Biomimetics for Applications in 3D Printed Greenhouses

Thesis

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Abstract

This document withholds the design and investigation of 3D printed greenhouses inspired by biological structures. This accomplished through the process of biomimicry defined as the inspiration of structural design taken from nature to optimise said structure. Therefore, within this thesis paper, the biomimetic approach is aimed to optimise a greenhouse resistance to both wind and gravitational loadings The biological structure that has been used as inspiration to allow for structural optimisation is honeycombs intertwined and modelled to the exterior of the greenhouse geodesic dome. The 3D printed element is concentrating on the structural aspect of greenhouses. Furthermore, evaluation of structural effectiveness is conducted utilizing finite element analysis method. Final part of this thesis is also to 3D print a scale model for potential purposes of physical testing.

Contribution of Work

- I have carried out and have written introductory background research and defined project aims and requirements.
- I have carried out literature review and documented/written content relevant to thesis project.
- I have designed and carried out all 3D models within Solidworks 2019 alongside researching and analysing design methods and tools along the process.
- I have documented all calculations and have utilised them through values collected within my designed methodology.
- I have defined the design requirements and investigative structure as well as all the methodology process that was followed except for 3D printing process.
    - Eugene Mah has assisted in the 3D printing process including; materials, exportation and importation, parameters of the models generated.
- I have completed the risk assessment regarding the 3D printing process.
- I have carried out physical experiments/testing using digital force gauge and similar/related handheld tools.
- I have carried out simulated experiments/testing using Solidworks 2019 CAD software, Finite Element Analysis Software and Flow Simulation plug-in.
- I have collected, documented, and analysed all results collated from both physical testing tools and simulation software for the physical and CAD model respectively.
- I have carried out and written the discussion and conclusion statements and documentation.
- I have created this document and have been the only individual that has contributed to the generation of this physical document.

The above points represent an accurate summary of my contribution.

Vishant Prasad Prasad   *06/11/2022*

Student   Date

Contents

Abstract i

Contribution of Work ii

1.0 Introduction & Background of Biomimetics 1

1.1 Project Aims 2

2.0 Context 3

2.1 Predicted Food Shortages 4

2.2 3D Printing 5

2.2.1 3D Printing of Larger Structures 6

3.0 Literature Review 7

3.1 3D Printing & Conventional Materials 7

3.2 Finite Element Analysis 9

3.3 Optimisation of Structures 9

3.4 Faunal Related Biomimicry 10

3.4.1 Beatle Wing 10

3.4.2 Wasp Nests 11

3.4.3 Spider Webs & Succulents 13

3.5 Floral Related Biomimicry 15

3.5.1 Coral Reefs 15

3.5.2 Rainforests 15

3.5.3 Seashells 16

3.5.4 Honeycomb 18

3.6 Geodesic Greenhouse Design 19

3.6.1 Pacific Domes Case Study 20

3.7 Greenhouse Tower Design Case Study 21

3.8 Community Farms & Landscape Repurposing Case Study 23

3.9 Modelling & Scalability 24

3.10 Forces 25

3.10.1 Wind Speed 25

3.10.2 Velocity Pressure 26

3.10.3 Force Coefficients 27

3.11 Energy Calculation & Usage Considerations 27

3.11.1 Reducing Energy Consumption 29

3.12 Safety Considerations 30

3.12.1 Risk Assessment for 3D Printing Process 32

4.0 Methodology 34

4.1 Design Requirements 34

4.2 Investigation Structure 34

4.3 Optimisation Factors 35

4.4 Greenhouse Shape Investigation 35

4.5 Biomimetic Approach 39

4.6 Dimensions & Scaling 39

4.7 Model Generation 41

4.8 FEA Process 48

4.8.1 Mesh Generation & Loading Conditions 50

4.9 3D Printing Process 51

4.10 Wind Forces 53

4.11 Control Variables 53

4.12 Wind Pressure 54

4.13 Physical Testing Process 54

5.0 Results & Analysis 56

5.1 Process of Gathering Results 56

5.2 Typical Geodesic Greenhouse Dome 56

5.3 Biomimetic Geodesic Greenhouse Dome 57

5.4 Analysis of Results 57

5.4.1 Typical Geodesic Greenhouse Dome Results 57

5.4.2 Biomimetic Honeycomb Greenhouse Dome Results 62

5.4.3 Physical Force Testing Results 66

6.0 Discussion 68

6.1 Recommendations 70

7.0 Conclusions 72

7.1 Future Work 73

8.0 References 74

9.0 Appendix 79

9.1 Appendix A 79

9.1.1 Wind Regions in Australia 79

9.1.2 Terrain Categorization 80

9.1.3 Shielding Factors 81

9.1.4 Topography Effects 82

9.2 Appendix B 83

9.2.1 Digital Force Gauge 83

9.2.2 Digital Force Gauge with Attachments 84

9.2.3 Orientation of Physical Tests 85

9.3 Appendix C 86

9.3.1 Scale-Down Model Loadings Derivations 86

9.4 Appendix D 87

9.4.1 Physical Testing Mould for Distributed Load 87

9.5 Appendix E 88

9.5.1 Mesh Generation 88

9.5.2 Loading Conditions 89

List of Figure

Figure 1: Gecko Skin inspiring Adhesive Design & Bandage Material 1

Figure 2: Leaf Topology inspiring Traffic Flow & Suburban Design 2

Figure 3: Biomimicry in Greenhouses & Geodesic Domes 3

Figure 4: United Nations - Population Estimates 4

Figure 5: World Agricultural Food Demand, Population & Income 4

Figure 6: Agricultural Food Demand by Categorization 5

Figure 7: 3D Printed Scale Model Geodesic Greenhouse Domes 5

Figure 8: Exemplar Geodesic Dome w/3D Printed Joints, PVC, and Plastic Sheeting 6

Figure 9: Different Shapes & Evolution of Greenhouses 10

Figure 10: Artistic Rendition of Wings that inspire Greenhouse Glass Design 11

Figure 11: Seawater Greenhouse Mechanism Fog-Basking Behavior 11

Figure 12: 3D-Printed Home inspired by a Wasp's Nest 12

Figure 13: WASP Organisation building 3D Printed Architectural Houses with Soil.................. 13

Figure 14: Team NexLoop Water Management System for Urban Food Producers..................... 14

Figure 15: AquaWeb Biomimicry Global Design Water Capture Unit 14

Figure 16: Exterior of Seawater Greenhouse Project in Port Augusta, Australia.......................... 15

Figure 17: Vertical Farms inspired by the layers of the Rainforest 16

Figure 18: Shell-Like Think Space Design 17

Figure 19: Artistic Render & Concept of Seashell House 17

Figure 20: Shell-Like Design Inspiration 18

Figure 21: Honeycomb inspiring the Sandwich Structure of Greenhouse Glass 19

Figure 22: Organic Design of House Structure using Honeycomb Topology Inspiration 19

Figure 23: Geodesic Greenhouse Design from Kleenex 20

Figure 24: Pacific Domes Greenhouse Specific Geodesic Dome 21

Figure 25: The Lower-Ground Floor of the Lendlease Tower below Greenhouse Layers............ 22

Figure 26: Gardens by the Bay Greenhouse 22

Figure 27: Solar Panel Tree Towers.. 23

Figure 28: Detroit Urban Farm Repurposing Neighborhood 24

Figure 29: Region Categorization across Australia 26

Figure 30: Design Wind Speed Calculations - Australian Regions 27

Figure 31: Typical Breakdown of Annual Energy Usage in North American Environment 28

Figure 32: Biodome Types.. 37

Figure 33: Trade Off Table - Different Greenhouse Designs 38

Figure 34: Advantages of Geodesic Dome - Vega Architecture 40

Figure 35: Dimensioning based on Structural Design & Base Surface Area 40

Figure 36: Design Iteration 1 - Typical Geodesic Dome 41

Figure 37: Design Iteration 2 – Typical Geodesic Dome 42

Figure 38: Design Iteration 3 - Honeycomb Lattice.. 43

Figure 39: Design Iteration 4 - Honeycomb Lattice.. 44

Figure 40: Design Iteration 5 - Honeycomb Lattice (Filled).. 45

Figure 41: Design Iteration 6 - Ground Surface 46

Figure 42: Design Iteration 7 - Typical Geodesic Dome.. 47

Figure 43: Design Iteration 8 - Biomimetic Honeycomb Geodesic Dome Design 48

Figure 44: Goals Tracked 50

Figure 45: 3D Printed Models Interior 52

Figure 46: 3D Printed Model 1 52

Figure 47: 3D Printed Model 2 52
Figure 48: 3D Printed Model 3 52
Figure 49: Vortex Effect from Wind Contact 53
Figure 50: Typical Geodesic Greenhouse Dome - Pressure Result 58
Figure 51: Typical Geodesic Greenhouse Dome - Velocity Result 59
Figure 52: Typical Geodesic Greenhouse Dome - Deformation Results 60
Figure 53: Typical Geodesic Greenhouse Dome - Strain Result 60
Figure 54: Typical Geodesic Greenhouse Dome - Von Mises Yield Result 61
Figure 55: Biomimetic Honeycomb Greenhouse Dome - Pressure Results 62
Figure 56: Biomimetic Honeycomb Greenhouse Dome - Velocity Results 63
Figure 57: Biomimetic Honeycomb Greenhouse Dome - Deformation Result 64
Figure 58: Biomimetic Honeycomb Greenhouse Dome - Strain Result 64
Figure 59: Biomimetic Honeycomb Greenhouse Dome - Von Mises Yield Result 65
Figure 60: Wind Regions in Australia 79
Figure 61: Australian Terrain Categories for Wind Load Classification 80
Figure 62: Shielding Factors for Wind Load Classification 81
Figure 63: Topographical Effects in different Scenarios 82
Figure 64: Digital Force Gauge - No Attachments 83
Figure 65: Digital Force Gauge with Attachments 84
Figure 66: Differing Directions of Force Applications 85
Figure 67: Distributed Load Mould - Top View 87
Figure 68: Distributed Load Mould - Side 1 87
Figure 69: Distributed Load Mould - Side 2 87

Figure 70: Flow Simulation - Mesh Settings.. 88

Figure 71: Wind Loading Condition - Air Gas Definition.. 89

List of Tables

Table 1: 3D Printing Material Qualities (Chen 2020) 7

Table 2: Risk Assessment 32

Table 3: Greenhouse Structures Comparison - Pros & Cons (Government 2016) 36

Table 4: Equations for Scaling Loadings 54

Table 5: Typical Geodesic Greenhouse Dome Results 56

Table 6: Biomimetic Geodesic Greenhouse Dome Results 57

Table 7: Peak Velocity Comparison 63

Table 8: Physical Force Test Results 66

Table 9: Summarized Resulting Improvements 72

Table 10: Scale the Load to Investigate this Behavior - Equation Derivations 86

List of Acronyms

Cases

ABS: Acrylonitrile Butadiene Styrene 9

AES: Agricultural Experiment Station 31

CAD: Computer-Aided Design 7

CC: Contour Crafting 8

FEA: Finite Element Analysis 4

HAF: Horizontal Air Flow 32

HIPS: High Impact Polystyrene 10

NSW: New South Wales 53

PET: Polyethylene Terephthalate 10

PETG: Polyethylene Terephthalate 10

PLA: Polylactic Acid 10

PPE: Personal Protective Equipment 36

PV: Photovoltaic 27

PVC: Polyvinyl Chloride 8

STL: Stereolithography 52

UK: United Kingdom 13

UV: Ultraviolet 10

WASP: World's Advanced Saving Project 14

List of Equations

- ET_{plant}: Hargreaves Equation
  - $where$
    - $E = Energy\ (J)$
    - $T_{plant} = Temperature\ (Kelvins)$

- $HL = A \times U\Delta T$: Heat Loss
  - $where$
    - $HL = Heat\ Loss\ \left(\frac{Btu}{hr}\right)$
    - $A = Surface\ Area\ of\ Greenhouse\ (sq. ft)$
    - $U = Heat\ Transfer\ Coefficient\ \left(\frac{Btu}{hr} - sq. ft - °\text{F} = 1.25\ to\ 0.6\right)$
    - $T = Temperature\ (°\text{F})$

- $\frac{h}{L^2} \times \frac{\pi^2 E}{12}$: Stress at Failure (Simplified) Buckling
  - $where$
    - $h = Height\ (m)$
    - $L = Length\ (m)$
    - $E = Young's\ Modulus\ (Stress/Strain)$

- $\frac{L}{bh^2} \times \frac{3}{2} \times P$: Stress at Failure (Simplified) Bending
  - $where$
    - $h = Height\ (m)$
    - $L = Length\ (m)$
    - $b = Base\ (m)$
    - $P = Pressure\ (Pa)$

- $\frac{h}{L^2}$: Factors Affected by Dimensional Scaling Buckling
  - $where$
    - $h = Height\ (m)$

            - $L = Length\ (m)$

- $\frac{L}{bh^2}$: Factors Affected by Dimensional Scaling Bending
    - *where*
        - $h = Height\ (m)$
        - $L = Length\ (m)$
        - $b = Base\ (m)$

- $F = A_m \rho a^2$: Wind Loading
    - *where*
        - $F = Force\ (N)$
        - $A_m = Contact\ Area\ (m)$
        - $\rho = Density\ (kg/m^3)$
        - $a = Surface\ Area\ (m^2)$

- $P = I \times V^2$: Wind Pressure
    - *where*
        - $P\ is\ wind\ pressure\ \left(\frac{pounds}{sq.ft}\right)$
        - $V\ is\ speed\ (mph)$

1.0 Introduction & Background of Biomimetics

Biomimetics, also known as biomimicry, can be summarized as the study of biological structures, formations, and patterns, whether it be materials, mechanisms, or substances, for the purpose of replicating and producing such structures [Webster, M. Biomimetics. (Webster)]. Therefore, mimicking the naturally occurring biological structures for purposes in human technology, design or for purposes of solving complex human problems. There have been numerous examples of such a process evident throughout human history. Some of the most prominent examples include gecko's abilities to walk up smooth surfaces on a microscopic level through the studies of their hairs being applied to the development and design of adhesives ["Nature's Unifying Patterns." (2015)]. Furthermore, through biomimetics applied in such a manner furthering the development of adhesives has permitted the growth in the field of medicine particularly in researching the closure of wounds and alternatives to stitches. This is highlighted within *figure 1*. Moreover, biomimetics can affect other areas of our daily lives such as traffic flow on highways being inspired by the flow of ants ["Biomimicry is Real World Inspiration." (Phillips)]. The insect world and studies of ant columns have inspired some of the most basic forms of highway traffic management and flow, even extendable and impactful in the development of autonomous vehicles. This is denoted in *figure 2*. Therefore, to better aspects of our human lives, through the engineering process, we can draw the conclusion that often the natural world can possess secrets to generating effective and efficient designs.

Figure 1: Gecko Skin inspiring Adhesive Design & Bandage Material

[(2022). "What is GeckSkin™?"]

Figure 2: Leaf Topology inspiring Traffic Flow & Suburban Design

(Grocoff 2016)

1.1 Project Aims

The aim of this investigation is to research a variety of naturally occurring biological structures for the application of farming. More specifically, designing a greenhouse structure that can be 3D printed, housing flora and plants, allows for an effective mechanism for holding and growing a source of renewable food. Furthermore, methods of finite element analysis (FEA) are to be utilized in the decision making for this application, allowing for a reduction in material, costs, and simplification of design. A small set of scalable 3D printed models is aimed for production through this investigation using identical material to the large-scale application for purposes of force testing, visualization, and other relevant physical analysis.

2.0 Context

The following paper outlines an investigation for the applications of biomimetics within the design of residential utilized greenhouses. With the constant change in global climate influencing water, land and energy production, the demand for resources are constantly on the rise. Furthermore, with a constantly growing economy and population, a global food shortage is a well predicted event that can plague humanity. As seen in *figure 3* the ongoing growth of the human population will inevitably call fourth greater consumptions of resources. Moreover, its effects can be especially detrimental in regions that are impacted by natural disasters or regularly suffer from seasonal climate catastrophes. With this consideration of the near future, crops can benefit from reducing their accumulation on landscapes and maximize produce through innovative designs of greenhouses that priorities effective crop growth. Furthermore, this can be extended into realms of hydroponics. Using biomimetics will allow for inspiration from the natural world, opening the capability to draw upon designs reducing material utilization, physical labour and explore original structures to allow for flora to prosper. Most prominent examples of this can be witnessed within the design of geodesic greenhouses or domes as seen in *figure 4*.

Figure 3: Biomimicry in Greenhouses & Geodesic Domes

(Biju 2022)

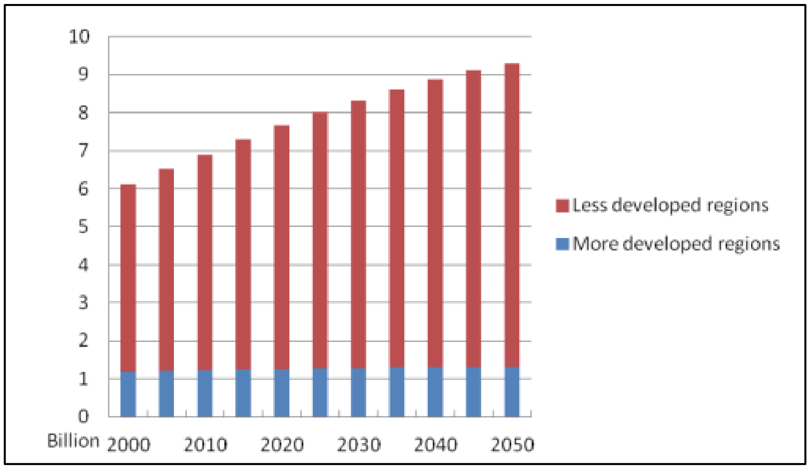


Figure 4: United Nations - Population Estimates

(Verity Linehan 2012)

2.1 Predicted Food Shortages

The primary issue that this investigation aims to influence aspects of is the predicted food shortage of the near future. Many scientific articles and papers predict a shortage impacting aspects of humanity and planet around the decade of 2050. A visualization of this is highlighted in *figure 5* and *figure 6*. (Affairs 2019)

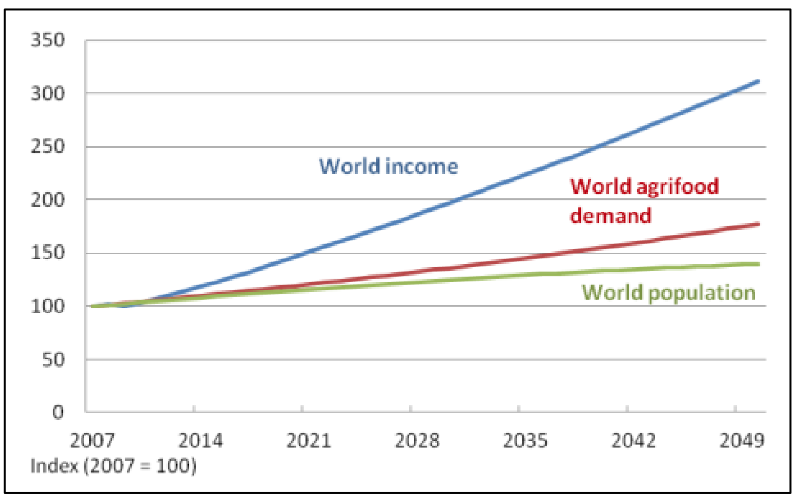


Figure 5: World Agricultural Food Demand, Population & Income

(Verity Linehan 2012)

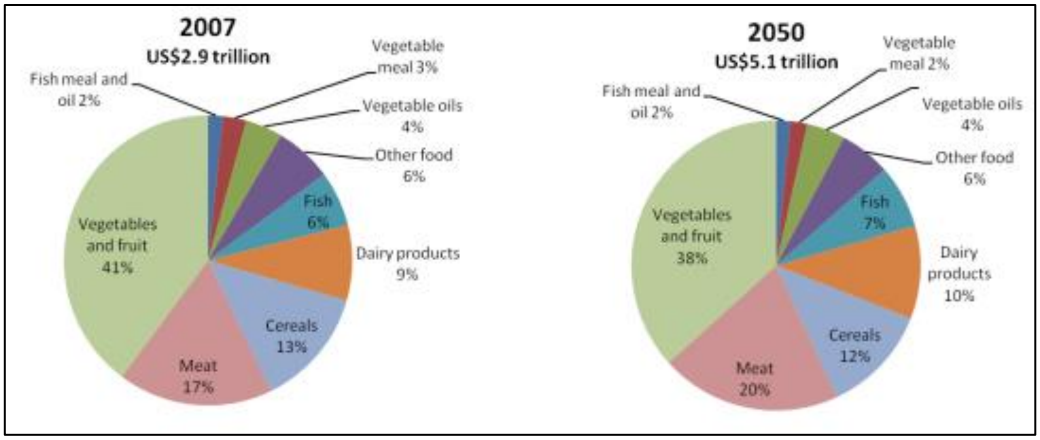


Figure 6: Agricultural Food Demand by Categorization

(Verity Linehan 2012)

2.2 3D Printing

3D Printing has been fast becoming a desirable manner to manufacture structures and components due to its rapid prototyping, strong and lightweight parts, fast design and production rate, minimal waste, ease of accessibility and finally, cost effectiveness. With the concerned realm of biomimetics being the forefront of this investigation, 3D printing would be a leading route to production as it allows the reduction of wastes. ["What are the Advantages and Disadvantages of 3D printing?" (2022)]

Furthermore, with the objective of manufacturing a greenhouse using 3D printing and eco-friendly material, there are many pre-existing designs and projects that have successful attempts and computer-aided design (CAD) models of various layouts for greenhouses. Some are highlighted in *figure 7* and *figure 8*.

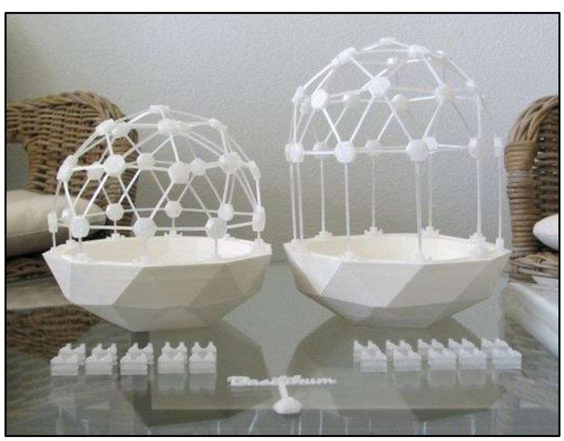


Figure 7: 3D Printed Scale Model Geodesic Greenhouse Domes

(Koslow 2018)

Figure 8: Exemplar Geodesic Dome w/3D Printed Joints, PVC, and Plastic Sheeting

(Connor 2021)

2.2.1 3D Printing of Larger Structures

The application of 3D printing in the design and manufacturing of large structures is a recent development. Slowly certain educational establishments and industrial organizations are steadily researching and progressing the capability to manufacture single-family dwellings, commercial structures, and buildings of similar nature. The primary factor that allows for such development is the 3D printing automation and fabrication process. For example, Behrokh Khoshnevis, a professor at the University of Southern California (Petrovic 2020), has developed a Contour Crafting (CC), 3D printing process that releases concrete pushing the boundaries of such a manufacturing process. Steps in the future building off this basis would enable constructions workers to develop frameworks for houses and larger scale 3D printed structures.

Such larger scale projects that can be delivered through the 3D printing process would result in economic viability as the cost savings generated are significant in comparison to traditional construction methods. This is evidenced by the Winsun custom 3D printed villa of 11,800 sq made from most of the recycled rubble, fiberglass, steel, cement, and binder, where the final costs were estimated to be half the conventional cost that employs traditional construction processes (Armstrong 2016). Therefore, the viability of 3D printing larger scale structures is one that is continuing to be proven and inevitably will become more prominent in construction around the world.

