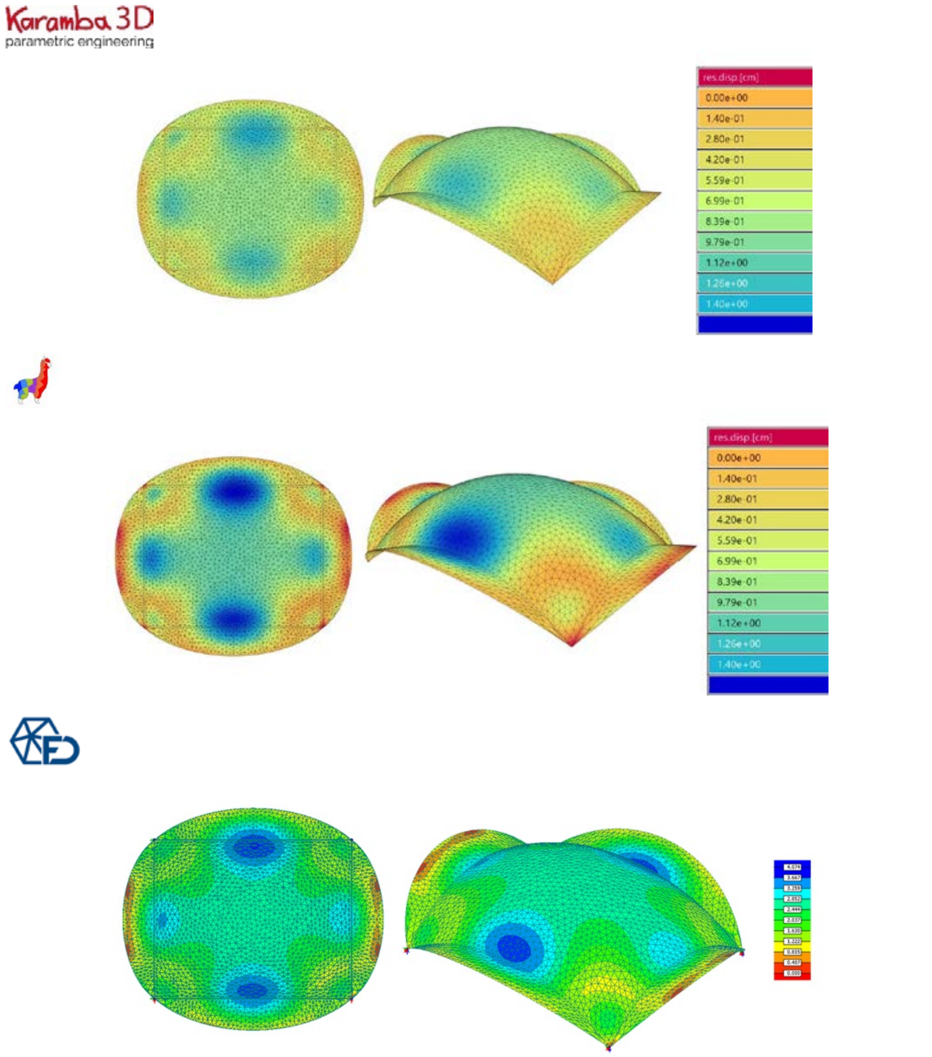

Figure 4. Test case (a) Wyss Garden Center, 1961. Trend of the vertical displacement: Upper definition Karamba3D; Mid - definition Alpaca4D; Lower Definition: FEM-Design by StruSoft.