3.0 Literature Review

The following section highlights related information, research and case studies that contribute to the investigation of both biomimicry, material utilization and agricultural relevancy.

3.1 3D Printing & Conventional Materials

Since the investigation concerns itself with an industrial application for 3D printing, the material selections are various with many denoting both advantages and disadvantages. The primary few that are commonly employed for such applications include:

Table 1: 3D Printing Material Qualities (Chen 2020)

Material	Characteristics	Disadvantages
Nylon	- Durability - Flexibility Ratio - Little Warpage - Easily Colored	- Keep Dry - Shelf Life: 12 Months - Shrinkage during Cooling - Low Print Precision - Printer Suitability Variable
ABS (Acrylonitrile Butadiene Styrene)	- Accessible & Cheap Materials for 3D Printing - Easily Available - Wide Variety of Color Choice - Long Material Lifespan - Mechanically Strong	- Used for High Quality Prototyping & Production - Requires Heated Bed - Experiences Warping if Cooled - Non-Biodegradable Toxic Material - Toxic Fume Release at High Temperature
Resin	- Many Applications - Low Shrinkage - High Chemical Resistance	- Expensive - Filament Expires - Needs Secure Storage (Photo-Reactivity)

	- Rigid & Delicate	- Premature Polymerization
PET/PETG (Polyethylene Terephthalate)	- Durable - Impact Resistant - Recyclable - Sterilized - Adhesion - Functionality of ABS (temperature Resistant, Stronger & PLA) - Easy to Print	- Weakened by UV Light - Prone to Scratching - Testing required with 3D Parameters
Ceramics	- High-Precision Components (Smooth & Glossy Surface) - Resistance to Acid, Heat & Lye. - Wide Range of Colours	- Great amount of Temperature to Melt - Not Suitable for Glazing & Kilning Processes. - Fragile - Not Ideal for Assembly Process
HIPS (High Impact Polystyrene)	- Good Machinability - Smooth & Lightweight - Water Resistant & Impact Resistant - Inexpensive	- Produces Strong Fumes - Requires Constant Heat Flow

The material selection will also influence the aspect of biodegradation and waste production that is imperative to the objectives of this investigation. Furthermore, the considerations for material selection overall would require the following qualities:

- Low Environmental Footprint

- Durability & Long Life
- Flexibility
- Corrosion Resistance
- Cheap & Easily Accessible
- Lightweight

3.2 Finite Element Analysis

Finite Element Analysis (FEA) is a "computerized method for predicting how a product reacts to the real-world forces, vibrations, heat, fluid flow and other physical effects" ["Finite Element Analysis Software." (2022)]. The FEA would intend to investigate the greenhouses behaviour, specifically with its torsion and bending when placed against wind and reaction forces.

The primary purpose of conducting such a process during this investigation is to allow for a standard, both quantitative and qualitative to classify the effectiveness (structurally) of the design. Furthermore, it allows a manner of rating the 3D printing process, CAD design and material selection for its applications within the greenhouse design.

3.3 Optimisation of Structures

Biomimicry throughout history has proven that turning toward nature tends to optimize structural design via reshaping. The results of biomimicry through structural replication processes consequentially reduces energy imbalance and material utilization. The concept of biomimetics is in itself an optimal process or aspect of design as nature functions on the principle of economy and optimal efficiency. A range of investigated and evolutionary design of greenhouses can be seen in *figure 9*. [Merriam Webster Dictionary. (Webster)]

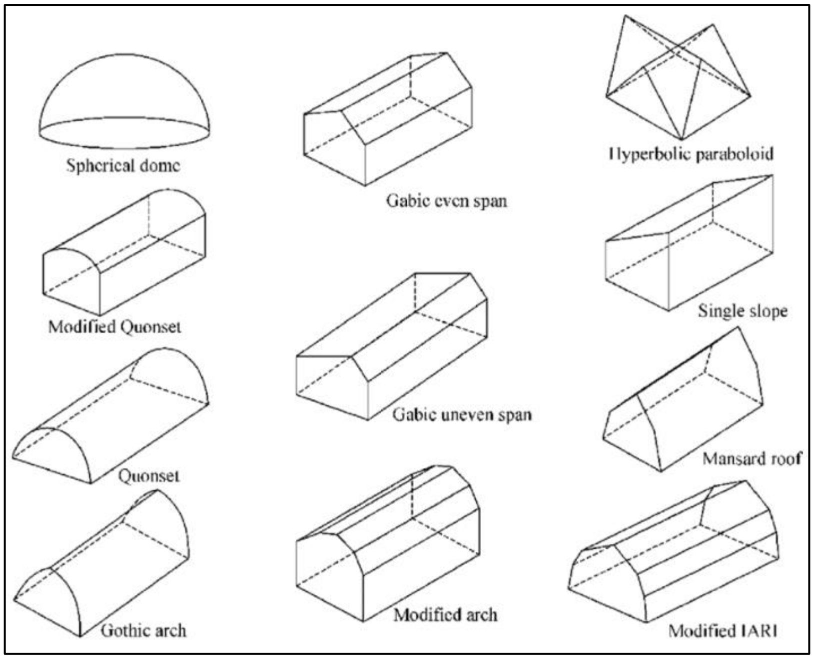


Figure 9: Different Shapes & Evolution of Greenhouses

(Maraveas Chrysanthos 2020)

By employing alternative shape design to the conventional greenhouse structure established, the consequential results of structures can reduce material utilization and better influence the systems allowing growth. Some examples include such aspects as lighting, air flow, water, and temperature control by alternating and optimizing the shape or overall design of the greenhouse structure. This is evidenced with the change in greenhouse structure straying from a typical cubic or house structure to a more circular and dome like structure. Furthermore, technology such as 3D printing implemented in the realm of structural design allows for more effective, lower cost and efficient prototyping that in result allows for calculations into energy models and performance evaluation. Therefore, utilizing 3D printing processes, biomimetics and continuous alterations and experimentations with structural shapes will enable optimization in several important aspects within the realm of this investigation.

3.4 Faunal Related Biomimicry

3.4.1 Beatle Wing

Seawater greenhouses utilize inspiration or biomimicry from the Namibian Desert Beetle with its capability to harness water from humid ocean air. Therefore, utilization of biological structure of the beetle's wing can provide organizations such as 'Alton Greenhouses' with information and designs that allow achievement of ideal growing conditions ("Biomimicry: Visualized." Alton Cedar Greenhouses). The beetle wing structure through this UK based organisation provides a greenhouse dome design that can be ideal in growth of flora all year round and within hot and arid climates. The overall structure and inspiration can be seen in *figure 10*. The structure more specifically gains the evaporation and condensation that converts saline water into fresh water, mimicking the beetle's wing function, using only the sun, wind with a small amount of energy exhausted. Within *figure 11* denotes the evaporation process of seawater at the front end of the greenhouse which creates a pool of freshwater that can be utilized for irrigation. As highlighted, air enters the greenhouse, is cooled, humidified by seawater, and then processed to pass over the evaporator. When the air leaves the area of crops, it passes to another evaporator with seawater flowing that is heated by the sun. This process alongside the network of irrigation that operates underneath the greenhouse allows for the conditions for growing crops to be optimal.

Figure 10: Artistic Rendition of Wings that inspire Greenhouse Glass Design

("Biomimicry: Visualized." Alton Cedar Greenhouses)

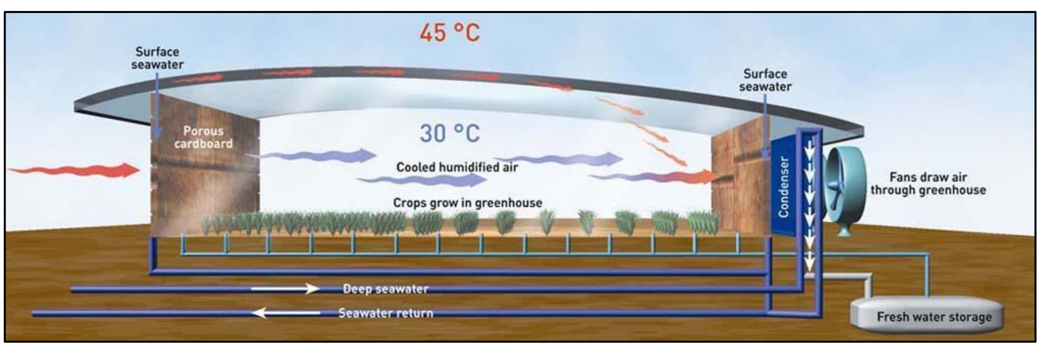


Figure 11: Seawater Greenhouse Mechanism Fog-Basking Behavior

(Anne Snijders 2016)

3.4.2 Wasp Nests

Wasp's nests have been a biological structure that has influenced, less specifically greenhouse design directly, but has influenced clay house designs. More specifically, wasp nests have been utilized in the creation of local clay homes and even in one project denote the creation of these houses using 3D printing processes. World's Advanced Saving Project (WASP) ("WASP – 3D Printing Eco-Building." Retrieved 26/05, 2022) is an organisation that has been focusing on construction processes that are viable on the principles of nature, reusability and lowering waste material in engineering processes. Furthermore, they have developed 3D printed houses in short periods of time through digital fabrication processes as depicted in *figure 12* and *figure 13*. Therefore, the unique aspect of this project being the utilization of various recyclable, naturally occurring and biodegradable material in manufacturing processes sets it aside from past structural endeavours. This would be a significant aspect to implement within the agricultural world or application as this sets a precedence of achievability with biomimicry and 3D printing processes. In contrast, the structural integrity and longevity would be aspects to experiment and investigate with purposes of greenhouses but correspondingly would lower building standards and requirements as they are outdoor non-living structures as opposed to the organisation of Mario Cucinella Architects (Jewell 2020). Furthermore, they establish a sustainability energy wise, with powering of many of these structures being through wind and solar.

Figure 12: 3D-Printed Home inspired by a Wasp's Nest

(Jewell 2020)

Figure 13: WASP Organisation building 3D Printed Architectural Houses with Soil

("WASP – 3D Printing Eco-Building.")

3.4.3 Spider Webs & Succulents

A related aspect of spider-webs and succulent plants is evident through the organisation NexLoop. Their project depicts biomimicry for purposes in water collection. Furthermore, the research and workshop production was extended to investigate and model its applications in greenhouses. Cribellate orb weaver spider webs inspires the system as they collect fog utilizing the air as depicted in *figure 14* and *figure 15*. The storage concepts mimicry employs the engineering mechanisms that are drought-tolerant such as those in succulents. From a technical standpoint the crystalline ice plant holds water. Moreover, the modular shape of the system takes hexagonal structure inspired by hives.

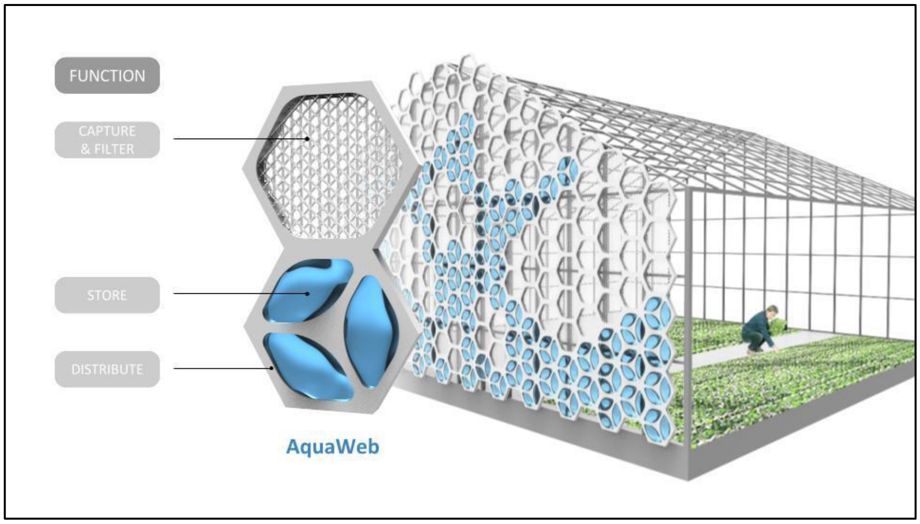


Figure 14: Team NexLoop Water Management System for Urban Food Producers

(Institute 2017)

The invention AquaWeb aims to mimics a natural ecosystem with the capture and storage with water. This project separates itself from competitors and is significant as it is not designed to cope with rainwater but also ambient moisture such as fog or precipitate through evaporation

(Clancy 2017). Furthermore, through the projects testing and results there is a particular practicality and effectiveness in assisting water management within vertical and container farms. Therefore, in summary this endeavour highlights methodology which is effective in terms of self-sufficiency.

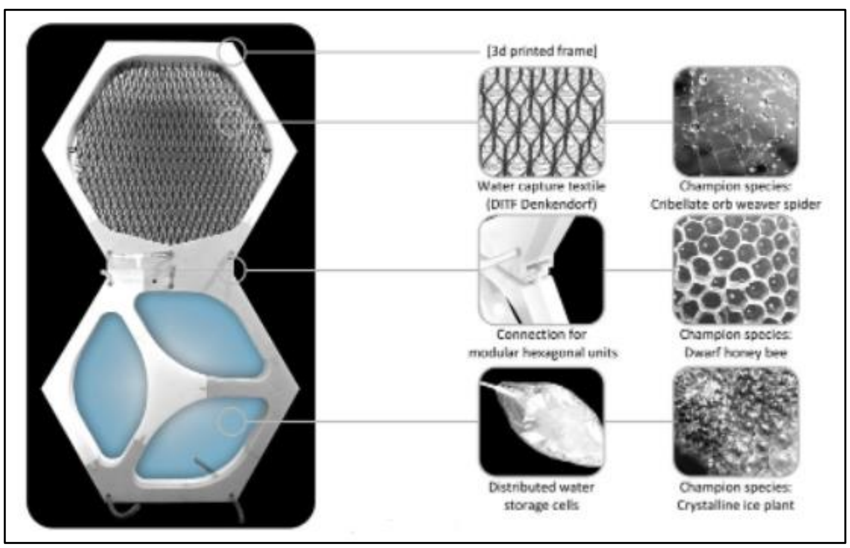


Figure 15: AquaWeb Biomimicry Global Design Water Capture Unit

(Anamarija Frankic 2017)

3.5 Floral Related Biomimicry

3.5.1 Coral Reefs

The inspiration drawn from coral reefs in application of greenhouses is evident in Sundrop Farms, Seawater Greenhouse a part of a project in Port Augusta, Australia highlighted in *figure 16* (Watson 2016). The greenhouse draws inspiration from both the desert beetle and a combination of coral and rainforests. These natural structures around the planet can reuse their own water by products, a process that is applied onto the project and greenhouse design especially important with also these environments being made of carbon. The circular process of producing calcium carbonate and releasing carbon dioxide is one that is therefore, applied to the greenhouse design and innovation with the process being mimicked on a systematic level. In summary, the coral reefs allowed for the building of greenhouses to draw forth limestone, a calcium carbonate result from water desalination, a material needed for the construction industry and not coincidentally the same material within coral reefs structures.

Figure 16: Exterior of Seawater Greenhouse Project in Port Augusta, Australia
(Watson 2016)

3.5.2 Rainforests

The previously mentioned Seawater Greenhouse also utilizes inspiration from rainforests with the process of water vapor. Within the design of the greenhouse, the organisation leader Paton lays claim that water vapor is more effective and more flexible form of humidity in comparison to liquid water within agriculture. Furthermore, humid environments such as rainforests more efficiently use water through evaporation and precipitation processes within their ecosystem allowing for improved photosynthesis. Statistically, the project depicts those tomatoes within the replicated hot, arid climate can accept to 300L of water however utilizing a more humid environment and replicated processes of water vapor can drop this figure to 20-30L of water (Clancy 2017). Therefore, the Seawater Greenhouse design focuses on creating a humid environment rather than water generation with the vertical layered design being highlighted in *figure 17*.

Figure 17: Vertical Farms inspired by the layers of the Rainforest
(D'Ambrosi 2015)

3.5.3 Seashells

Delugan Meissl Associated Architects have demonstrated a design of botanical greenhouse gardens within the city of Taiyuan in China that take inspiration from seashells (Benkö). The design more specifically is a three timber-framed dome possessing lattice shell structure. The project itself was a means of researching into ecosystems under the infrastructure as seen in *figures 18 - 20*. The location includes three greenhouses that take shape of clam shells with the main factors that this shape preferable being energy design, lighting, water catchment for plants, thermal protection and regulation and wind/air flow or circulation. ("A Wide-open Entrance leads to a very welcoming Shell-Like Structure to create an Inquisitive Gravity of what happens in there?". Retrieved 26/05, 2022). The primary inspiration from nature is also extendable to the beams that hold the glass panes of the dome denoting the shape of seashells as they fan out generating the replicating topology of the dome. This application, therefore, differs itself from other designs as it allows for sunlight to be most effective through the opaque and ultra-transparent along the south and north facing surfaces, respectively. Furthermore, considerations that arise from this design include the utilization of thermal power stations operated with the biomass suppling the building with energy and temperature regulation of a warmer climate.

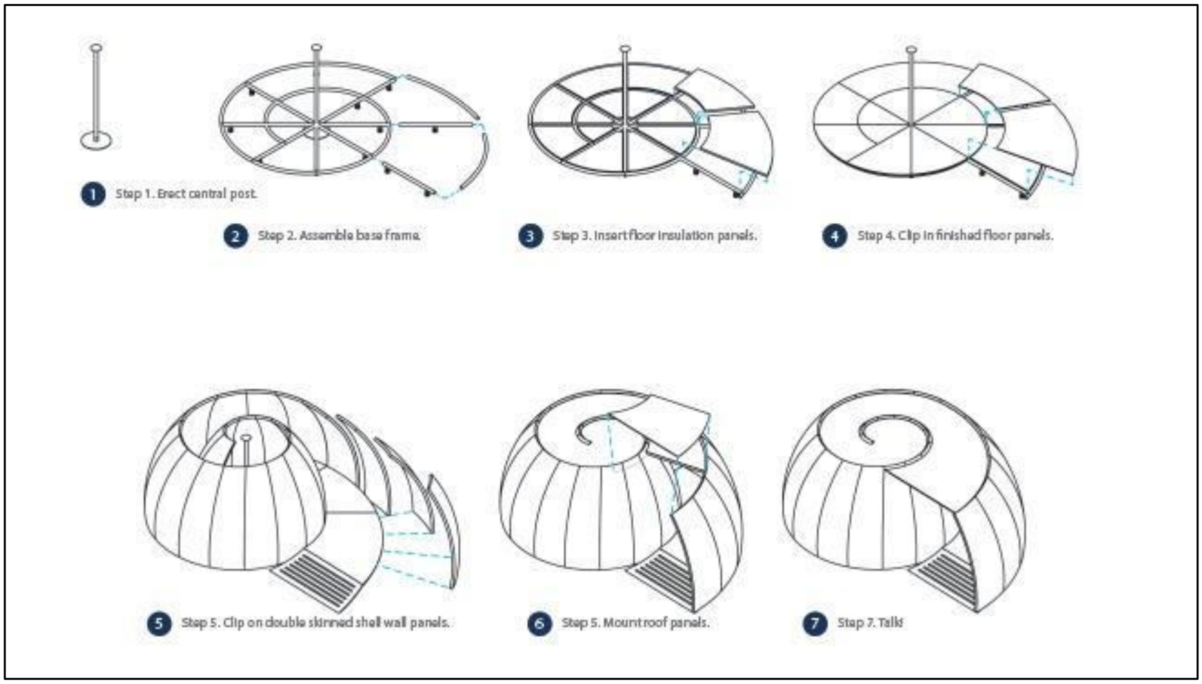


Figure 18: Shell-Like Think Space Design

("A Wide-open Entrance leads to a very welcoming Shell-Like Structure to create an Inquisitive Gravity of what happens in there?")

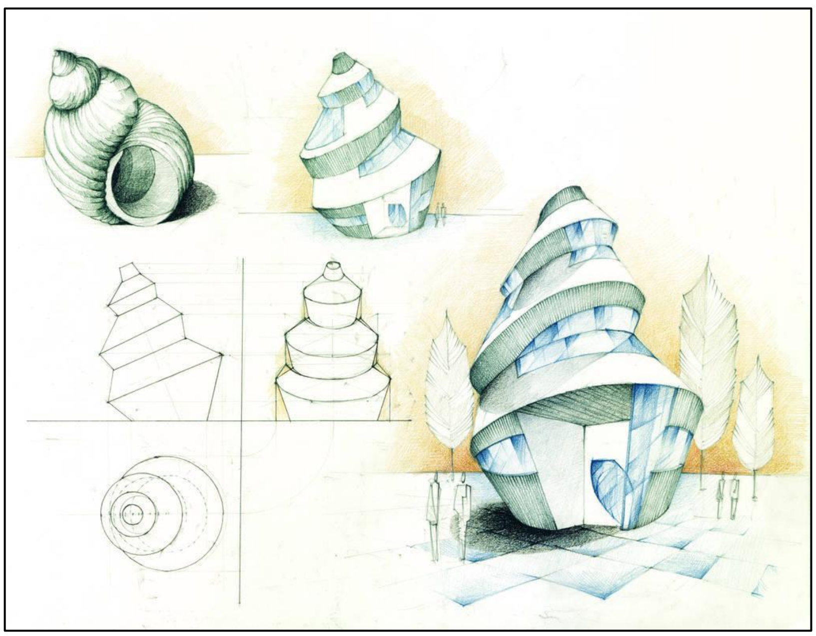


Figure 19: Artistic Render & Concept of Seashell House

(Radu 2013)

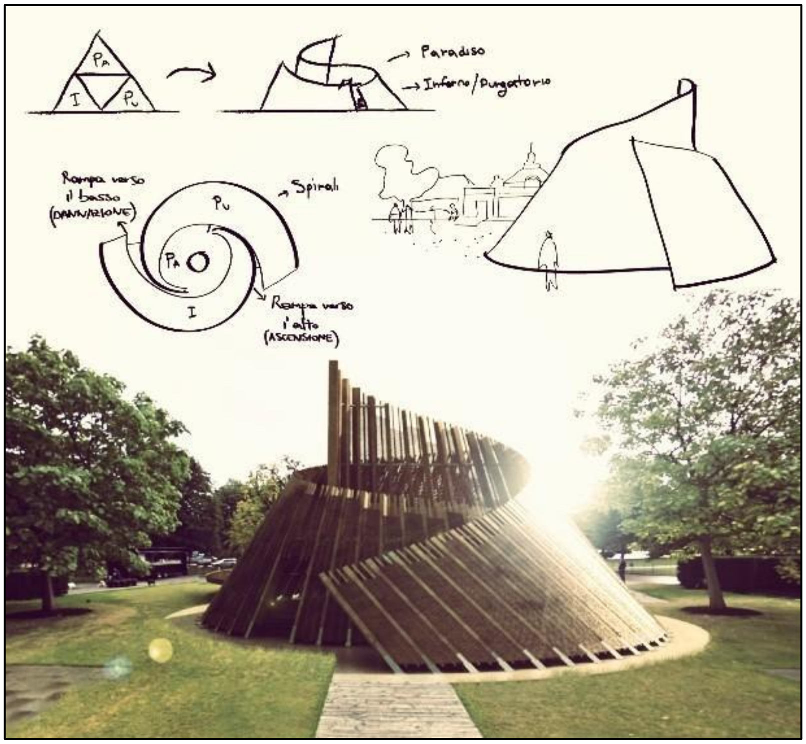


Figure 20: Shell-Like Design Inspiration

(Savvador 2014)

3.5.4 Honeycomb

As previously mentioned, the hive structure has been utilized by NexLoop in the AquaWeb endeavour (Dormehl 2017). On a slightly tangible however, incredibly significant aspect, biomimicry has been employed in the realm of greenhouses and energy for generations within solar cells and glass design. This hexagonal structure (see *figure 21* and *figure 22*) that is evident through the glass of greenhouses as well as solar cells take inspiration from the eyes of flies and honeycomb hive structures. The cells being so tightly packed together increases the durability when the cells contact heat, moisture, and mechanical stress. Correspondingly, this replicating photovoltaic material often utilized in solar cells are known as perovskite which is desirable with its low production cost and simplified production process. Finally, with the development and improvements in the material production process since its introduction to such industry application in 2009 (Gretchen Schimelpfenig 2022), there has been greater fracture resistance allowing for more efficient power conversion.

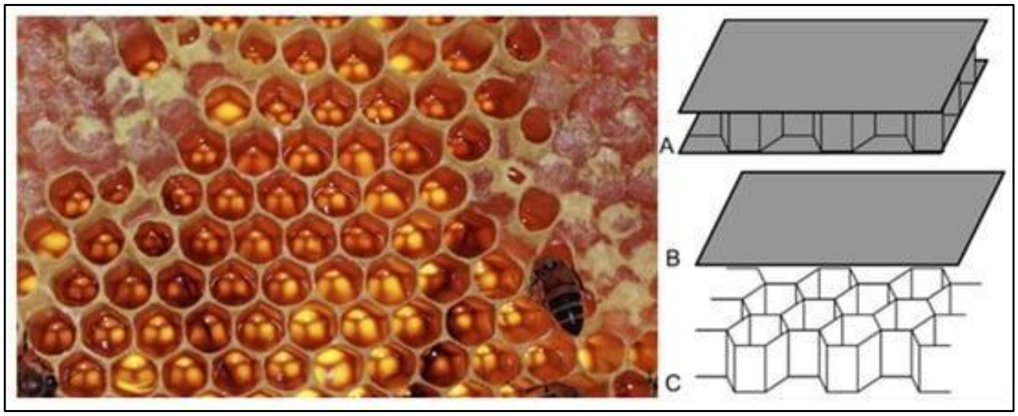


Figure 21: Honeycomb inspiring the Sandwich Structure of Greenhouse Glass

(Elmira Jameil 2021)

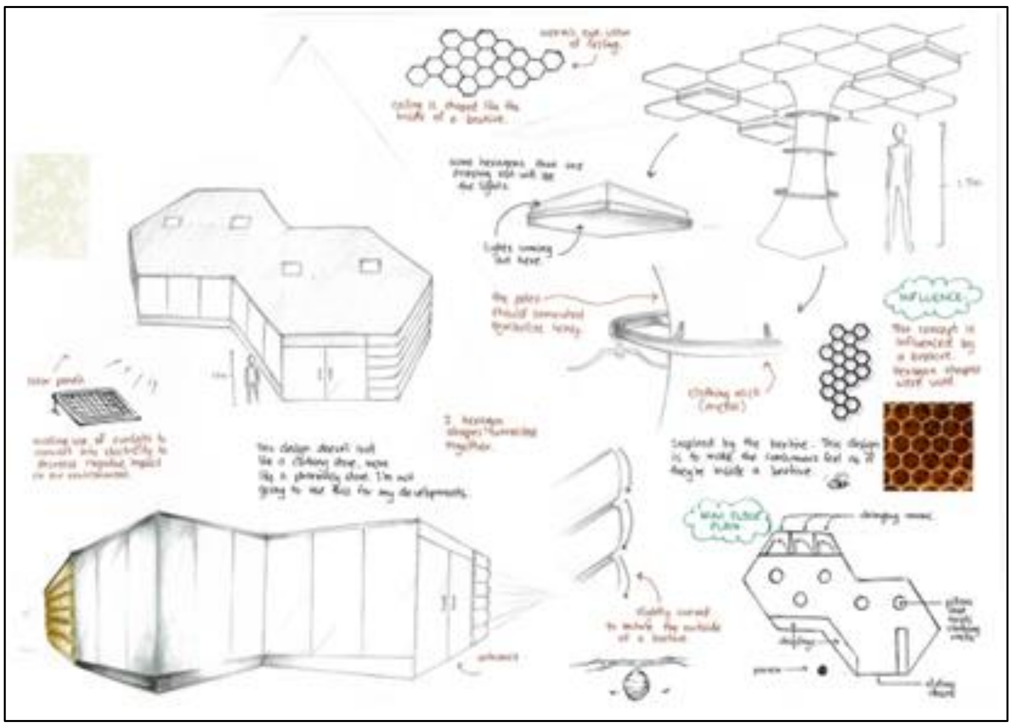


Figure 22: Organic Design of House Structure using Honeycomb Topology Inspiration

(Atlan 2014)

3.6 Geodesic Greenhouse Design

Within the production of geodesic domes and their applications for agriculture, majority that are designed through companies utilize prefabricated kits. Furthermore, these kits are also most appropriately applicable for residential use and demographics looking toward efficient and affordable gardening solutions in the most challenging of climates. The overall design is visualized below in *figure 23*.

Figure 23: Geodesic Greenhouse Design from Kleenex

(Tim Fryer 2020)

3.6.1 Pacific Domes Case Study

Pacific Domes is a company which concentrates on sustainable, eco-friendly living through the utilization of Geodesic Greenhouses (see *figure 24*) that generate an ideal biosphere for a local climate catering to the growing season and produce of healthy plants. The organisation demonstrates a multitude of differing applications for the dome and can be specially designed to each application. These applications include ["Pacific Domes." (2022)]:

- Aquaponics
- Algae Production
- Mycoculture
- Bee Havens
- Vermiculture
- Drying and Trim Rooms
- Organic Food and Herb Production

The domes themselves are specifically built to accommodate the specific applications therefore, consideration is made carefully toward their purpose. Furthermore, the domes built as prefabricated greenhouses or as geodesic grow dome kits for home gardening enthusiasts or for industrial level applications and growth.

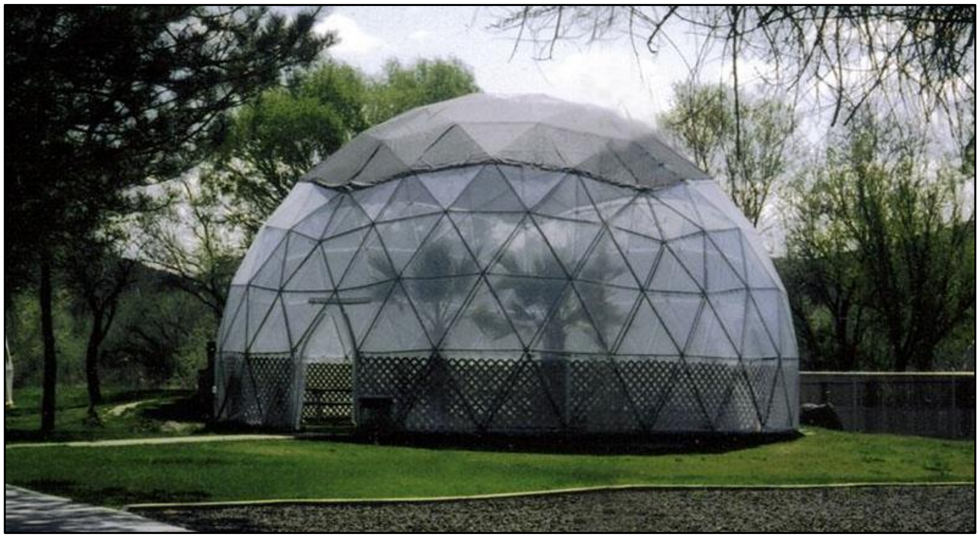


Figure 24: Pacific Domes Greenhouse Specific Geodesic Dome

[(2022). "Pacific Domes."]

3.7 Greenhouse Tower Design Case Study

Greenhouse design is also something that has been evolving to fit urban environments and city centres to lower pollution, assist with air quality and layout/city density regulation. The urban design of greenhouse have been evident in Sydney and Singapore to be innovated to fit the density of the already established environment in some areas due to space being previously occupied and repurposed or in some cases spaces being limited or in expandable. Therefore, these cities employ vertical or tower design to greenhouses with the capability to be multi-purposeful having parks, restaurants, and leisure within the structures fuelling business while balancing environmental sustainability.

This is evidenced within Lendlease's 56-storey tower within Sydney with evidence of the greenhouse supporting over one hundred businesses reducing Australia's climate emissions and increasing jobs opportunities (see *figure 25*). (Hansen 2021)

Figure 25: The Lower-Ground Floor of the Lendlease Tower below Greenhouse Layers

(Hansen 2021)

The tropical climate of Singapore allows for an interesting and exceptional climate for furthering and developing greenhouse or garden structures. The 'Gardens by The Bay' in downtown Singapore (see *figure 26*) is an example of this innovative implementation of greenhouses within urban environments in recent years. The botanical park houses almost five thousand species of plants and is a forest dome which reaches thirty-five metres high pushing the boundaries of conserving plants beyond the typical house structures.

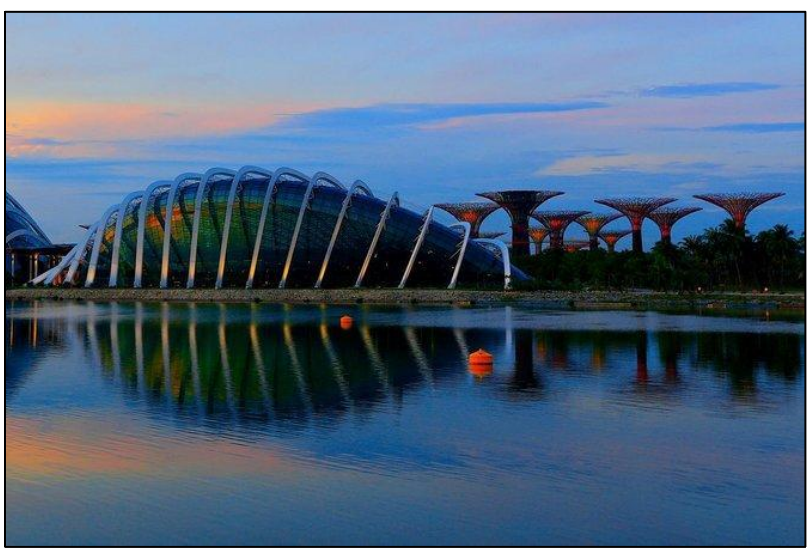


Figure 26: Gardens by the Bay Greenhouse

["Gardens by the Bay with 2 Flower Dome + River Cruise + Marina Bay Sands Skypark." (2020)]

Furthermore, the unique consideration of this greenhouse and employment in this environment is the temperature and humidity regulation with it being constantly kept at 23 and 25℃ (see *figure 27*). ["A Masterpiece of Gardens by The Bay" (2012)] The glass panels are specific for minimization of solar heat, dehumidifiers use liquid desiccant systems to reduce energy consumption and the results denote a possibility for energy-efficiency, all with the structure being derived from biomimicking design as a redefined geodesic/shell dome. Finally, the power generation is partially powered by the solar panels on tree trunk replicated towers. During the past decade it has been evidenced these solar tree towers generates up to eight percent of the electricity required for the system. (Huang 2012)

Figure 27: Solar Panel Tree Towers

["Gardens by the Bay with 2 Flower Dome + River Cruise + Marina Bay Sands Skypark." (2020)]

3.8 Community Farms & Landscape Repurposing Case Study

Greenhouses that fit within urban environment has been an innovative and ongoing development or concentration of investigation within the previous decade. An innovative example of this can be seen in regions that have required repurposing or regions where structures have needed to be demolished due to natural disasters and abandonment. The city of Detroit is an example of this with the dying automotive industry causing an urban decay in the environment, land farming and community farming is an aspect that has been popularized within the region (see *figure 28*). The primary reason for this rising in urban farming and the unique aspect within the environment of the city is the already overgrown ruins of the abandoned structures and streets. Furthermore, the demographic of more individualistic demographic of the community groups which fuel the farming in the region is one that is unique to the more industrialist endeavours. Therefore, targeting such a demographic can be beneficial in the revitalization of cities or areas that have been overlooked, ignored or in some ways forgotten. The non-profit community groups in Detroit such as Hantz Farms are backed by large funding, however, do not currently employ aspects of biomimicry, follow conventional established manners of farming in the overgrown region. (Harris 2010) In summation design with consideration of these dense urban environments can result in multiple positive impacts such as transformation landscapes, repurposing land, lowering farming costs and even increasing influence on community groups, the job market, and youths (Hester 2016).

Figure 28: Detroit Urban Farm Repurposing Neighborhood

(Gerard 2019)

3.9 Modelling & Scalability

Within this investigation, there are potential for two routes of prototyping:

- Creating a scale model that is in accurate de-scaled dimensions to allow for valid testing and behaviour experimentation when subjected to forces.
- Printing the greenhouse on a larger scale however, with multiple pieces.

The second option would be preferable even if on a smaller scale, but this would allow for the connections and multipiece to be subjected to forces and yield more accurate and expected results to a larger, backyard commercial greenhouse. The considerations of upscaling the model greenhouse would also include the lighting (quantity and layout) alternation, extensions to piping and watering system, power and/or energy requirements, sizing (surface area) with impact upon heat calculations and temperature regulation, costs, efficiency impact upon plant growth and material requirements.

More specifically, the thermal and moisture models, constants, heat transfer coefficients, radiation properties and factors based on literature will need to be adjusted. Scalability investigation, therefore, can be properly and accurately performed when referring to the fundamental aspects of the design. For example, testing with the heat transfer between singular PV panels oppose to the entire system or structure. When in the design process, the convention and intensity values in relation to the heat transfer process can be sought out and employed (same is applicable for radiation factors and surface properties for testing materials). In general, the heat transfer for typical construction materials and soil are scalable without any restrictions.

The scaling of humidity values requires Hargreaves equation for evapotranspiration of water from planters with correction factor (0.525) (Michael E. Evans 2022). This is determined by comparison with datasets in relation to measured humidity – see equation below.

$$ET_{plant} = 0.525 \times 0.0022 \cdot R_a \cdot TR^{0.5}(TC + 17.8)$$

3.10 Forces

3.10.1 Wind Speed

The primary force of concentration to the greenhouse both in a modelled lower scale and upscaled scenario is that of wind loading and wind speed. To assist with this in the methodology and modelling stage a wind map (see *figure 29*) can be utilized based on data from Nation Weather Bureau and Bureau of Meteorology. On average these datasets denote wind speed measurements thirty feet above ground level (see *figure 30*) and on open terrain based on a 50-year period (recurring). (Lysaght 2017)

The wind classification of domestic building sites according to the Australian Standard AS4055-2012 require four factors (see *appendix A* for more specifics on classification process):

- Region
- Terrain Category
- Shielding Factor

- Topography

3.10.2 Velocity Pressure

Therefore, the basic wind speeds from the south-western region (around Sydney) of the country is within ranges of 0.80 to 12.55 kilometres per hour at surface [Weather Spark, (2022)]. The basic wind speeds, therefore, within greenhouse structures require conversion to velocity pressure (per square foot – psf). This would be a variable value per square that accounts for wind speed reduction with relation to buildings under approximately thirty feet (correlating to the estimated wind speeds that are given from Australian weather datasets). On average, aside from extreme weather conditions such as hurricanes, the factor of importance is of 0.87 to 1 for wind pressure calculations. For a simplified example, 12-foot greenhouse structure in a suburban setting (non-hurricane prone area) with potential 145 kph wind speeds would result in a 14.4 psf approximately. ["Wind Loads on Greenhouses." (Resources 2018)]

$$P = I \times V^2, where\ P\ is\ wind\ pressure\ \left(\frac{pounds}{sq.ft}\right), V\ is\ speed\ (mph)$$

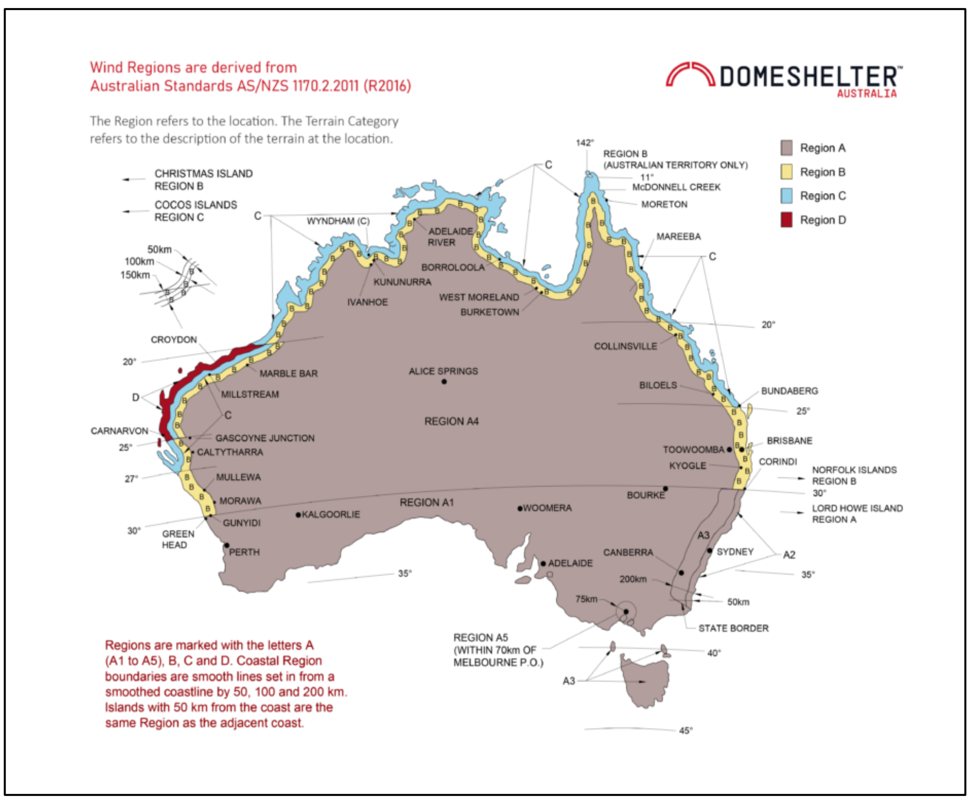


Figure 29: Region Categorization across Australia

["Wind Regions of Australia." (2022)]

Design Wind Speed Calculations

Design working life 25yrs/Max avg height of 10m

AUSTRALIAN WIND REGION	ULTIMATE REGIONAL WIND SPEED (km/h)	IMPORTANCE LEVEL	TERRAIN CATEGORY	DESIGN WIND SPEED (km/h)
Region A	162	1	2	148
		2	2	155
Region B	205	1	2	164
		2	2	178
Region C	248	1	2	202
		2	2	219
Region D	316	1	2	250
		2	2	273

Figure 30: Design Wind Speed Calculations - Australian Regions

["Wind Regions of Australia." (2022)]

3.10.3 Force Coefficients

The wind pressure may not occur on all surfaces of the greenhouse dependent on design shape and orientation. Therefore, for such cases force coefficients can be utilized to determine the effect of loading as wind hits surfaces at specific angels. (Jr. 2007) A structure can withstand various loading when shape and sizing of structural design is determined.

The structural members of the greenhouse design and glazing are calculated after design is created and determined through a combination of FEA as well as typical dataset figures on buildings. If there are openings, this will have an impact upon individual members and structural integrity as well as consequentially create impacts on wind flow and aerodynamic effects on the exterior and interior of the structure ["Wind Loads on Greenhouses."(Resources 2018)]. Therefore, this will affect the pressure calculations and have a resulting danger of the greenhouse being either uprooted or lifted. In summation the objects of the force analysis would be for longevity in utilization as well as effective strength against wind forces.

3.11 Energy Calculation & Usage Considerations

Energy consumption and requirements are often calculated by various methods but often the plants themselves can allow for a reasonable figure to the required energy of the system. Therefore, the plants within this investigation and the purpose of the greenhouse will determine the total energy required and therefore, play a role in the consumption. In general terms, most of the energy demands within greenhouses stem from a necessity to regulate heat and temperature – see *figure 31*.

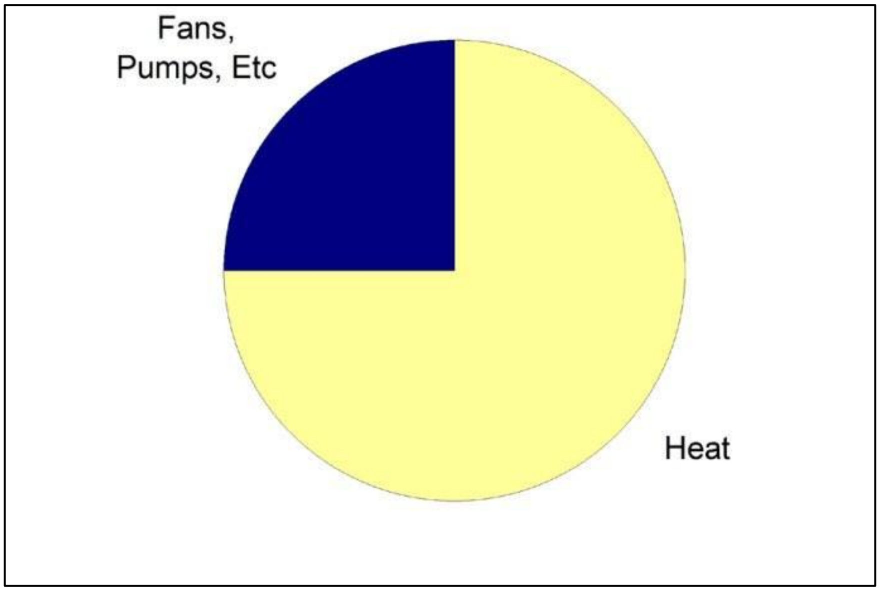


Figure 31: Typical Breakdown of Annual Energy Usage in North American Environment

["Things a Greenhouse Grower Can Do to Improve Energy Efficiency." (2016)]

From a biomimetics aspect, the energy consumption using a design that follows a biological structure will in most cases (as evidenced from the case studies and examples) reduce energy consumption as the design will optimize aspects such as temperature regulation and heating or the humidifying process.

Typically, the energy consumption of each singular plant is determined overtime using the following considerations:

- Use heating requirements of Cornell AES greenhouses over four years. [CUAES Greenhouses - Energy Consumption and Equivalents. CUAES Cornell Cals. (2014)]
- Use the average indoor temperature of location (typical for greenhouses is 70°F).
- Growth lighting energy provides a 14-hour photoperiod (all year round – typically off during high sunlight periods or for outdoor greenhouses). ("Energy Use and Savings in Greenhouses and Growth Chambers." Sustainable Greenhouses & Growth Chambers.)
    - Annual average lighting of 11 hours per day.
- The heat loss of a greenhouse can be determined using the following equation:

- $HL = A \times U\Delta T\ where, HL = Heat\ Loss\ \left(\frac{Btu}{hr}\right), A = Surface\ Area\ of\ Greenhouse\ (sq.ft), U = Heat\ Transfer\ Coefficient\ \left(\frac{Btu}{hr} - sq.ft - °\mathrm{F} = 1.25\ to\ 0.6\right), T = Temperature\ (°\mathrm{F}).$ (Jr. 2015)
- Note: Heat Transfer Coefficient alters based on glass material and finish.

- Horizontal Air Flow (HAF) calculation allow for the total circulation fan capacity to be calculated.
- Australian building standards and energy consumption estimate that deviation from of just one degree between indoors and outdoors can increase energy usage by 10 to 20%. (Tim Grant 2010)
- A typical larger outdoor scale greenhouse consumes anywhere from 1 to 2 kilowatt hours of electricity per square foot of floor area per year $\left(\frac{kWh}{sq}ft - yr\right)$. (Jr. 2017)
- Once energy requirements of plants, temperature control and circulation is calculated, the humidifier system can be considered if electrically implemented and watering to calculate the total cost.
  - A typical portable humidifier consumes around 30 to 50 watts dependent on generation of mist (size) and type. (Stec 2021)

In summation, the primary aspects that will determine the energy consumption and place a major impact or influence on the resulting quantitative figure is both the heat control and plant specifications and amount. ["Things a Greenhouse Grower Can Do to Improve Energy Efficiency." (2016)]

3.11.1 Reducing Energy Consumption

There are a variety of manners in which energy consumption of a typical greenhouse can be lowered. This includes firstly the employment of circular design through the process of biomimetics of the structure's exterior. Overall, the fauna requires a near full range to sunlight to assist in decreasing external temperature control dependence and therefore, reduce energy consumption.