Table 2. Results comparison of the Test Case (b) Deitingen Service Station (1968)

Solver	Displacement [mm]	Mass [kg]
Karamba 3D	59.24	151877.17
Alpaca 4D	59.91	154871.83
FEM - Design	59.32	153275.16

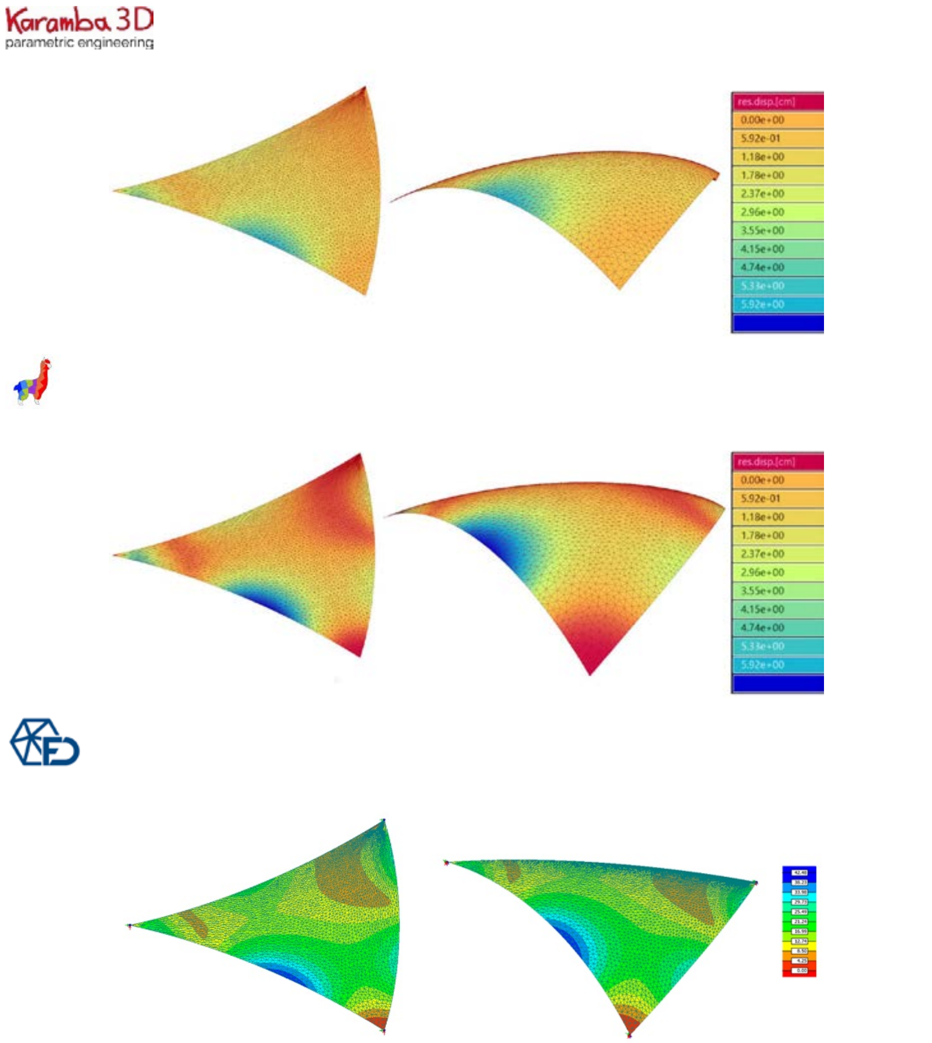

Figure 5. Test case (b) Deitingen Service Station 1968. Trend of the vertical displacement: Upper definition Karamba3D; Mid - definition Alpaca4D; Lower Definition: FEM-Design by StruSoft.

Table 3. Results comparison of the Test Case (c) Bürgi Garden Center (1973)

Solver	Displacement [mm]	Mass [kg]
Karamba 3D	66.96	146495.55
Alpaca 4D	70.39	149384.10
FEM-Design	68.16	147548.61