Furthermore, the utilization of biomimicry within the humidifying process assisted or driven by a typical humidifier system can improve the efficiency of heating in an enclosed environment and provide a warmer temperature through the drying of the air. ["How Humidifiers Save Energy in the Winter." (2013)]

Moreover, the energy consumption of a typical humidifier can be reduced by employing a timer system and automatic humidistat for set duration consequently allowing for greater controllability over the performance of the system. Lighting in a greenhouse can also be experimented with as typical and older generation greenhouses would utilize bulbs. Reflectors can be placed upon LEDs to concentrate light and replace the higher power usage methodology of older greenhouses. Using carefully placed lighting concurrent with reflectors can also reduce the number of fixtures reducing cost and energy. Experimentation and investigations would be required with standards of optimal lighting as performance will differ based on plant, area, concentration or size of greenhouse, colours of lights and intensity. [Rutgers University (2020)]

Thermal screens can influence minimizing heat loss in winter and providing insulation reducing heating costs by a margin as high as 30 to 40%. Correspondingly, insulating the perimeter of the greenhouse can also allow for margins of 5% energy consumption reduction as energy losses are lowered. Similarly, if sun rise and set is accounted for in the design process of circulation and insulation, further energy can be saved, and the efficiency of the greenhouse can be improved. ["Things a Greenhouse Grower Can Do to Improve Energy Efficiency." (2016)]

Therefore, with all factors considered there are multiple ways that current energy saving methods can be improved by turning to some of the biomimetic process or ideas that have been employed in the world of agriculture. The biological structures and processes of tropical areas can allow for energy being saved upon the humidifying and lighting aspects of the greenhouse however, equipment would have to be considered and balance must hence be checked regarding cost of the final design.

3.12 Safety Considerations

A majority of greenhouse commercial growers voice that safety considerations include:

- De-clutter
    - Setout access for personnel/users on a larger scale – prevent water slips, trips and allow for access/walkway.
- Weather Watch

    - Must adhere to the environmental conditions specifically with consideration to extremity of temperatures, humidity, wind, and various weather conditions of the environment selected for the investigation and modelling.
- Proactive Practice
    - Safety considerations of the perpetual performance or utilization of the greenhouse.
    - Safety precautions when managing the mechanical or electrical components of the design. ["Greenhouse Safety Checklist for Commercial Growers." (2018)]
- Equipment Safety
    - Compartmentalization of the greenhouse with zoning and sections for equipment (humidifier, temperature control, etc.)
- Fire Hazard
    - On an upscaled greenhouse the fire resistance and zoning must also consider spread of flames and heat.
    - Consideration of heat transfer through glass or similar transparent material.
    - In a case of fire, material must be considered for toxic fumes because of heat or melting.
        - Acrylic greenhouse is highly flammable and release toxic fumes that are hazardous when inhaled.
        - Polycarbonate firebreak can be a subsequent solution. ["Greenhouse Safety Checklist for Commercial Growers." (2018)]
    - Non-combustible materials be utilized and consideration of glazing.
- Electrical Hazards
    - Electrical panels, switches, controls, heating, piping, generators be considered as part of the zoning and be separated from cloth, shades, or glazed/flammable material. ["Greenhouse Safety Checklist for Commercial Growers." (2018)]

3.12.1 Risk Assessment for 3D Printing Process

Table 2: Risk Assessment

Risk Identification		Risk Controls	Risk Rating
1	Burns from contact with heated plate or material.	- Activate controls in enclosed area. - Hot hazards are labelled with warning stickers/text or print. - Allow objects to cool before handling. - Appropriate training taken prior to operation.	Medium
2	Entanglement with mechanical moving parts.	- Mechanical components are to be in an enclosed area. - Warning signs on moving mechanical components. - Keep goods, wires, products and/or other equipment clear of walkways and paths. - Ensure distance from the installed printer.	Low
3	Electric shock from contact with powered and exposed electrical components.	- Printer to be in an enclosed area when operational. - Check wires and connections state and wear prior to operation. - Repairs and modifications to be conducted by correctly qualified and trained personnel. - Labelled electrical characteristics. - Ensure power points are safely operational and of appropriate safe status.	Low

4	Burns from fires.	- No flammable material in the printer or near heated areas of printer. - Regular maintenance and servicing of equipment.	Low
5	Sensitivity to exposed plastic fumes.	- Print in a well-ventilated area. - Use fans or ventilation system in laboratory. - Use only recommended material in the printing process.	Low
6	Injury from moving support structure.	- Use PPE to prevent injury on hands or eyes (glasses, close-toe shoes, and gloves).	Low

4.0 Methodology

4.1 Design Requirements

The overall minimum requirement of this project needs to cater to the growth and containment of plants alongside the structure to be mimicking natural occurring structures. Furthermore, the primary requirement, with the implementation of biomimicry in this project, would be that the design effectively and positively requires to influence an aspect or aspects of the already established greenhouse or agricultural structure design. The replicated biological structure(s) furthermore, do not need to be implemented in just one aspect of the design (such as only the structural exterior of the greenhouse) but can also be implemented in others such as temperature regulation, air flow, planters, containment, etc. The necessary requirements of this investigation can be summarized in the following list:

- Resistant to wind and reaction forces
- Mimicking natural occurring structure(s)
- Model structure that is scalable
- Designed to fit hobbyist/consumer standard
- Fit into an Urban Environment
    - Location wise the Design will be based upon a manufacturing and utilization in Australian/Oceanic Region.
- Effectively hold and allow floral or crop growth
- Low environmental footprint (long term and short term)
    - Both in production and perpetuated utilization

4.2 Investigation Structure

The investigation structure are as follows simplified to a set of steps. An overview of the steps and concentrations in this investigation includes:

- Selecting an optimal greenhouse design and parameters prior to modelling.
- Justification of selection through reference to research and literature review.
- Modelling the typical geodesic dome structure utilizing 3D CAD software.
- Modelling the biological structurally inspired greenhouse design utilizing 3D CAD software.

- Scale both models to physical measurements and parameters to perform and gather realistic FEA and simulation results.
- Scale both models to 3D printable measurements and parameters to perform physical force testing.
- Convert wind loadings to FEA parameters to allow for the collection of deformation and stress results upon structure.
- Print both models using 3D printer and ABS material – additional filled and non-filled models.
- Add environmental and base surface for wind simulation.
- Design and 3D print (or model via alternative methods) an additional point load model to allow for physical testing via hand tools – replicate a force (wind and gravitational) from a single direction onto the greenhouse.

4.3 Optimisation Factors

The factors that will influence the research design are selected based on factors that most impact the commercial and private utilization of greenhouses within the farming markets. Through research of the international greenhouse enthusiast level communities the most significant factors that influence the decisions behind the design of greenhouses are as follows:

- Cost
- Natural Lighting Permeability
- Volume
- Strength
- Energy Requirements
- Heat Regulation

These optimisation factors have been concluded to be the most significant when reviewing literature surrounding differing greenhouse types and structures (Kacira 2013).

4.4 Greenhouse Shape Investigation

Through reviewing of different readily available and established greenhouse structural designs, a conclusion on the most optimal basis structure can be made allowing for commencing the investigation of applying biological inspired structural elements. Some of the conventional greenhouse types include:

Table 3: Greenhouse Structures Comparison - Pros & Cons (Government 2016)

Greenhouse Structure	Advantages	Disadvantages
Quonset	Cost Effective Light Exposure	Restricted Volume
Geodesic Dome	Cost Effective Strong Energy-Efficient Light Exposure	Restricted Volume
Ridge & Furrow	Volume Energy-Efficient	Restricted Light Exposure – Casting Shadows
Dutch Venlo	Cost Effective Energy-Efficient Light Exposure Heat Regulation	Restricted Strength
Even Span	Volume Light Exposure	External Heating Required
Barrel Vault	Volume Cost Effective	Risk of Disease Spread
Shade House	Light Exposure Cost Effective	Restricted Strength
Sawtooth	Strong Heat Regulation	Restricted Volume

With reference to the below trade off chart displayed in *figure 33* that has been generated in conjunction to design research and literature review, the ideal shape that balances the selected factors is geodesic domes. Furthermore, the primary emphasis on FEA within this investigation allows the structural design and shape of geodesic domes to have a greater realm of optimization opportunities with relation to the factor of strength, material/cost and light permeability. Establishing the overall structure being a dome formation, the biomimetic influence can be set as an objective that optimizes the aforementioned factors through lattice design. Experimenting with biologically inspired lattice structures is an initial approach which will allow for redefinition of the exterior of the geodesic dome. Furthermore, testing with lattice structures will focus and initiate potential in results offering high stiffness and strength, surface area optimization for natural light permeability, elongation/deformation, and energy absorption.

With reference to geodesic domes, the structural design often can vary in design with biodomes conventionally having a range of sizes and alternative rounded hemispherical shapes based on applications and conditions of construction. Some of the most conventional market available and constructed geodesic dome shapes are illustrated in *figure 32,* with which research has been conducted to determine the most suitable for both farming or greenhouse utilisation as well as the climate and conditions of the Australian environment. The following denotes a summary of the research and selection criteria based on these common shapes of geodesic domes:

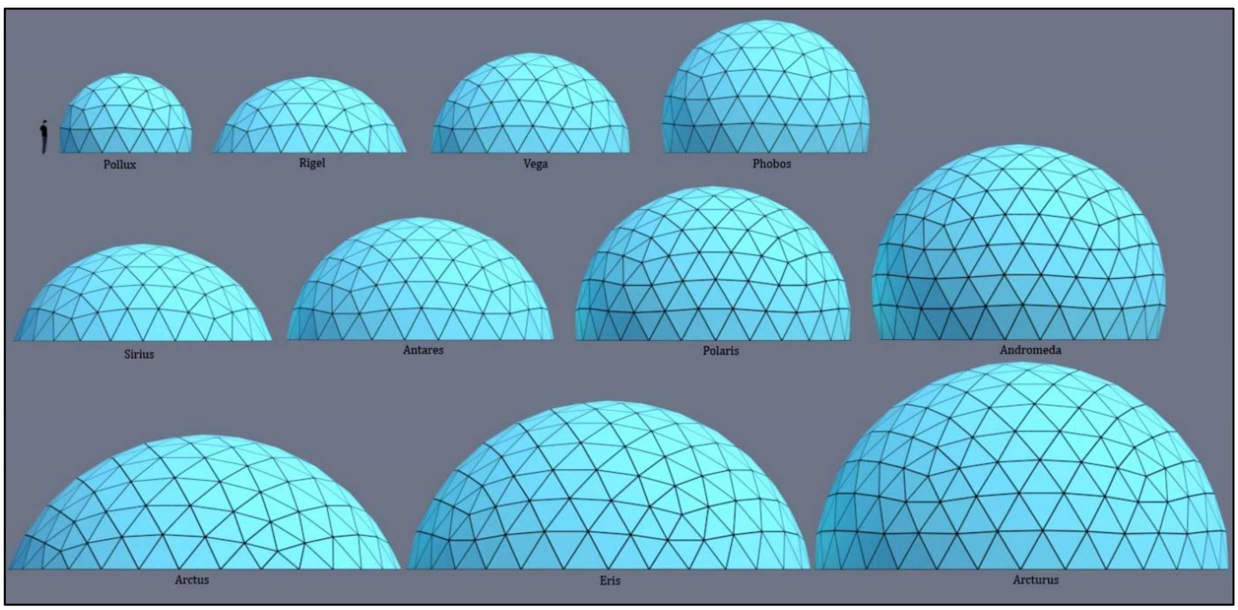


Figure 32: Biodome Types

[(2016) Biodomes]

Based on the design requirements of this investigation revolving around hobbyist and private use of the greenhouse the volume would be required to be maximized, with vertical height allowing for greater freedom regarding the internal crop design. Furthermore, the base surface area is required to be within a magnitude of 6 to 10 metres for typical backyard residential utilization hence, broadening the applicability for consumers. Therefore, the Vega architecture or design allows for the satisfaction of such factors.

Trade Off Table

Greenhouse Structural Design & Shape

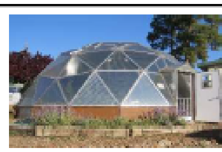
Shape	Image	Cost	Light	Volume	Strength	Energy	Heat
Barrel Vault		Low	Moderate	High	Moderate	Moderate	Moderate
Dutch Venlo		High	High	Moderate	Low	High	High
Even Span		Moderate	High	High	Moderate	Moderate	Low
Geodesic Dome		Low	High	Low	High	High	Moderate
Quonset		High	High	Low	Moderate	Moderate	Moderate
Ridge & Furrow		Low	Low	High	Moderate	High	Moderate
Sawtooth		Moderate	Moderate	Low	High	Moderate	High
Shade House		Low	High	Moderate	Low	Moderate	Moderate

Figure 33: Trade Off Table - Different Greenhouse Designs

Since the geodesic dome denotes the greatest advantages in terms of the factors evaluated against, this has been the selected greenhouse structure type to be further developed in this investigation. Reasoning for this is since the dome design is already posing various advantages, it would justify utilising it as a basis structure that can be further improved through a biomimetic approach. Finally, the dome structure depicts greater structural optimisation opportunities in contrast with a variety or majority of the other structure types. Therefore, there can be a multitude of approaches and factors that can be altered to address its resistance to wind and gravitational loadings.

4.5 Biomimetic Approach

The biomimetic aspect of this design investigation links to heading *'4.10 Wind Forces'* whereby the selected biological structure inspiration is aimed to influence the exterior design of the dome model. The dimple design inspired from honeycomb structures is justified under this section which in summary allows for a strengthened and a more wind resistant structural design. Exterior design is chosen as the biomimetically optimised aspect of the dome due to its expected influence upon the wind loading. Comparative to other loadings typical upon greenhouse structures, the wind loadings have the greatest potential and consequential differing design approaches that can address or influence their behaviour. The exterior design is aimed to redefine the typical triangular pattern by implementing a new lattice structure based on a biological structure that influences or optimises the wind loadings. The biological structure that has been selected for implementation on the exterior surface of the dome is a honeycomb dimpled lattice design aiming to reduce the wind loading.

4.6 Dimensions & Scaling

The initial CAD design is going to take formation of the physical real-world model. In addition to section *4.2 Greenhouse Shape Investigation*, the geodesic dome Vega architecture allows efficient air circulation, temperature regulation and allows for a quoted two-four times more energy efficiency than a traditional alternative greenhouse design (Verlaunte Hawkins 2018) (refer to *figure 33*, for some examples of the alternative structures). With a more vertical edge to the ground within the Vega design, this allows for greater effective light refraction forcing the incident light to remain inside the dome especially to the lower heights closer to the soil. Moreover, the Vega, Phobos and similar more defined hemisphere shapes allow for greater strength against ground forces.

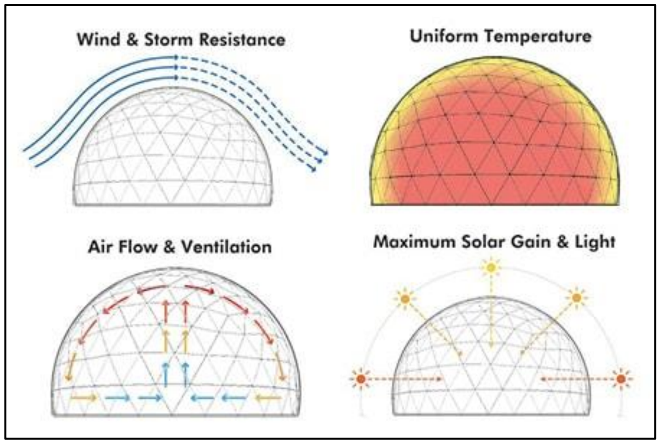


Figure 34: Advantages of Geodesic Dome - Vega Architecture

(Verlaunte Hawkins 2018)

The dimensioning and initial designs have been sourced through measurements published by Biodomes organisation excelling in the scaling of different architectural designs of geodesic dome structures (see *figure 35*). These measurements where initially utilized as the basis and drafted design however altered with the implementation of the lattice or biomimetic exterior design.

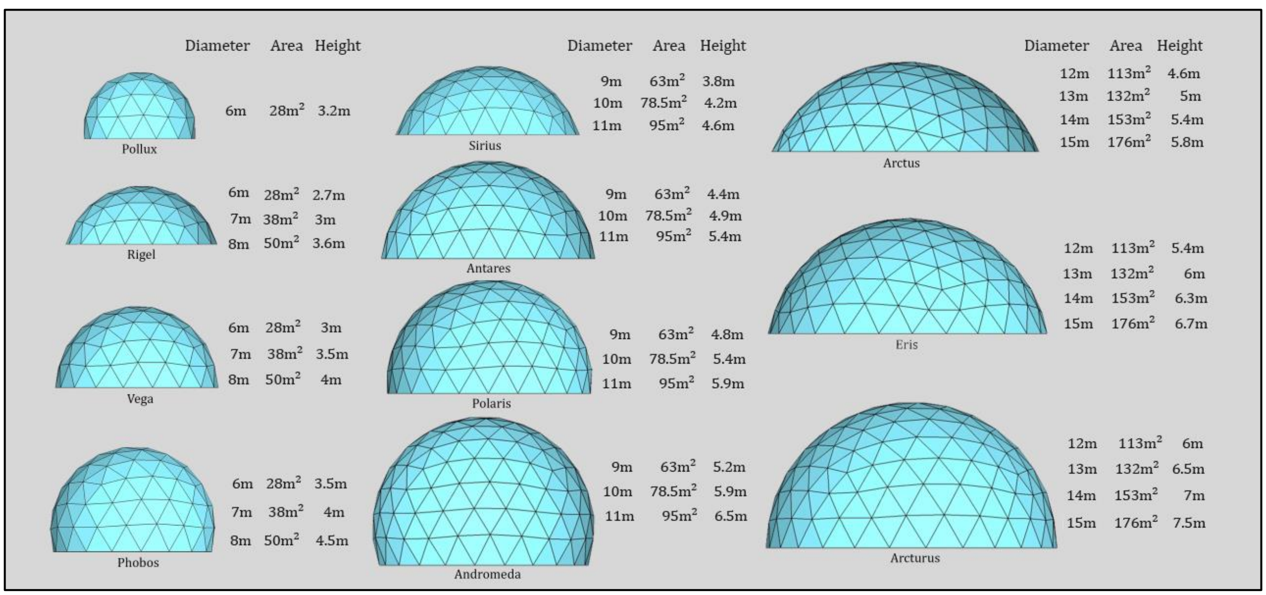


Figure 35: Dimensioning based on Structural Design & Base Surface Area

[(2016) Biodomes]

4.7 Model Generation

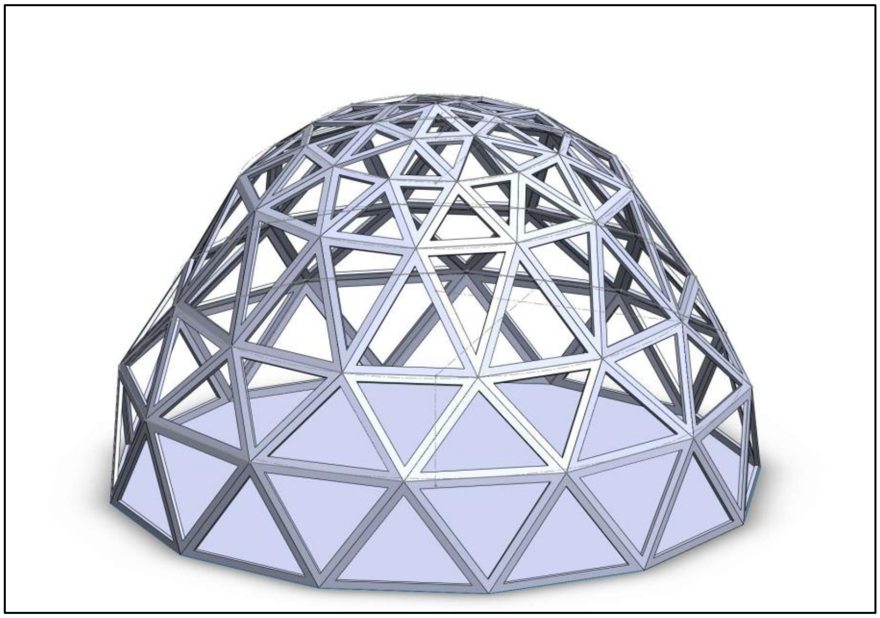


Figure 36: Design Iteration 1 - Typical Geodesic Dome

The model generation of the CAD model involved design and creation of a typical geodesic dome design. This initial design replicated formation of Pollux as illustrated within *figure 35*. The first iteration can be seen below in *figure 36*, with the primary issues being an elongated vertical section and hollowed truss structure within the design of the dome that add complexities to the printing process. Therefore, the following iteration requires additional modifications to measurements and dimensioning, infill within the truss structure and appropriate thickness to the base alongside each lattice edge.

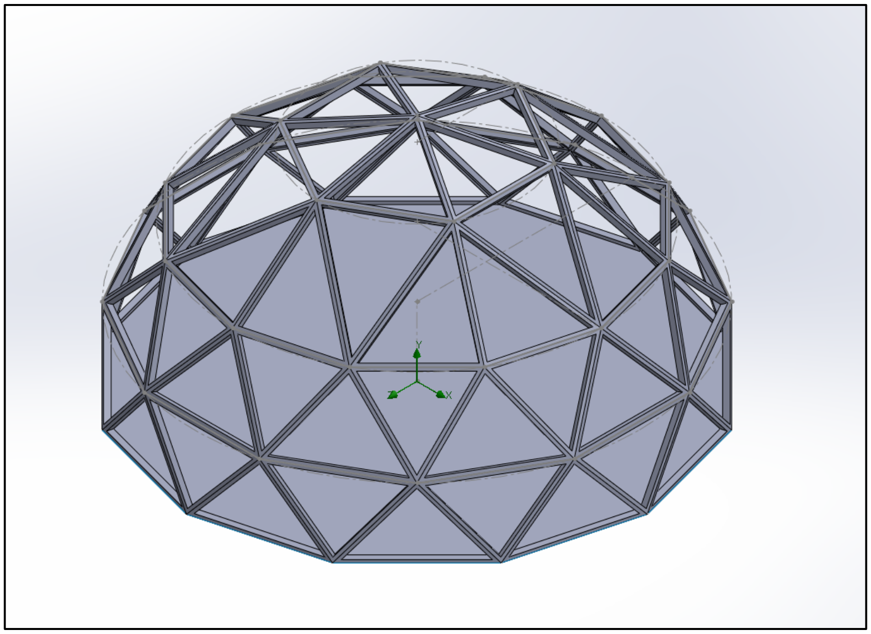


Figure 37: Design Iteration 2 – Typical Geodesic Dome

Following the editing of the issues addressed mentioned above, the second iteration of the typical geodesic focused on the manipulation of the structural orientation and shape (see *figure 37* for the renewed design). Ideally, the information gathered from sources such as Biodomes, Pacific Domes and Domerama were evaluated through this iteration whereby the dimensions of each truss was altered. Furthermore, within Solidworks 2019 CAD software, each triangular shape was generated upon a singular side and reflected or mirrored throughout a circular pattern. Utilizing the already established and researched dimensions allowed for the replication pattern allowed each to be perfectly fitting within the model. The primary issues that have been discovered within this design iteration is that 3D printing once again is not feasible due to the support needed per truss or the increased size overall to support the printing of each truss. Therefore, printing the supports would have an impact on each truss possibly deforming during the 3D printing process due to heat and lack of supporting structures. Adding supporting structures would require a multitude of them and therefore, inflate cost, time, and accuracy of the print. Due to the requirement of smoothing each truss and the lack of material in between each truss, not replicating the translucent material in a real greenhouse structure has been decided for future design iterations. Therefore, generated 3D models following this would be simplified by not accurately modelling the glass, perplex or plastic since this investigation focuses on utilizing 3D printing materials. Furthermore, modelling and adding a perplex or plastic material between each truss structure would have an impact on the FEA results and stray from the aim of investing the usability of 3D printing materials.

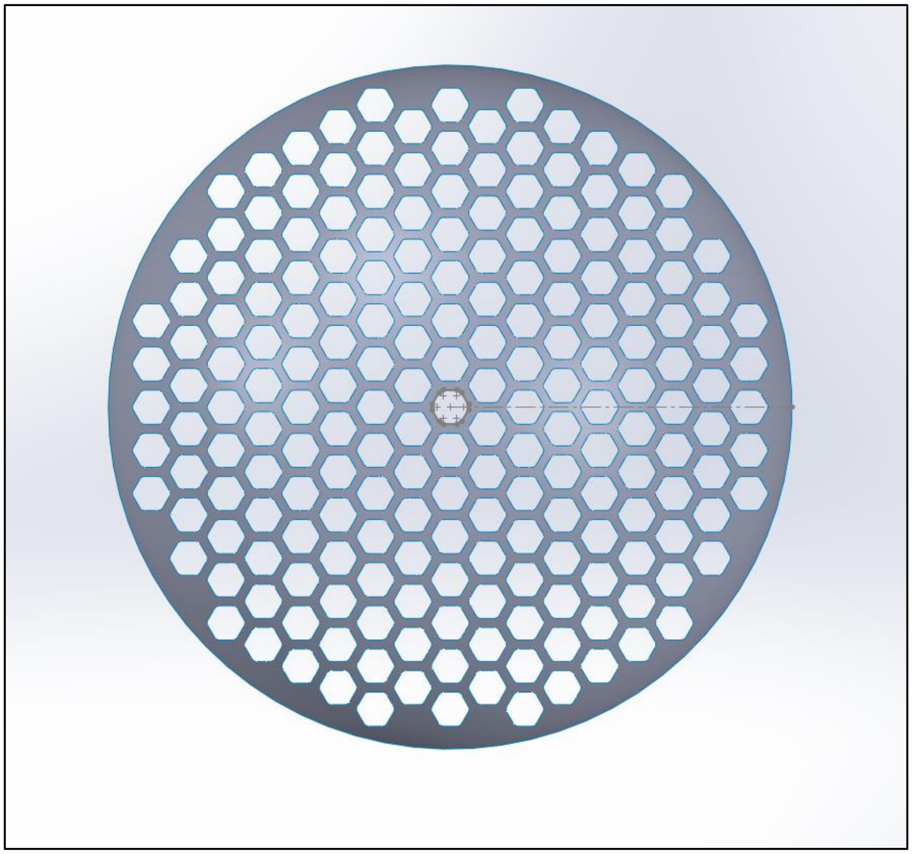


Figure 38: Design Iteration 3 - Honeycomb Lattice

Following the issues that have been addressed from the above design iteration one, the following design iteration two illustrated in *figure 38* was a general implementation of the honeycomb lattice within a spherical surface. The hexagonal lattice surface pattern has been developed utilizing a similar replication technique as previously mentioned of circular repetition. With this technique explored, the next iteration was planned to have layered hexagonal lattice patterns to replicate the honeycomb structure evident within bee's nests. Furthermore, this next iteration would have a solid exterior to partially replicate the solid and filled structure of a physical greenhouse. The design iteration three illustrated in *figure 38* employs a honeycomb lattice within the geodesic dome exterior design that has been selected as a solution to influence the air impacting the structure. The surface of the dome will come in direct contact with the air and cause the air to be directed or slip into the rear side or opposing section. This allows the dome to ideally form around the air incoming and successive flow generates a barrier that adds stability to the dome structure. Therefore, utilizing this lattice formation will allow for the results to denote a more resistant and strengthened outcome to wind effects. This design was accomplished through configuring circular pattern options with the CAD software however, consideration is required into the spacing to allow for practical 3D printing with minimal errors.

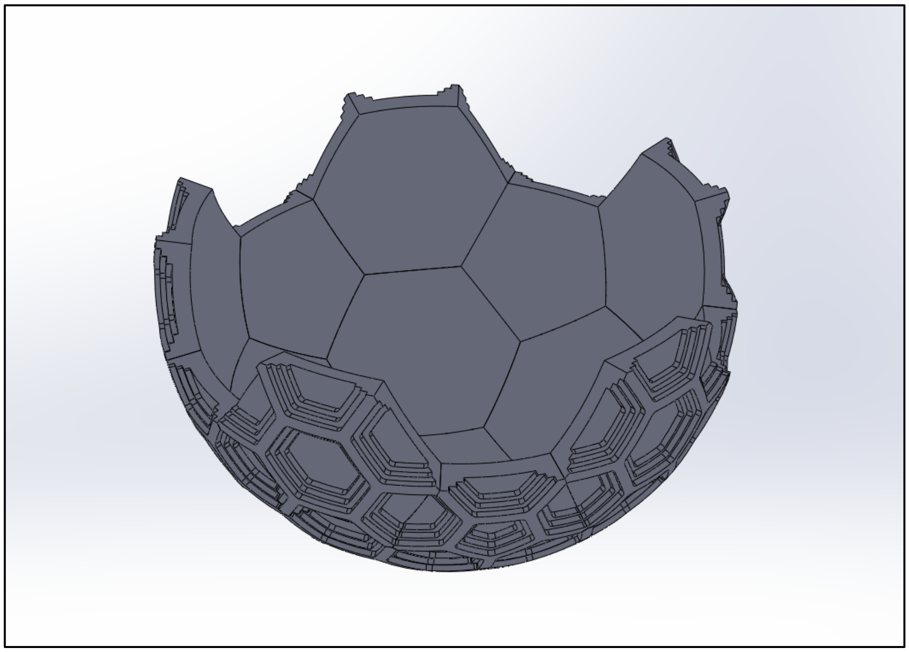


Figure 39: Design Iteration 4 - Honeycomb Lattice

The final design iteration in *figure 39* utilizes the previous hexagonal lattice design which was offset over the exterior of the dome resembling the structure of a beehive as the reduced gaps in the circular lattice allows for greater strength. Furthermore, with inspiration from real beehives, the hexagonal lattice is established to hold the most weight with the least amount of material. Furthermore, the gradual concavity of the pores or hexagons allows for wind resistance and protection by breaking direct impact with wind forces.

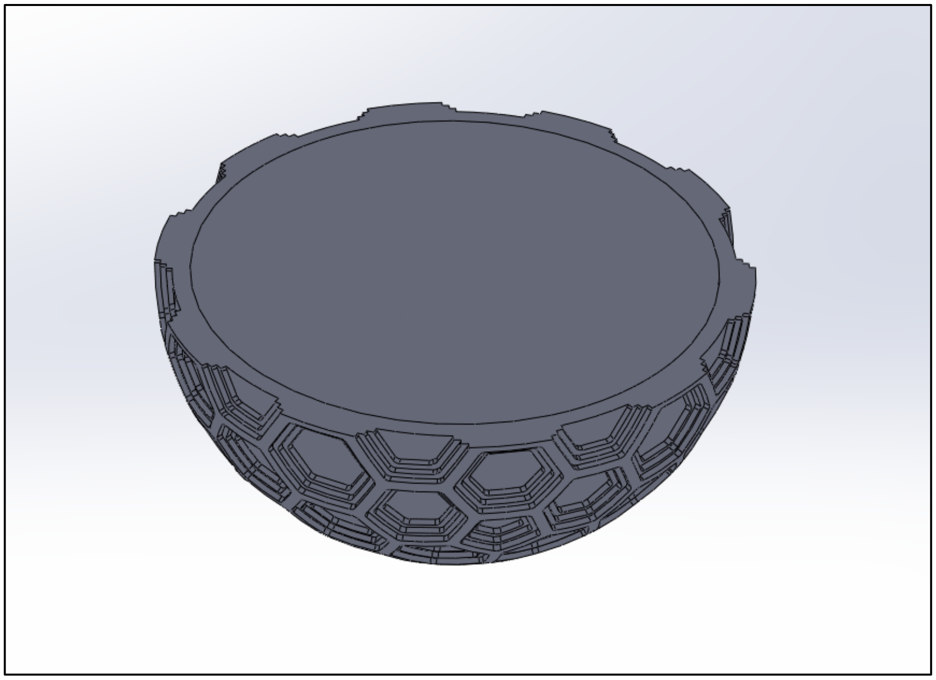


Figure 40: Design Iteration 5 - Honeycomb Lattice (Filled)

The infill of the model in *figure 40* is initially implemented within the 3D model plan as a method to address the flow simulation illustrating or operating under conditions that infiltrate the lower section of the dome and therefore, generate a vortex within the interior of the model. The filling of the model with material, however, was concluded to not be a viable solution regarding the issue as this would increase weight, mass and structure upon the model influencing results to be ideally inaccurate. Hence, the model would not be accurate to the physical geodesic greenhouse. To address this issue there has been proposed two solutions being a creation of a physical ground to the model or defining within the flow simulation software the computational area of model, ideally restricting the impact zone of the wind upon the structure.

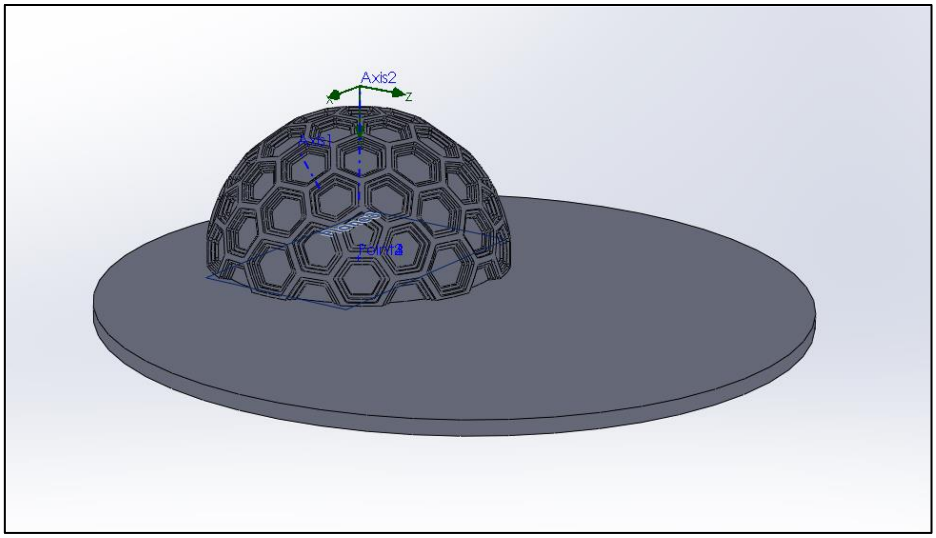


Figure 41: Design Iteration 6 - Ground Surface

Design iteration six within *figure 41* therefore, employed the solution of simulating a ground surface to potentially accommodate wind bouncing or reflecting effects replicating the real-life behavior of wind. In doing so however, the structure designed as a base or ground would then denote deformation when imported into the FEA software analysis tools. Furthermore, definition of the material of the ground structure within the CAD software would be both inaccurate as realistic ground would ideally be soil and grass surfaces, concrete, synthetic grass, etc. Therefore, these vast surfaces are difficult to determine the characteristics of to perform flow simulation. Moreover, defining multiple materials can cause inaccuracies in performance and results gathered through the FEA process due to flow simulation computation requiring a larger range of factors to satisfy. The deformation would also occur on the ground surface affecting the investigation's ability to address the original goals being to concentrate on FEA upon the greenhouse rather than surrounding environment.

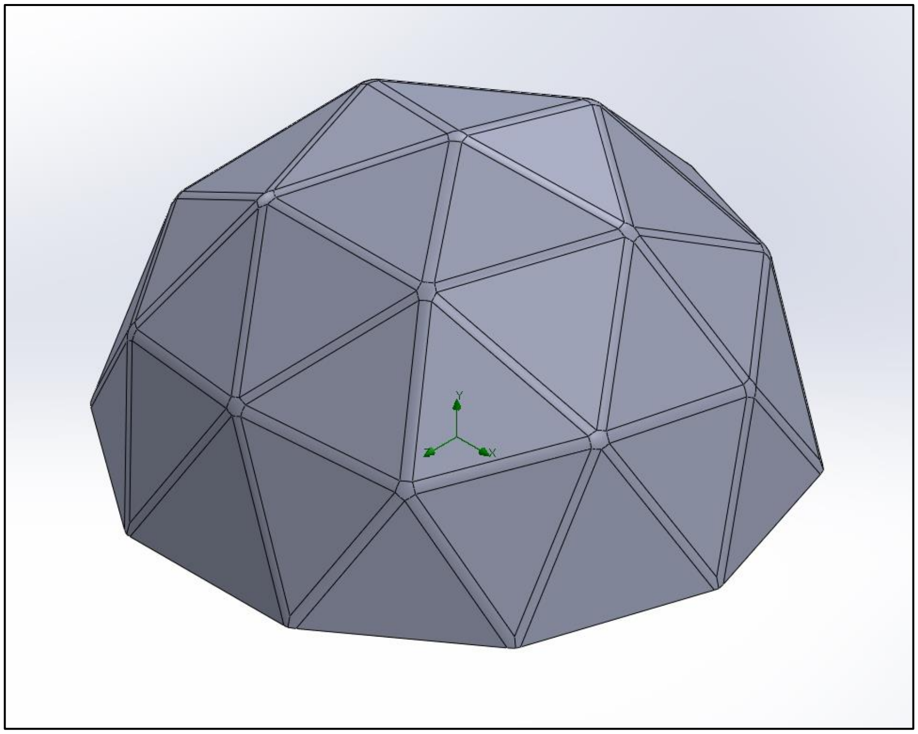


Figure 42: Design Iteration 7 - Typical Geodesic Dome

The design iteration in *figure 42* was the final typical geodesic dome model that was utilized for the purpose of comparisons in results between this and the honeycomb biomimetic design (design iteration eight). This design involved addressing issues around the frame widths and simulated connections within the model which was addressed by using edge rounding replicating the pipes that would hold together a typical geodesic dome. The dome design replicates the previously mentioned Pollux orientation or structure with dimensioning based initially off the information and measurements in *figure 35*.

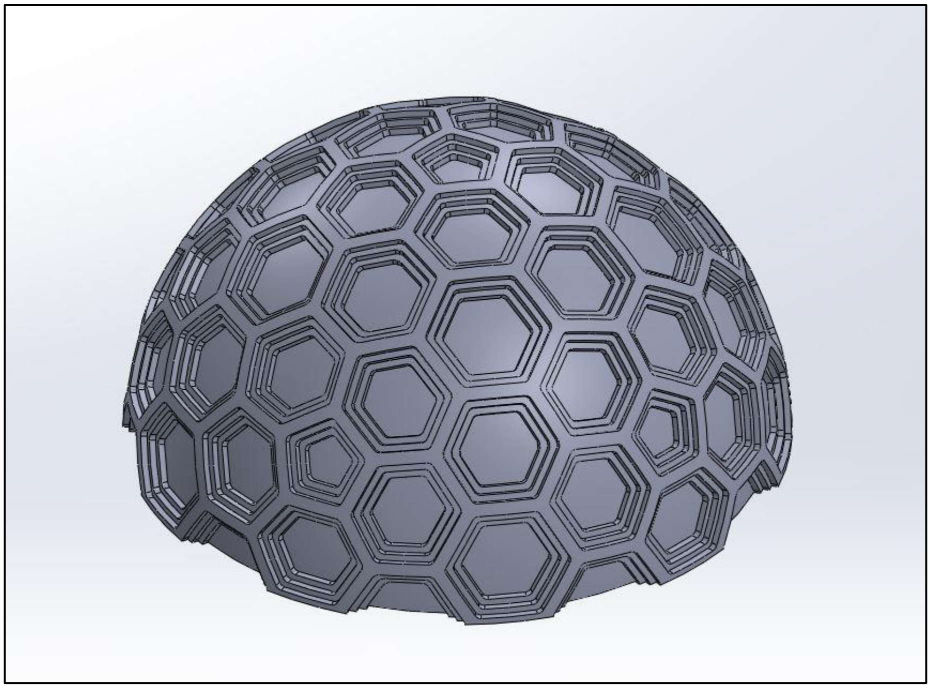


Figure 43: Design Iteration 8 - Biomimetic Honeycomb Geodesic Dome Design

The final design iteration for the biomimetically inspired geodesic greenhouse dome has addressed most of the previously mentioned issues that had arisen and the *figure 43* above illustrates the resulting structure. Notable changes are a thickness of the overall walls and a removeable of the floor to replicate more accurately the greenhouse structure as would be implemented within typical backyard utilization.

4.8 FEA Process

The FEA process utilising Solidworks 2019 software involved firstly defining the material properties of the dome model. The library had not included PLA material therefore, definition of this material would require manual data entry. Contrastingly, ABS material is defined and can be used for future investigations. The PLA material definition was selected for this investigation as it corresponds to the material that the scale model was 3D printed with. Following the definition of the material, the next step involved defining the computational parameters of the flow simulation. This involved the definition of the direction and axis of flow being simulated alongside the units and velocity. Once defined (in this case a $-12.55km/h$ flow along the x-axis) the substance was defined as air with some predefined parameters that correspond to conditions of an average $25℃$ environment with air flow under the previously mentioned velocity ["Wind Regions of Australia." (2022)]. Following this the flow simulation was configured to external analysis translating to the results or flow being concentrated upon the exterior of the model and therefore, it is assumed that wind will not penetrate the model. This allows for the system to be assumed as fully enclosed.

Following setting these parameters of the flow simulation some further configurations had been made to the computational area to omit the ground effects, the axis and direction of the flow was further configured to a definite three-dimensional starting vector and goals, or objectives of collated data readings set in place of the software. The objectives will allow for the software to automatically save and track the parameters set out while the flow simulation runs for the defined iterations or time scale.

Within the flow simulation, a variety of different goals can be tracked. For this investigation, conclusions and results have been gathered through a combination of tracking the following parameter goals seen on *figure 44*. The individual results and tracked parameters over the investigative iterations can be exported and displayed in a variety of manners from graphs, exported raw data files for FEA importing and other software, tabloid form and visualisations. The most comprehensible visualisation of the results have been concluded to be cut plots and flow trajectories which allow for an easy differentiation of areas of separate designs that impact the results being analysed.

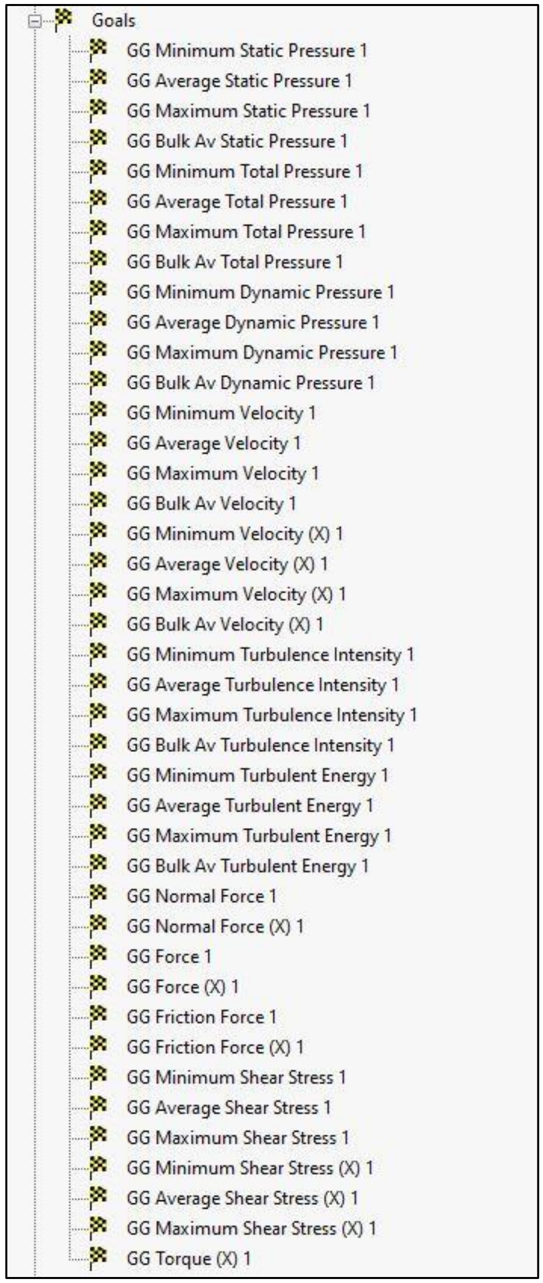


Figure 44: Goals Tracked

4.8.1 Mesh Generation & Loading Conditions

The mesh generation process has been automatically evaluated utilizing Solidworks 2019 Flow Simulation plug-in whereby the software evaluates the most appropriate mesh structure based on the concavity and curvature of the structure as well as the general dimensions. The mesh generation factors can be witnessed in *appendix E* alongside the loading conditions which have been defined through the software. The flow simulation plug-in has defined properties of air which is included in *appendix E*. The loadings are then automatically saved and loaded into the FEA software within Solidworks 2019 as a distributed loading.

4.9 3D Printing Process

The 3D printing process involved exporting the CAD model as a stereolithography (STL) file that is imported into the 3D printing software that was supplied/available with the printer. The 3D printer utilised was of model, 'FlashForge Adventurer 3' with PLA filament employed for the printing process. The printing software scales down the original model size automatically to fixed ratios that fit the hardware – different settings of scaling is accomplished through percentages (70% scale down). Within this investigation the specifications of sizing are: $x = 140.00mm, y = 138.30mm, z = 69.54mm$ & $x = 98.00mm, y = 96.81mm, z = 48.68mm$. The print parameters for the are upon the final model:

- Shell Count: 2
- Infill: 15% (Fill Density)
- Fill Pattern: Hexagonal
- Overlap Perimeter: 15%
- Top Solid Layers: 4
- Bottom Gap: 3
- Support Type: Linear
- Layer Height: 0.40mm (Bottom), 0.40mm (Middle) & 0.25mm (Top)
- Raft Enabled
- Bridge Enabled
- Estimated Print Time: 8 Hours 9 Minutes
- Estimated Material 88.35g/29.59m.

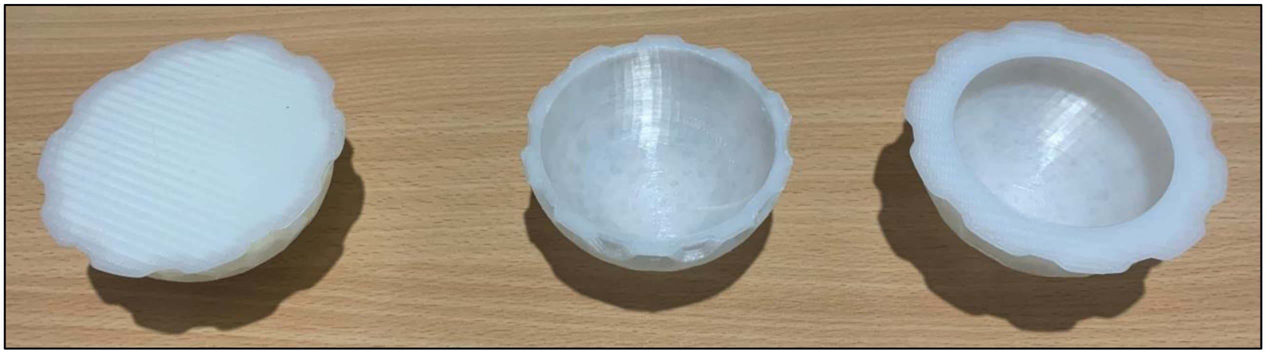


Figure 45: 3D Printed Models Interior

The *figure 45* above denotes the most accurate prints encompassing differing fill parameters or processes. The model within *figure 48* illustrates the print process without a raft and therefore, required tooling inclusive of sanding and cutting to remove the uneven surface distortions. More specifically, the unevenness was evident very slightly through the top interior section, however, is limited to surface roughness. The base or edging that neatened reflecting, in final form, quite accurately the 3D model within the CAD software. The secondary model that was printed as displayed in *figure 46* denoted a fully filled model which was initially planned as a method to replicate a passable physical model for display or close lattice inspection. The exterior print quality and accuracy was however, of same acceptable magnitude in comparison with the previous. Furthermore, print time was increased to approximately 12 hours in comparison to the hollowed model(s) and hence, no benefit was concluded from the fully filled model. The third model iteration that was printed as displayed in *figure 47* was printed with the previously mentioned parameters listed and had shown very minimal inaccuracies or surface distortions requiring little to no cleaning, cutting, or sanding.