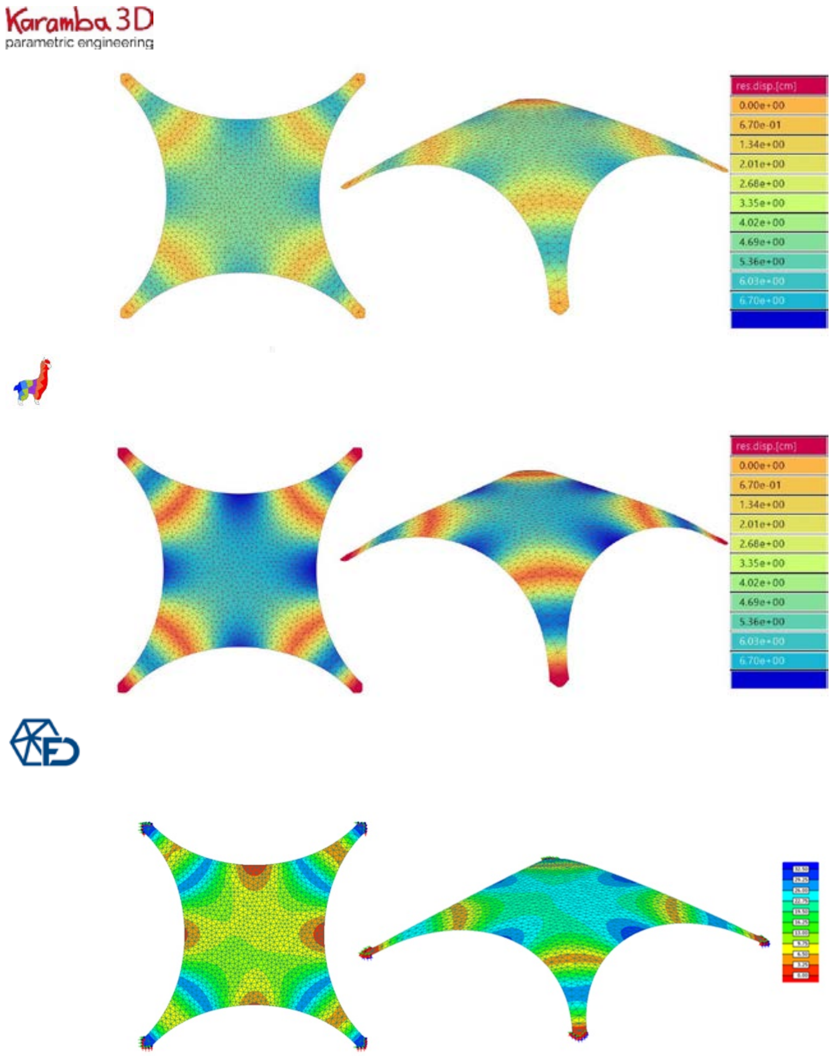

Figure 6. Test case (c) Bürgi Garden Center, 1973. Trend of the vertical displacement: Upper definition Karamba3D; Mid - definition Alpaca4D; Lower Definition: FEM-Design by StruSoft.

4 Conclusions

In this research, three of Heinz Isler’s shells are re-modelled and assessed through reverse engineering techniques. The modelling data for the development of the samples are retrieved by exploiting numerical and visual data from several references. The evaluation of the shell structures is processed within several software packages to estimate the accuracy of the results between the Finite Element Software employed within the Grasshopper© environment, a Visual Language environment, i.e., Karamba3D©, Alpaca4D© and FEM-Design© by StruSoft©.

The work shows a high degree of conformity to Isler’s shells however, the possibility of a degree of deviation from the real Isler's shell must be considered, due to the purpose of this document, which is not to estimate Isler's result, but is instead to assess the performance of new production FE software, such as Alpaca 4D© and FEM-Design©. The indicator data for the software's evaluation are represented by the Mass and Displacement for each analyzed sample, and, considering the numerical results summarized in Tables (1), (2), and (3), the different analyses show good accordance between them, validating the analyses conducted with the three independent software for three different samples. Current research on the frontiers of concrete material and sustainability aspects [**12**][**13**] may also provide some near future promising research paths, also involving life-cycle assessment and optimization-related aspects of thin shell structures [**14**][**15**][**16**].

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