Filled with Raft	**Hollow with Raft**	**Hollow without Raft**
 *Figure 46: 3D Printed Model 1*	 *Figure 47: 3D Printed Model 2*	 *Figure 48: 3D Printed Model 3*

4.10 Wind Forces

The force of wind requires to be calculated from the initial average wind conditions at surface of typical locations of greenhouse construction or placement. Given the average wind speed in NSW at surface level is approximately $12.55 km/h$ ["Wind Regions of Australia." (2022)], the average density of air can be utilized to in conjunction with force calculations to determine a definitive value for force analysis upon the modelled greenhouse. If the density of a mass of air is approximately $1.229 kg/m^3$ the following formula can be utilized to calculate in newtons (Bank 2018):

$$F = A_m \rho a^2 = (1)(1.229)(3.49)^2 = 14.97 N/m^2$$

With the wind impacting the surface of the geodesic dome, the hypothesis of the honeycomb design is aimed to reduce not only the impacting contacting forces with the wind, however, also reduce the generation of a vortex on the opposite side of impact. This vortex effect is depicted in *figure 49*. This is accomplished as mentioned under heading '*4.5 Biomimetic Approach*' whereby the dimples upon the honeycomb lattice reduce contact loading and generate a more aerodynamic structure that deflects wind and therefore, generates less drag and creates a smaller vortex.

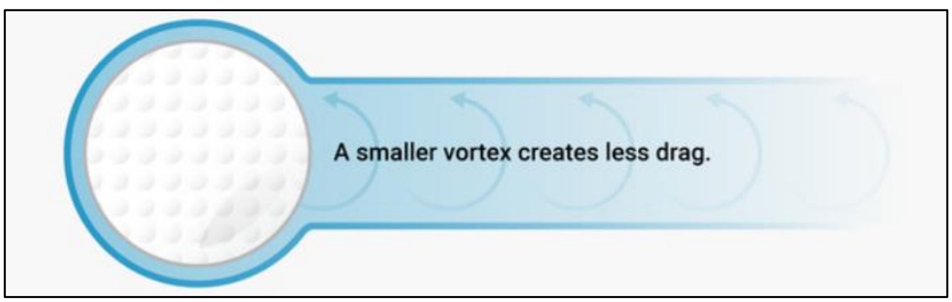


Figure 49: Vortex Effect from Wind Contact

(Karnani 2019)

4.11 Control Variables

<u>Control Variables</u>

The control variables within the investigation can be summarised from the list below:

- The base diameter dimension of the models being six meters.
- The wind simulation neglecting the ground effects.
- The direction of wind is from one side/direction.

- The wind velocity is uniform and constant.

4.12 Wind Pressure

The result that is being most key to investigate within the collected analysis of flow simulation and FEA has been deduced to be pressure, velocity, and strain. The result of pressure allows a method to calculate or quantify wind loading. This has been deduced with the concentration of the investigation being on horizontally directed winds causing intense pressure since wind effects are dependent upon the size and shape of the structure. The estimated average wind pressure loadings are researched to be in the magnitude of $100kPa$ (Haby 2018).

4.13 Physical Testing Process

The physical testing has been accomplished using a 'Starr: Digital Force Gauge' whereby forces have been scaled down using pressure calculations as follows in *table 4* whereby the calculations have been derived through scaling down the real physical model to the approximated 3D model printed which was in a 1:60 ratio reduction. The digital force gauge metre and utilised models alongside the attachments is denoted in *appendix B*. The calculations denote the simplification and alterations to the pressure loading calculations for both bending and buckling behaviours. Using these equations with reference to the force results that will be gathered will allow a benchmark for testing the physical force threshold on the printed dome model shown in *figure 48*. The appendix item *appendix C* denotes the derivation of these equations.

Table 4: Equations for Scaling Loadings

Loading Condition	Buckling	Bending
Stress at Failure (Simplified)	$\frac{h}{L^2} \times \frac{\pi^2 E}{12}$	$\frac{L}{bh^2} \times \frac{3}{2} \times P$
Factors Affected by Dimensional Scaling	$\frac{h}{L^2}$	$\frac{L}{bh^2}$
Reduction to Scale 1:8	$\frac{\frac{h}{60}}{\left(\frac{L}{60}\right)^2} = 60\frac{h}{L^2}$	$\frac{\frac{L}{60}}{\frac{L}{60}\left(\frac{L}{60}\right)^2} = 60^2\frac{L}{bL^2}$

(Mech 2021)

The mould has been created using modelling clay due to limitations upon the timescale of this investigation. Using modelling clay also is a cost effective and simply mouldable material that can bend to cover the curvature of the printed model. The moulding allows for sectional truss like structures to be extended from the dome to make a contact point for the force metre to create a distributed loading mould. This structure that attaches to the digital force metre is illustrated in *appendix B*.

5.0 Results & Analysis

5.1 Process of Gathering Results

The mass was determined through the CAD software where the material definition and parameters generates an estimated mass for the structure. The volume is also gathered through a similar method with the software generating an estimate of the volume of the structure regarding the capability of plants or flora that can be housed in the greenhouse dome. The maximum force value is a quantitative value that is tracked through the flow simulation analysis that outputs the maximum force that the dome experiences upon any area. This is a significant value in quantifying the wind force impact upon the two designs. The cost estimations have been firstly estimated through the material specifications given within the CAD software and therefore, the outputted USD quantitative value is generated automatically accounting for the milling, material, and machining processes. The second cost value is estimated through market research using a similar base dimension and materials that the models are structured around. Finally, the production time has been sourced similarly in conjunction with the cost estimations through the CAD software. This period is inaccurate as it omits the process of assembly and installation, simply only the machining processes to generate the model structure or parts.

The physical results using the digital force gauge has been collected by recording a set of three different results with the force metre in two orientations. The first is illustrated in *appendix B* under *figure 66* where the force metre attachment makes direct vertical contact on the dome. The second is illustrated in the same appendix figure where the force metre is attached to the clay moulded distributed load skeleton.

5.2 Typical Geodesic Greenhouse Dome

The typical geodesic dome had denoted the following results with relevancy to the originally laid out objectives to be evaluated. In summation the factors of significance are denoted below:

Table 5: Typical Geodesic Greenhouse Dome Results

Variable	Result	Units
Mass	4250.99	kg
Volume	57.44	m^3

Peak Wind Loading	70.70	N
Cost Estimate - Material	3630	USD
Cost - Market Value	3000-5000	
Estimated Production Time	430	$Hours$

5.3 Biomimetic Geodesic Greenhouse Dome

The biomimetic geodesic dome had denoted the following results regarding the original set out objectives to be evaluated. In summation the significant factors tracked are denoted below:

Table 6: Biomimetic Geodesic Greenhouse Dome Results

Variable	Result	Units
Mass	128.53	kg
Volume	38.54	m^3
Peak Wind Loading	95.02	N
Cost Estimate - Material	804.70	USD
Cost - Market Value	1000-3000	
Estimated Production Time	363	$Hours$

5.4 Analysis of Results

The analysis of the results denoted quantitatively the following conclusions regarding the initial optimisation factors that were set within this investigation. Between the biomimetic and typical geodesic dome designs they denote respectively a:

1. Cost Difference: $2000 USD
2. Mass Reduction: 96.98%
3. Volume Reduction: 67.10%
4. Pressure Surface Area Spread: Increased by Factor of 2.
5. Force Resistance Increased: 25.43%

5.4.1 Typical Geodesic Greenhouse Dome Results

The typical geodesic dome model was placed under flow simulation with the control variables previously mentioned and denoted a low pressure result however, displays capability for optimisation through the biomimetic greenhouse design. The results collected through the visualisation in *figure 50* illustrates valid results due to researched average and expected pascals in the magnitude of $100kPa$ because of average wind conditions.

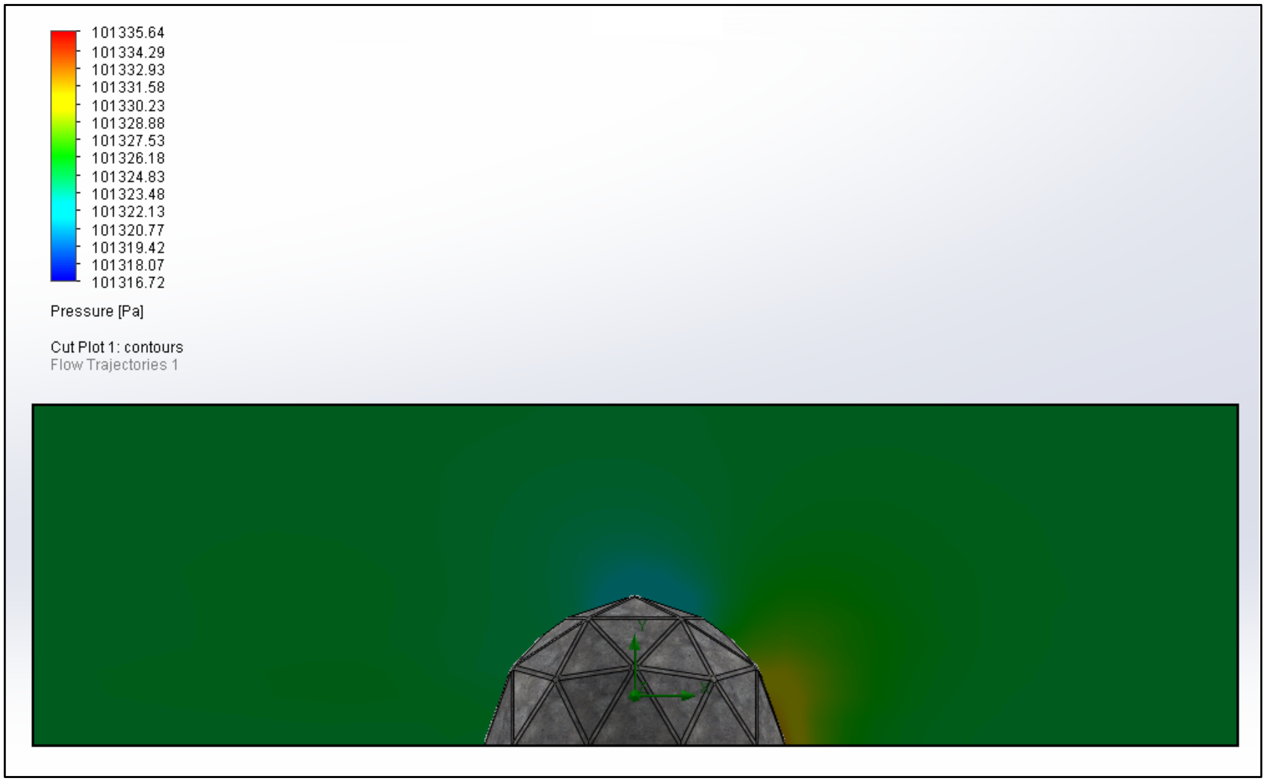


Figure 50: Typical Geodesic Greenhouse Dome - Pressure Result

The biomimetic approach, therefore, shall be aimed upon the results of flow simulation to portray a more distributed loading of pressure as well as a lower value in the results and visualisation. The exported pressure value of average $101325.26Pa$ with peak and minimum values being close. The surface area over which the pressure is applied is approximately $57.86m^2$ in terms of the area of contact and dispersion of air flow. The peak force results denote this dome design to have yielded a result of $95.02N$ of force generated with respect to the direction of the wind flow. The biomimetic design, therefore, can be aimed to reduce the pressure loadings at the peak or top of the dome along with the impacting or side curved regions contacting incoming wind.

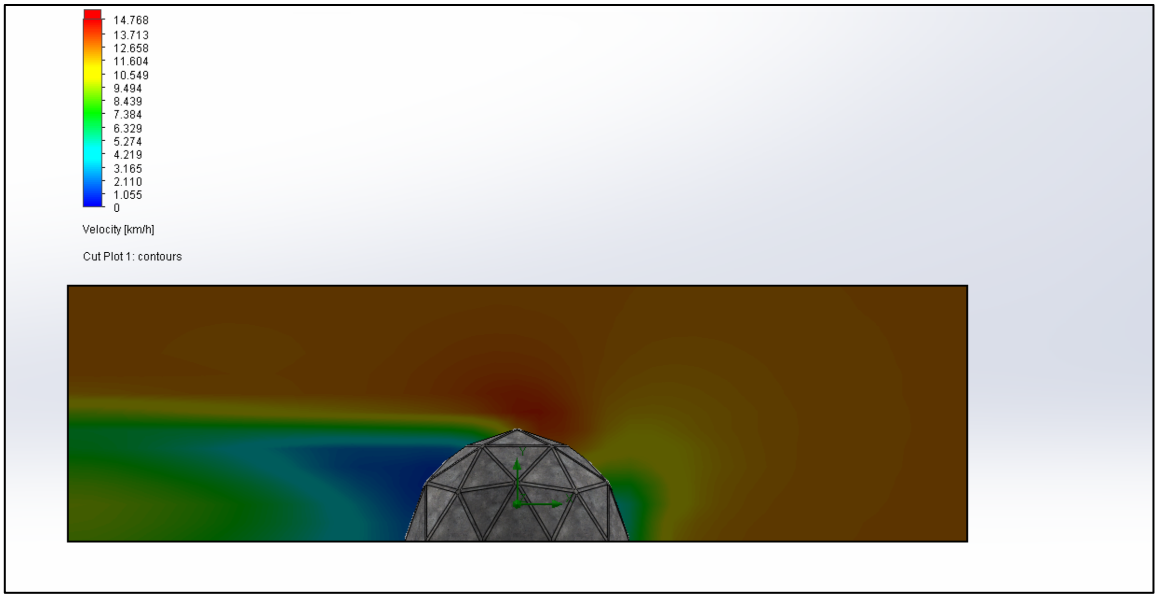


Figure 51: Typical Geodesic Greenhouse Dome - Velocity Result

The wind velocity peak can be utilised as an alternative method to calculate wind loading. Therefore, through tracking the wind velocity in the corresponding direction to the flow, the wind pressure can be determined alongside visually analysing the areas of the dome that result in greater wind contact. Firstly, through the visualisation of the results in *figure 51* denotes that the velocity peak is orientated or contacting the upper section with a deflection upward. Due to the triangular exterior shape of the surfaces, there is a generation of a circular vortex upon the impact face. Therefore, the biomimetic design would require an optimisation of the exterior surface to reduce all the drag regions denoted as blue and green within the above *figure 51*. This would allow for the wind loading or impact of the wind upon the structure to not be as greatly impeded hence, reducing frictional forces that would have the potential to shift the dome as the velocity magnitude increases in cases such as storms or high winds.

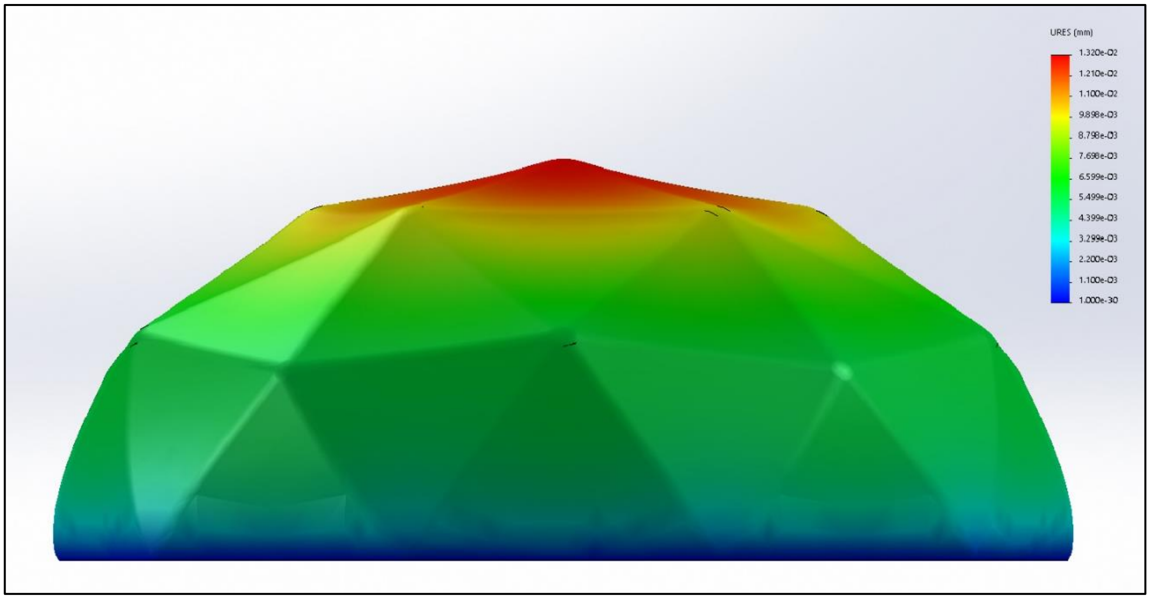


Figure 52: Typical Geodesic Greenhouse Dome - Deformation Results

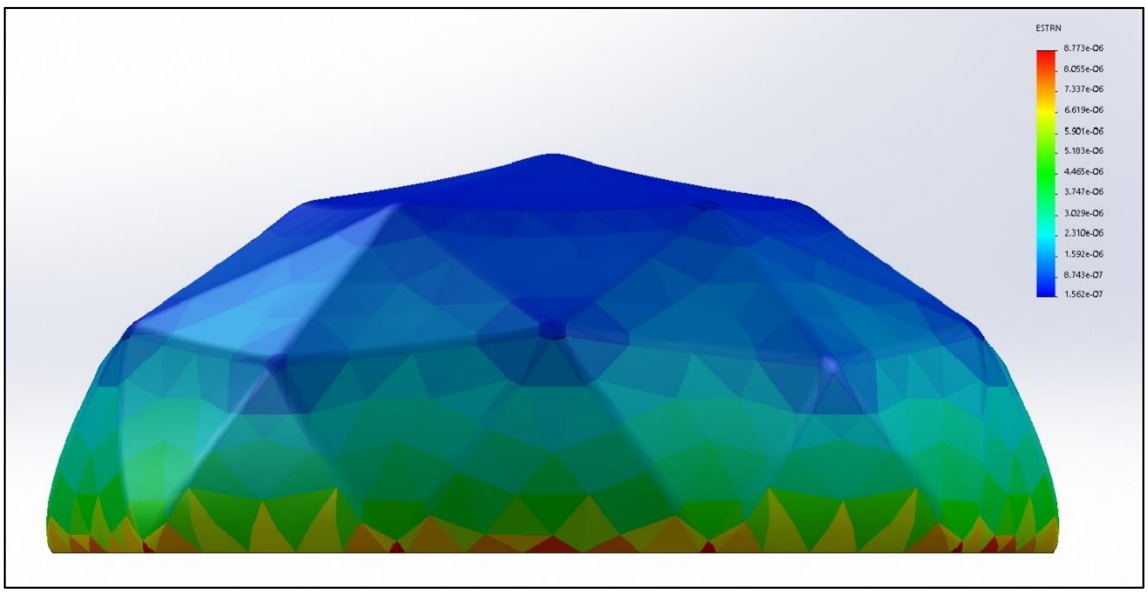


Figure 53: Typical Geodesic Greenhouse Dome - Strain Result

Once completed with analysing the flow simulation results, the quantitative values have been automatically inputted into the FEA software within Solidworks. The results denoted that due to gravitational forces, the deformation or displacement was of magnitude approximately $1.320 \times 10^{-2} mm$ peak value in the vertical or y directional axis. This can be visualised within *figure 52*. Therefore, the biomimetic design can benefit from optimisation of both the exterior shape and overall structure to accommodate for the gravitational forces. Investigating the strain results denotes a magnitude of 8.773×10^{-6} peak value with specific strain at the base of the dome evident within *figure 53*. The Von Mises stress results denote the yielding forces or region of failure would occur at the anchor of the dome to the ground. It can be concluded that the peak strain being at the base of the dome is expected due to the anchoring of the dome to the ground and therefore, the biomimetic design can benefit from optimisation of base region. These regions can be seen within *figure 54*, enhanced to the regions being referred to.

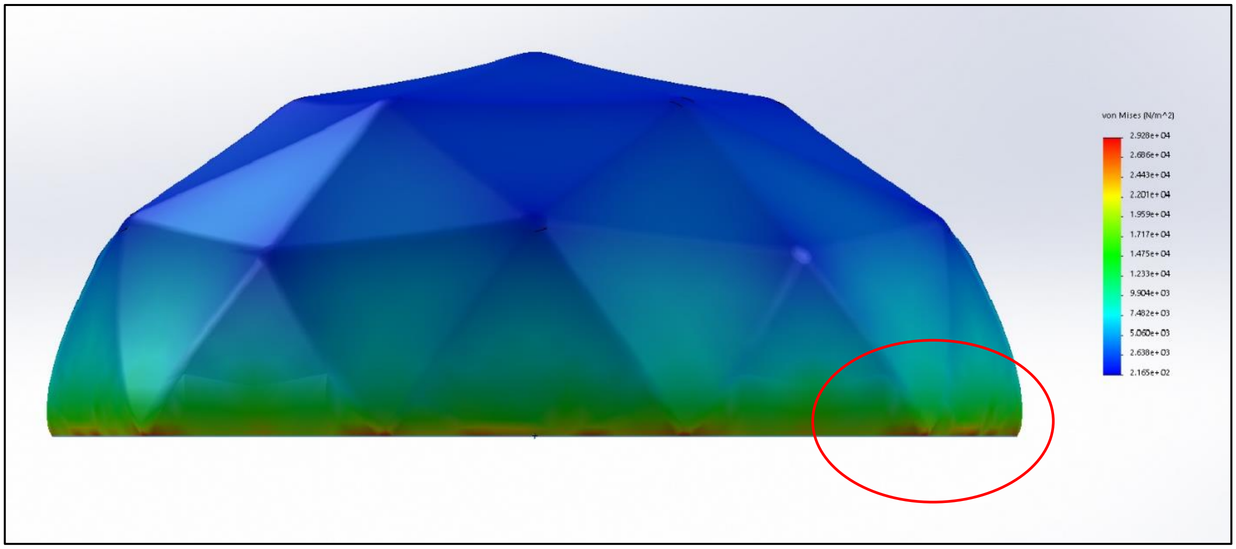


Figure 54: Typical Geodesic Greenhouse Dome - Von Mises Yield Result

The typical geodesic dome results in terms of volume displays the interior region to be large for purposes of accommodating flora and crops. The volume is influenced by the thickness of exterior structure that is realistic to the conventional dome design. The mass of the dome is also matching the weight of the typical steel based design and is estimated through the defined steel material within the Solidworks software. Results denoted an estimated weight of $4250.99kg$. This weight can be optimised through the biomimetic approach utilising PLA material within the 3D modelling process whereby the definition of the material will allow results to be compared to this typical geodesic dome mass. Furthermore, cost and volume results are accomplished in an equivalent manner with the cost estimation being based off material usage and United States market of machining and material rates. The results of cost estimation is $3630 USD with the typical geodesic dome of equivalent size being researched to range from a market value of $3000-5000 USD. The volume is estimated as $57.44m^3$ with the software spacing measurements based on the dimensions of model designed.

5.4.2 Biomimetic Honeycomb Greenhouse Dome Results

The biomimetic honeycomb greenhouse dome model was placed under flow simulation with the control variables previously mentioned and denoted a comparatively lower pressure result than the typical geodesic greenhouse dome. This affirmed the hypothesis of the investigation stating that the honeycomb lattice exterior design would reduce the wind loading effects through pressure results. The results collected through the visualisation in *figure 55* illustrated a removal of any peak pressures that spike into $101.34kPa$. More significantly however, is the wind and gravitational loading being more evenly distributed over the structure as to reduce any regions having an obviously larger loading.

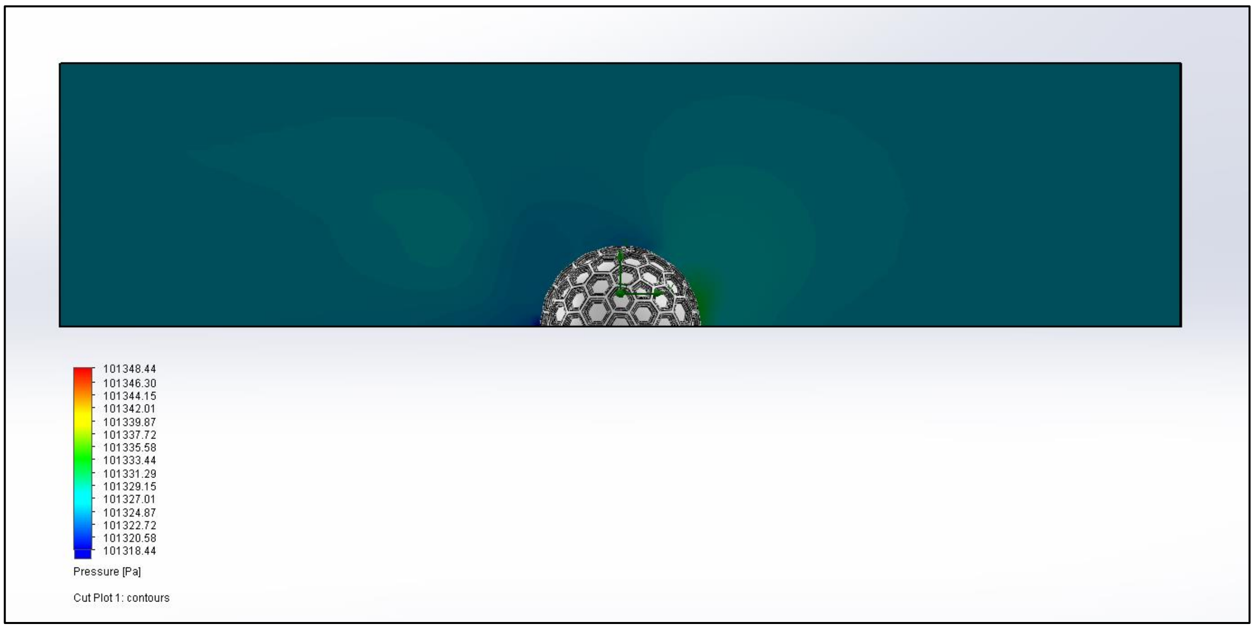


Figure 55: Biomimetic Honeycomb Greenhouse Dome - Pressure Results

The biomimetic approach and honeycomb greenhouse dome design evidently denotes a greatly distributed air flow over the design. There is evident to be a more effective handling of the gravitational normal force and the wind force. It can be concluded through the quantitative results and comparison that the honeycomb lattice exterior indeed has reduced the wind loading. The peak pressure values are evident on the contacting side of the wind flow. Furthermore, the generated vortex on the opposing side to initial wind contact has been reduced in magnitude. This can be witnessed within the visualisation of the velocity results highlighting a reduction in frictional forces that would have the potential to shift the dome in *figure 56*.

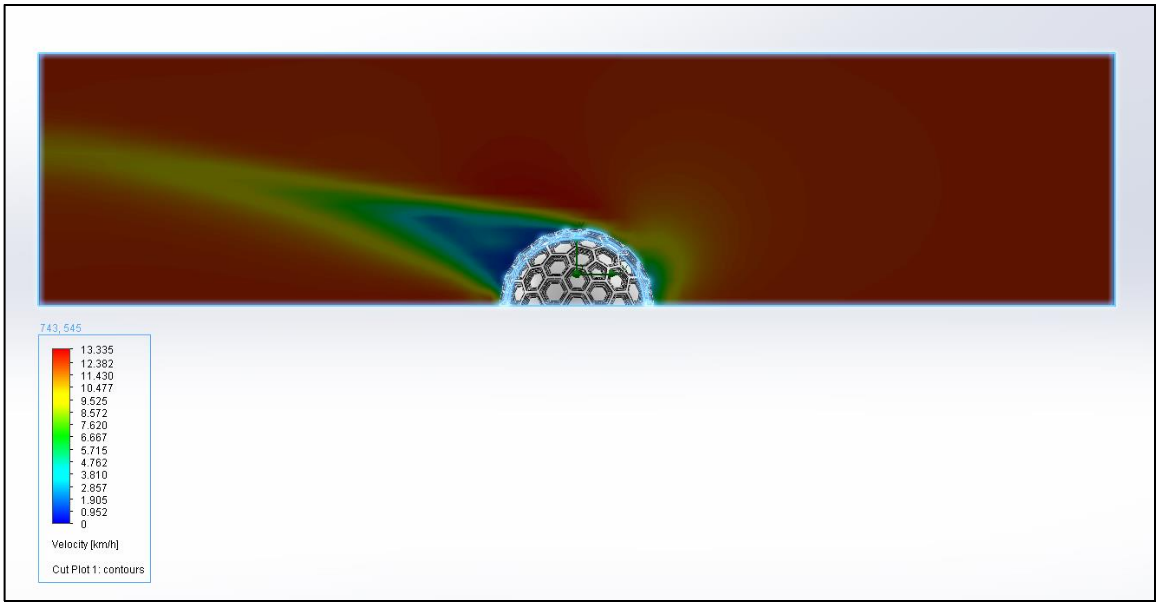


Figure 56: Biomimetic Honeycomb Greenhouse Dome - Velocity Results

The velocity results denote a more concentrated flow of the wind being directed upward. Furthermore, a greater magnitude of velocity being highlighted by the red regions depicts a lower region that is inhibited or affected by the dome. This less obtrusive design that displays a lower frictional force being generated concludes that the exterior concave structure has allowed for a more aerodynamic influence on the flow. The spread of the wind on opposing sides to the initial wind contact is more concentrated in a cone fashion. There is a possibility to a greater lift being created due to the directional flow of wind rising and would be an element of this investigation that can be further investigated by future optimisations of the honeycomb design. Furthermore, there are no areas of the dome that have a resulting acceleration of the wind vectors with this design depicting all wind vectors having a magnitude equal to or lower than approximately $13.34 km/h$ correct to two decimal places. In comparison with the typical geodesic dome design therefore, the biomimetic structure has an effect of accelerating the wind to a lower magnitude.

Table 7: Peak Velocity Comparison

Dome Design	**Peak Velocity Magnitude (km/h)**
Typical Geodesic Greenhouse	14.77
Biomimetic Honeycomb Greenhouse	13.34

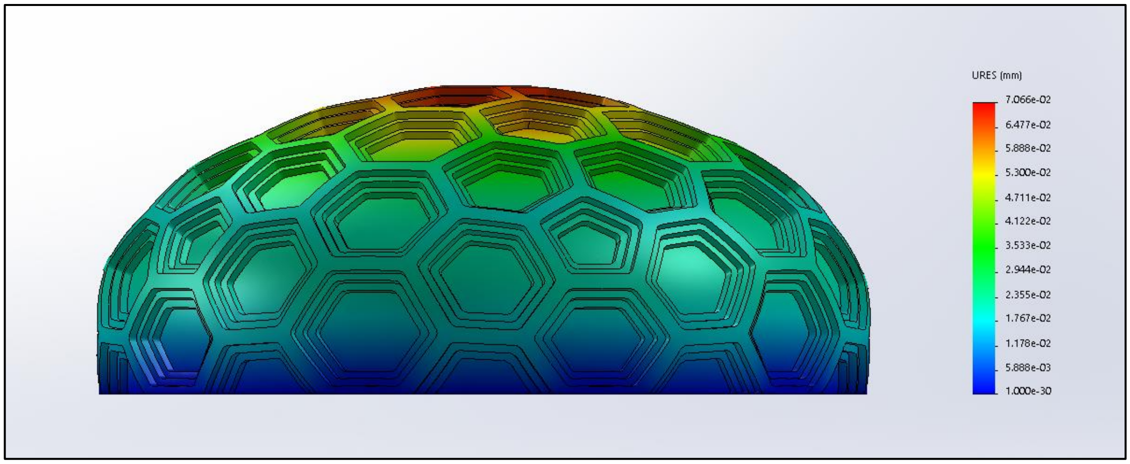


Figure 57: Biomimetic Honeycomb Greenhouse Dome - Deformation Result

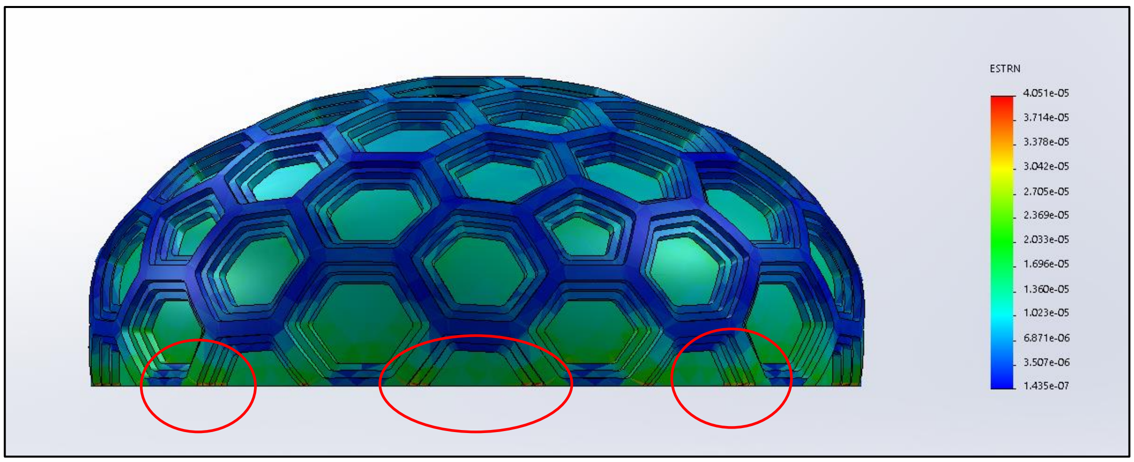


Figure 58: Biomimetic Honeycomb Greenhouse Dome - Strain Result

The flow simulation results, inputted into the FEA software results in the visualisation of results displayed within *figure 57* which depicts a deformation due to both gravitational and wind force. The peak displacement due to deformation was approximately $7.066 \times 10^{-2} mm$ in the vertical or y directional axis. This is expected due to the change in material definition since there is a utilisation of PLA 3D printed material. The deformation results are still within a lower displacement factor however, future investigation can be performed to confirm structural integrity is acceptable for practical application. Investigating the strain results denotes a magnitude of 4.051×10^{-5} peak value with specific strain at the base of the dome evident within *figure 58*. These peak values at the anchor of the dome to the ground compared to the typical geodesic dome design however, with a significantly lower magnitude and area, it can be concluded that the strain effect has been reduced via the biomimetic approach. This can be seen in *figure 58* where the layered hexagonal design continuing to the ground reduces the area of strain or failure. The

Von Mises stress results denote the yielding forces or region of failure and within *figure 59* no immense potential failure would occur with the typical wind loading conditions of $12.55 km/h$.

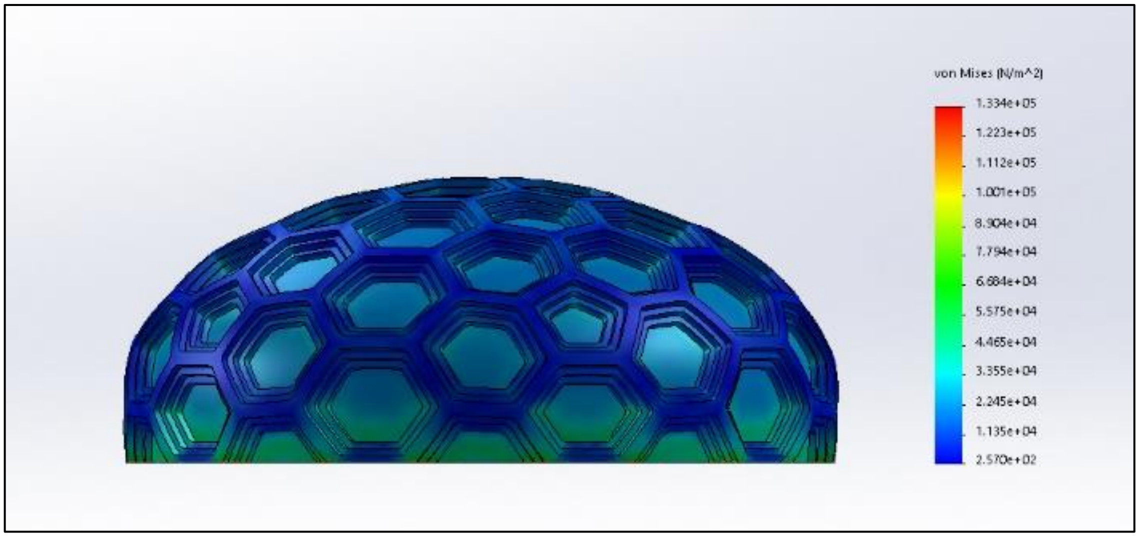


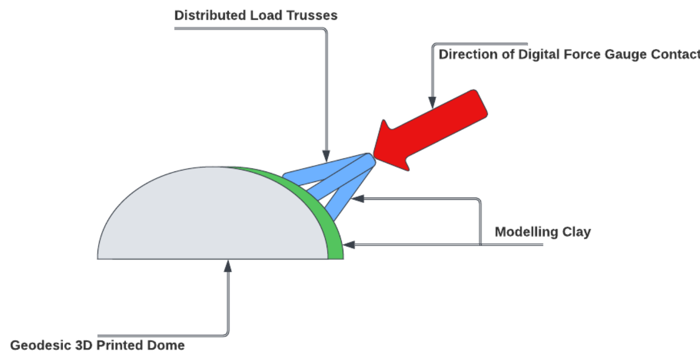
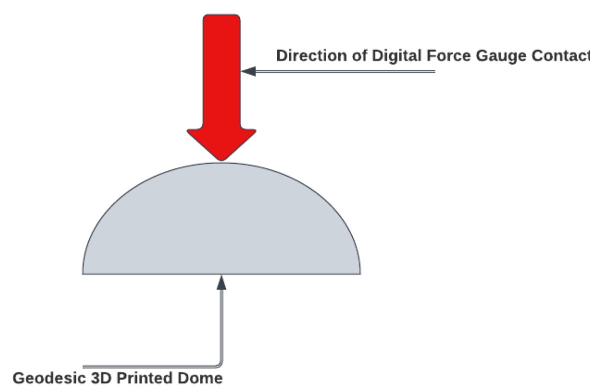
Figure 59: Biomimetic Honeycomb Greenhouse Dome - Von Mises Yield Result

It can be concluded that the peak strain being at the base of the dome is expected due to the anchoring of the dome to the ground and therefore, the biomimetic design can benefit from optimisation of base region. In terms of volume, the interior region is large enough in containing flora and crops however, due to the thicker region needed to create the layered honeycomb. The volume is influenced by the thickness of exterior structure therefore, the volume is reduced compared to the typical geodesic dome design restricting the space available for flora and crops to $38.54 m^3$. This was estimated with the software spacing measurements based on the dimensions of model designed. The mass of the dome is also estimated with the PLA material defined upon the structural design and is as $128.53 kg$. This weight has shown a significant optimisation to the structure in comparison with the typical steel-based geodesic dome design. This can benefit from future investigations with extreme wind or storm cases to determine if the wind effects will cause instability with the dome anchorage. Furthermore, cost results are accomplished in a comparable manner of determination with the estimation being based off material usage and United States market of machining and material rates. The results of cost estimation is $804.07 USD based off the dimensions, machining processes and PLA material. The equivalent size plastic domes had been researched to range from a market value of $1000-3000 USD therefore, justifying the realistic cost to range between these values using PLA material.

5.4.3 Physical Force Testing Results

The physical testing results verify that the scale printed model of the parameters outlined in heading '*4.9 3D Printing Process*' has the capability to withstand with no deformation or cracking to the structure. The full results of the two arrangements are defined in the *table 8*.

Table 8: Physical Force Test Results

Load	Scaled Force (N)	Peak Force (N)	Visual Orientation
Distributed	24.53	90.13	
Top Point	7.54	91.25	

The scaled force denotes the resulting limitation that was placed on the force gauge given the calculations from scaling down the loading from the large scale model in Solidworks to the smaller physical scale printed model. Therefore, the resulting force within this column highlights the scale model can withstand the wind forces and pressure loadings in ratio with the physical model. The peak forces results are the maximum force that was able to be applied manually to the dome via hand and therefore, affirms that the PLA material and structural design has the capability to withstand forces magnitudes greater than the typical wind conditions that simulations are based on. Therefore, these practical results allow for the investigation to add validity and a verification to the practicability of 3D printed materials in greenhouse structure design.

6.0 Discussion

The results, therefore, denote that multiple of the optimisation factors that were initially aimed to be optimised have been improved using the biomimetic design process and aspects influencing the structure of the geodesic greenhouse dome. To summarise the factors that have been improved are cost, strength and wind resistance and mass. Contrastingly, the volume has been negatively impacted with a reduction in space for the containable plant and flora due to the thickness required when designing the honeycomb surface lattice.

The accuracy of the investigation via simulation has been of high order or magnitude. All results gathered have been round to two decimal places and kept within SI units. The cost estimations can benefit from improved accuracy via discussions or contact with suppliers and manufactures to impact the validity of the materials and processes necessary. Similar can be stated for production time with the denoted results being broad indicators that, once more, only use estimation of machining and similar processers timing. Alike, this can be improved to give more accurate timeframes by contacting suppliers and manufacturers of both steel and PLA or other 3D printed materials. The strength calculations are dependable upon the density definition of the materials and therefore, the material parameters inputted for PLA was researched and then manually defined within the CAD software.

With respect to the reliability of this investigation, the behaviour of wind vectors within the Solidworks Flow Simulation software and results collated are as expected and comply with the established literature that documents honeycomb house designs (Jewell 2020). Furthermore, exterior structural design of dimples with the biomimetic approach yielding results that complement the established effects upon aerodynamic allows the investigative comparison between greenhouse models to be reliable (Karnani 2019). They results coincide with the established literature of mechanical design such as the 'The Aerodynamic Effects of Dimples on the Fuselage of an Aircraft' (Klaib 2018). The results have denoted the expected results in conjunction to projects such as the previously mentioned and analysed WASP or World's Advanced Saving Project ("WASP – 3D Printing Eco-Building.") with the material choice of PLA 3D printed material denoting a complementing magnitude of reduction in mass while sustaining strength or structural integrity. The literature concerned with the wind forces and velocities conveyed the flow simulations effects of typical and realistic wind conditions. Hence, importing the flow simulation software results into the FEA depicted reasonably accurate and conforms with the previous literature mentioned to a factor of 98.98% of quantitative accuracy with regard to pressure loadings (Haby 2018). This is calculated using the typical $100kPa$ results compared to the slightly greater pressure results gathered. The honeycomb lattice investigated and proposed furthermore, confirms the reviewed literature, and has denoted a clear impact upon the strength of the structure. Moreover, the reliability and validity of this results, both simulated and physical, have been verified and kept to an acceptable standard through running multiple tests with identical conditions. It can be concluded that the results collected are reliable without outlier results with comparison with other tests or any abnormal values, performance issues or glitches. Utilising market cost value research upon similar materials and greenhouse for the typical case allows the reliability on the cost quotes to be valid however, with the biomimetic approach there are inaccuracies in cost estimations. This is primarily due to the biomimetic approach and literature on 3D printed greenhouses to be limited within the realms of machining, printing, and material costs. To allow for the biomimetic approach costs to be valid, estimations of cost have been researched through plastic designs as a comparison and estimations of PLA material. Furthermore, cost estimations for the biomimetic approach have been also validated through investigating the printing process and machining costings within the United States market as there is greater data available.

Implications of the results collated confirm that as hypothesised, the biomimetic approach optimised a range of factors and aspects of greenhouse design, specifically focused on dome greenhouse structures. These factors as shown in the results from *table 5* & *table 6* affirm that the biomimetic approach has optimised the cost, mass and maximum wind loading or reduction of contact forces and pressure due with the defined wind conditions. About these factors, the implications of the costing results denotes a clear reduction in cost when materials are compared, however, limited information and validity surrounds the 3D printing, assembling, and machining processes. With that being stated, these processes are estimated to be still less expensive then utilising a conventional steel based greenhouse design. The mass results also complement such a result but can be further optimised through investigating differing 3D printable materials and comparing mechanical properties through future FEA and flow simulations. The mass results imply that utilising 3D printing processes the lightweight design can optimise assembly and disassembly processes and material/physical transportation demands. The volume, however, was not optimised through the biomimetic approach in accordance with the results and dimensioning, due to the requirement of a thicker exterior layer when designing the dimples that replicate the honeycomb lattice. Regarding the force and pressure optimisations, the investigation implies that the honeycomb exterior has reduced the spread of the wind influence, reduce the magnitude of peak velocity and force making the dome more resistant to wind conditions and reducing the direct impact upon the structure.

6.1 Recommendations

As previously mentioned, the first recommendation for future investigations is to seek greater accuracies regarding PLA material definitions and details, specifically for industrial standard employment. Furthermore, communication with a range of suppliers and manufacturers can denote costs and production times with greater accuracy and reliability. Researching further on the material property and definition of PLA and altering settings added into the CAD software can potentially impact and increase the validity of the FEA. This would directly impact the density if PLA parameters and definition is altered and consequently impacting the strength, force and pressure results gained from the investigation.

Furthermore, the investigation can benefit from development of the models to be defined with multiple varied materials to demonstrate and perform the FEA process more accurately. By defining multiple materials such as fibreglass, alternate plastic connections and gauze, the combination of materials will more accurately replicate the real-life greenhouse design and structure. Correspondingly, the window modelling is another aspect that can be improved from the CAD models to replicate the physical greenhouse more realistically. Alongside specific defining of materials within the 3D model, the investigation in future can benefit from having stricter defined dimensions when comparing results or performance between models. Given the shape selected for future investigations, rather than only restricting base dimensions between model comparisons, models would yield a more valid result if thickness of materials and height are also restricted between the typical and biomimetic cases to a definitive value. This is referring to the thickness and height of the structures being modelled to allow FEA dependant factors or variables to be controlled.

As previously mentioned regarding the optimised weight of the biomimetic approach, this project can benefit from future investigations to determine whether the reduction in mass can have negative effects such as lift generated in more extreme wind conditions. Furthermore, with the velocity wind vector trace, it is recommended that research is continued into determining if the biomimetic approach can be structurally optimised to reduce lift generated. Optimisation with future work upon the biomimetic approach can allow more successful results that address the strain at the dome anchorage or ground contact region. In conjunction further testing with extreme wind or storm cases can influence results upon the strain and determine if the wind effects will cause instability with either the current or future designs of the dome anchorage.

7.0 Conclusions

To conclude, when revisiting the requirements of this investigation it is clear that the biomimetic approach has accomplished; resistant to wind and reaction forces, modelled natural occurring structure(s) in the form of a honeycomb lattice, modelled 3D a structure that is scaled down for physical printing and testing, designed to fit hobbyist/consumer standard, wind conditions are reflective of Australian environment, the dome can accommodate floral growth and optimisation of environmental footprint with material utilisation. Therefore, in terms of judging the successfulness of this investigation, the designed biomimetic approach has addressed all the requirements and they have been considered in the design process with documented justification. To reiterate the main results that have been deduced through comparison between the typical geodesic greenhouse versus the biomimetic approach the optimisation factors below have been majority improved via the biomimetic approach.

Table 9: Summarized Resulting Improvements

Optimisation Factor	**Magnitude of Improvement with Biomimetic Approach**	**Unit**
Cost Difference	2000	USD
Mass Reduction	96.98	%
Volume Reduction	67.10	%
Pressure Surface Area Spread	2	$Factor$
Force Resistance	25.43	%

The pressure surface area spread that has displayed through the results to have been increased by a factor of two or ideally doubled via the biomimetic approach more comprehensibly means the wind loadings have been effectively deflected. This result affirms that the honeycomb exterior lattice has had the hypothesised effect of being more aerodynamic in comparison to the typical geodesic dome structure. The pressure loading is therefore, distributed more evenly over the structure via the deflecting effect of the lattice exterior rather than having a direct contact onto a single region evident in the typical geodesic dome case.

The implications of the investigation on the research area has established literature and practical results into the feasibility of utilising 3D printable materials within the application of agriculture and specifically in greenhouse dome structural design. Furthermore, this investigation has affirmed the positive influence and optimisation of utilising biomimicry within the realm of greenhouse dome exterior design. Contribution to the research area regarding agriculture is that of having a basis greenhouse design that can be utilised by hobbyist and residential utilisation within the Australian (NSW) average climate. This thesis requires further investigation regarding printing processes if attempting to create the real-world physical 3D printed greenhouse model, however, has established a biomimetic greenhouse using honeycombs as inspiration. Finally, the biomimetic structure of honeycombs that was investigated in this thesis has contributed to establishing and verifying the aerodynamic and force benefits hypothesised in the research area.

7.1 Future Work

The future scope of this investigation can include the following realms of expendability:

- Investigate a range of differing 3D printable material to identify the most optimal material in regards to some of the similar factors mentioned in this investigation such as, cost, strength, and mass.
- Investigate the process of flow and FEA simulation with defining differing materials specifically through CAD software.
- Simulating realistic and multiple differing wind conditions.
- Optimisation of the honeycomb structure to allow for greater reduction in wind loadings.
- Evaluation of marketability of the biomimetic approach design.
- Developing a more valid distributed loading mould for physical scale testing.

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9.0 Appendix

9.1 Appendix A

9.1.1 Wind Regions in Australia

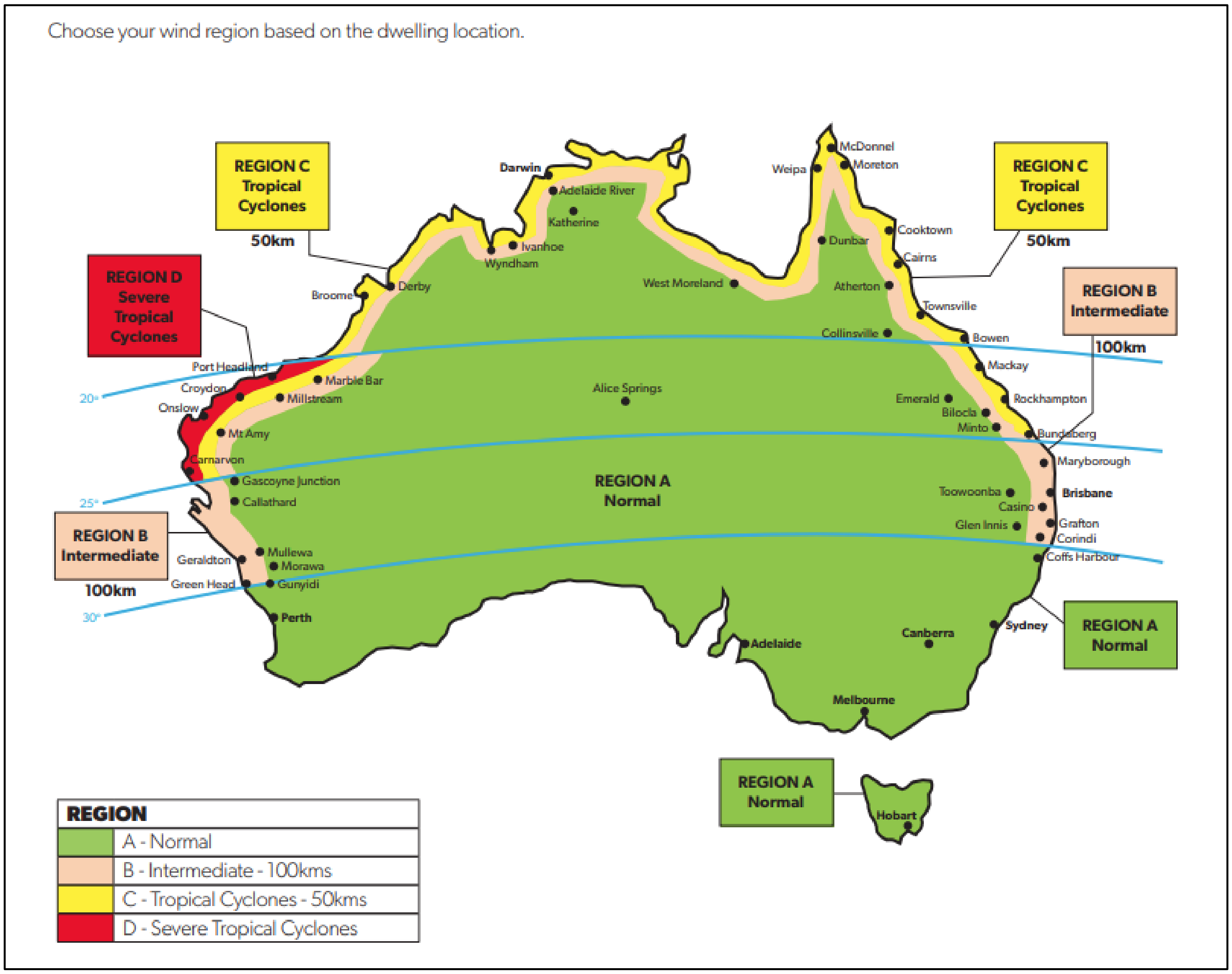
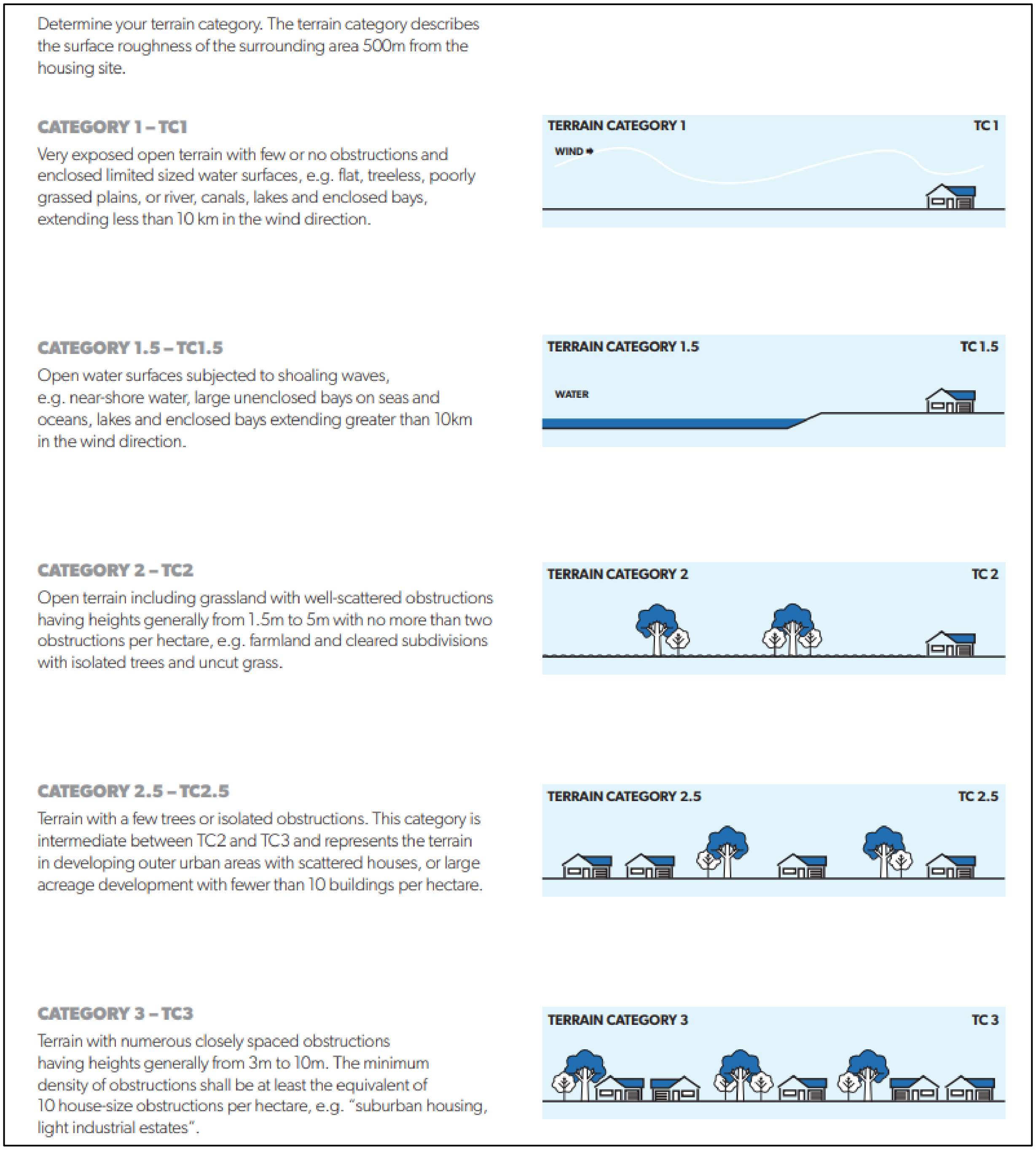


Figure 60: Wind Regions in Australia

(Lysaght 2017)

9.1.2 Terrain Categorization


Determine your terrain category. The terrain category describes the surface roughness of the surrounding area 500m from the housing site.

CATEGORY 1 – TC1

Very exposed open terrain with few or no obstructions and enclosed limited sized water surfaces, e.g. flat, treeless, poorly grassed plains, or river, canals, lakes and enclosed bays, extending less than 10 km in the wind direction.

CATEGORY 1.5 – TC1.5

Open water surfaces subjected to shoaling waves, e.g. near-shore water, large unenclosed bays on seas and oceans, lakes and enclosed bays extending greater than 10km in the wind direction.

CATEGORY 2 – TC2

Open terrain including grassland with well-scattered obstructions having heights generally from 1.5m to 5m with no more than two obstructions per hectare, e.g. farmland and cleared subdivisions with isolated trees and uncut grass.

CATEGORY 2.5 – TC2.5

Terrain with a few trees or isolated obstructions. This category is intermediate between TC2 and TC3 and represents the terrain in developing outer urban areas with scattered houses, or large acreage development with fewer than 10 buildings per hectare.

CATEGORY 3 – TC3

Terrain with numerous closely spaced obstructions having heights generally from 3m to 10m. The minimum density of obstructions shall be at least the equivalent of 10 house-size obstructions per hectare, e.g. "suburban housing, light industrial estates".

Figure 61: Australian Terrain Categories for Wind Load Classification

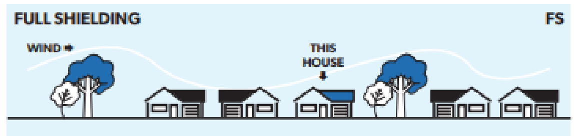
(Lysaght 2017)

9.1.3 Shielding Factors

Determine your terrain category. The terrain category describes the surface roughness of the surrounding area 500m from the housing site.

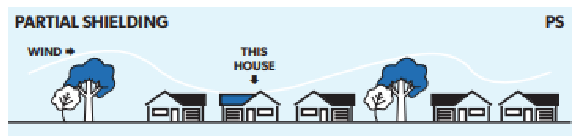
FULL SHIELDING – FS

Full shielding where at least two rows of houses or similar size permanent obstructions surround the house being considered. In Regions A & B, heavily wooded areas within 100m of site provide full shielding. The effects of roads or other open areas with less than 100m measured in any direction shall be ignored. Full shielding is for typical suburban development greater than 10 houses per hectare. The first two rows of houses abutting permanent open areas with a least dimension greater than 100m, such as parklands, large expanses of water and airfields, shall be considered to have either partial shielding or no shielding.



PARTIAL SHIELDING – PS

Partially shielded where there are a least 2.5 houses, trees or sheds per hectare such as acreage type suburban development or wooden parkland. The second row of houses are classified as partially shielded.



NO SHIELDING – NS

No shielding where there are no permanent obstructions or where there are less than 2.5 obstructions per hectare, such as the row of houses or single houses.

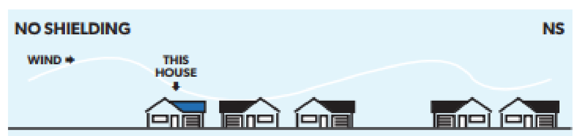


Figure 62: Shielding Factors for Wind Load Classification

(Lysaght 2017)

9.1.4 Topography Effects

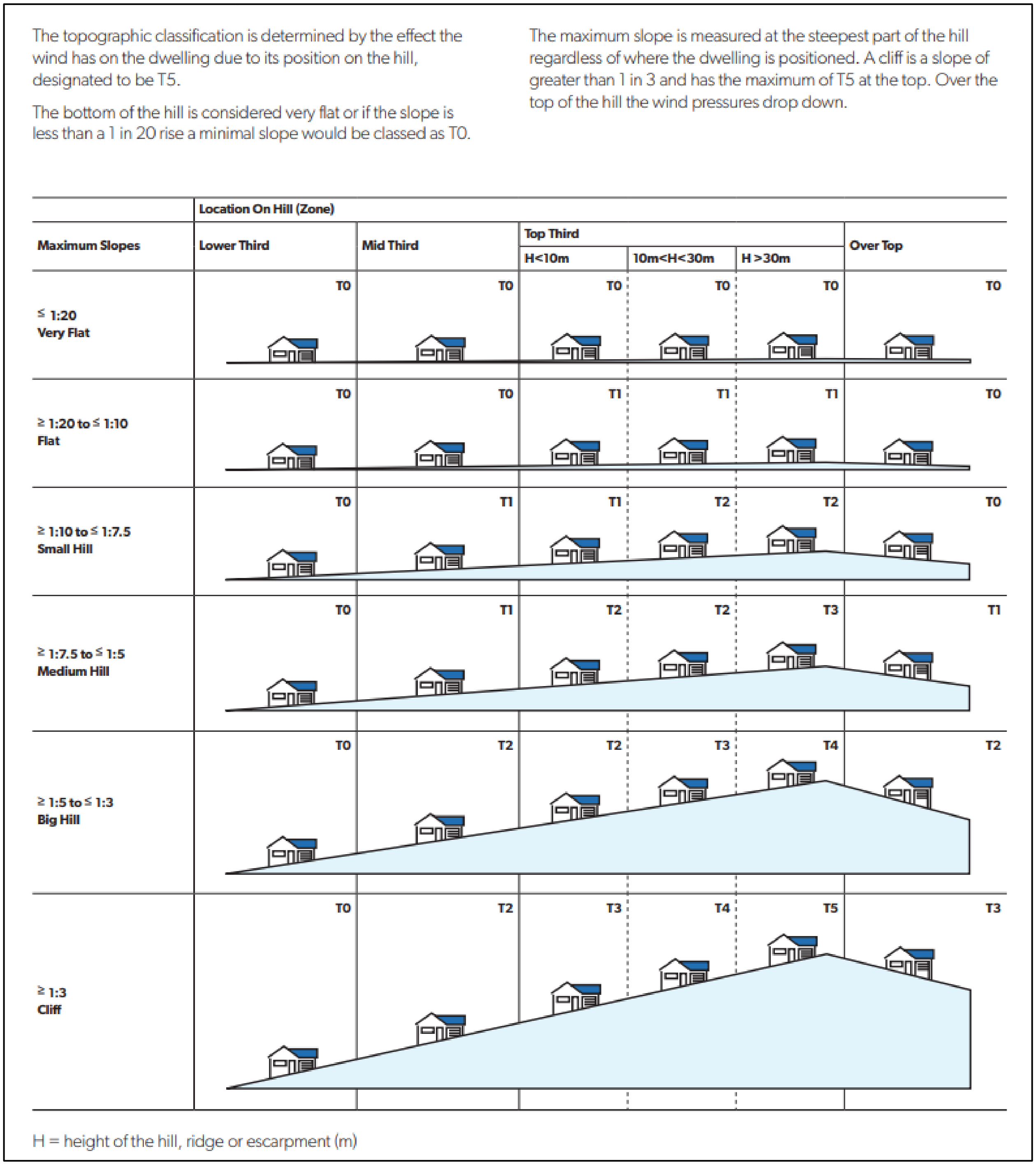


Figure 63: Topographical Effects in different Scenarios

(Lysaght 2017)

9.2 Appendix B

9.2.1 Digital Force Gauge

Figure 64: Digital Force Gauge - No Attachments

9.2.2 Digital Force Gauge with Attachments

Figure 65: Digital Force Gauge with Attachments

9.2.3 Orientation of Physical Tests

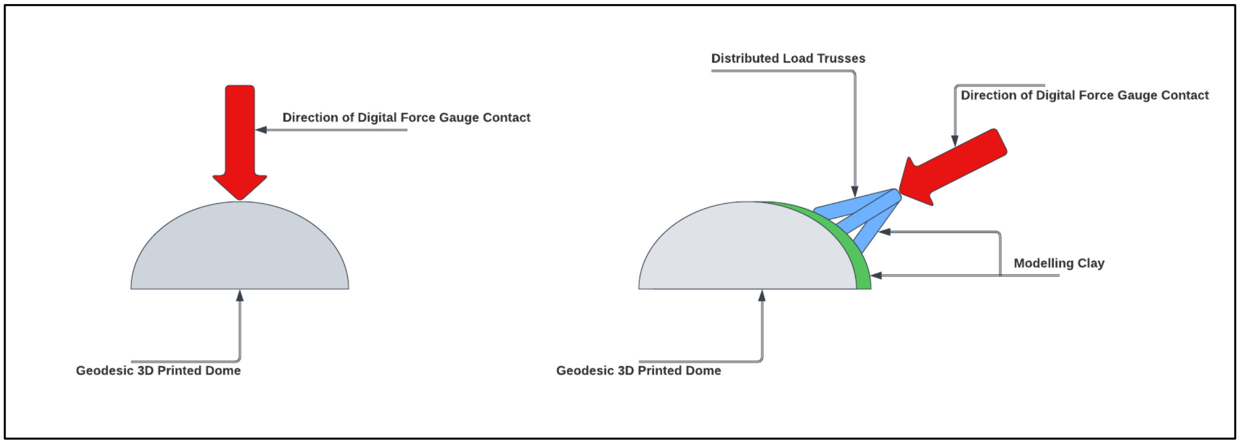
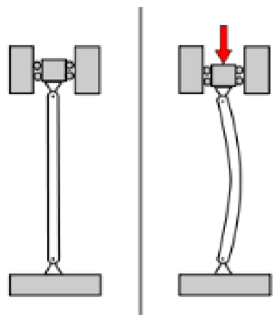
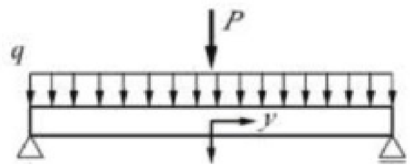


Figure 66: Differing Directions of Force Applications

9.3 Appendix C

9.3.1 Scale-Down Model Loadings Derivations

Table 10: Scale the Load to Investigate this Behavior - Equation Derivations

loading condition	buckling	bending
representation		
beam breadth	b	b
beam thickness	h	h
beam cross-section	bh	bh
(moment area) I	$\frac{b\,h^3}{12}$	$\frac{b\,h^3}{12}$
load at failure	$P_{buck} = \frac{\pi^2 EI}{L^2}$	$P_{bend} = q \cdot L$
stress at failure	$\frac{\pi^2 EI}{A \cdot L^2}$	$\frac{PL}{4 \cdot I} \frac{h}{2}$
operating stress at failure after simplification	$\frac{h}{L^2} \frac{\pi^2 E}{12}$	$\frac{3PL}{2b\,h^2}$

9.4 Appendix D

9.4.1 Physical Testing Mould for Distributed Load

Figure 67: Distributed Load Mould - Top View

Figure 68: Distributed Load Mould - Side 1

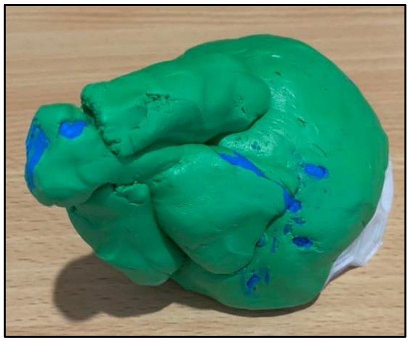


Figure 69: Distributed Load Mould - Side 2

9.5 Appendix E

9.5.1 Mesh Generation

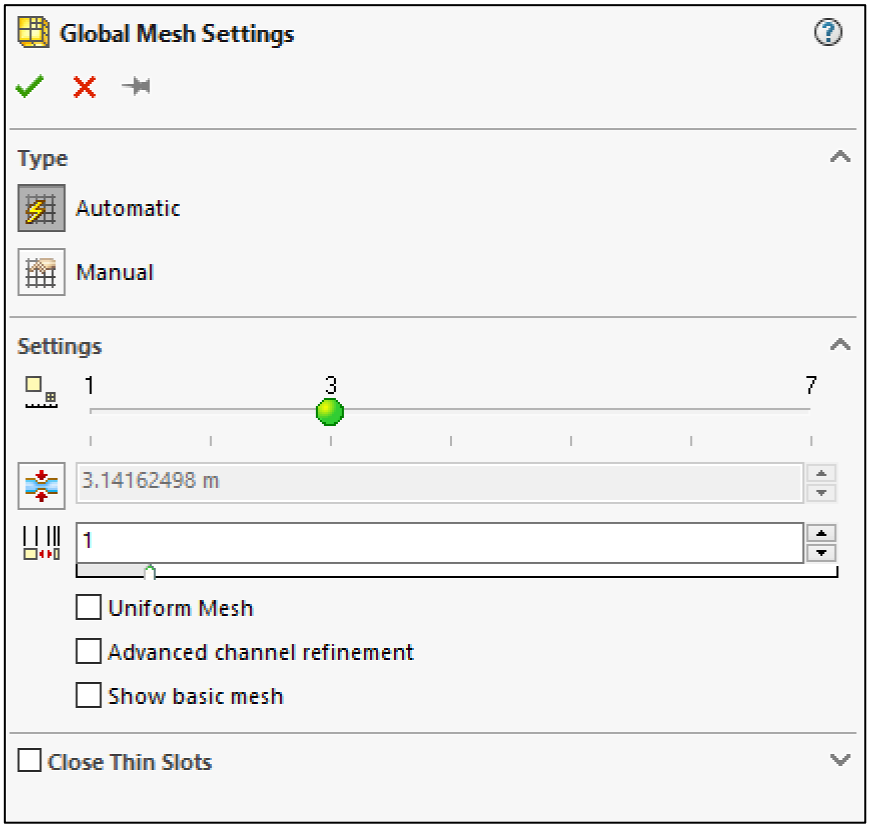


Figure 70: Flow Simulation - Mesh Settings

9.5.2 Loading Conditions

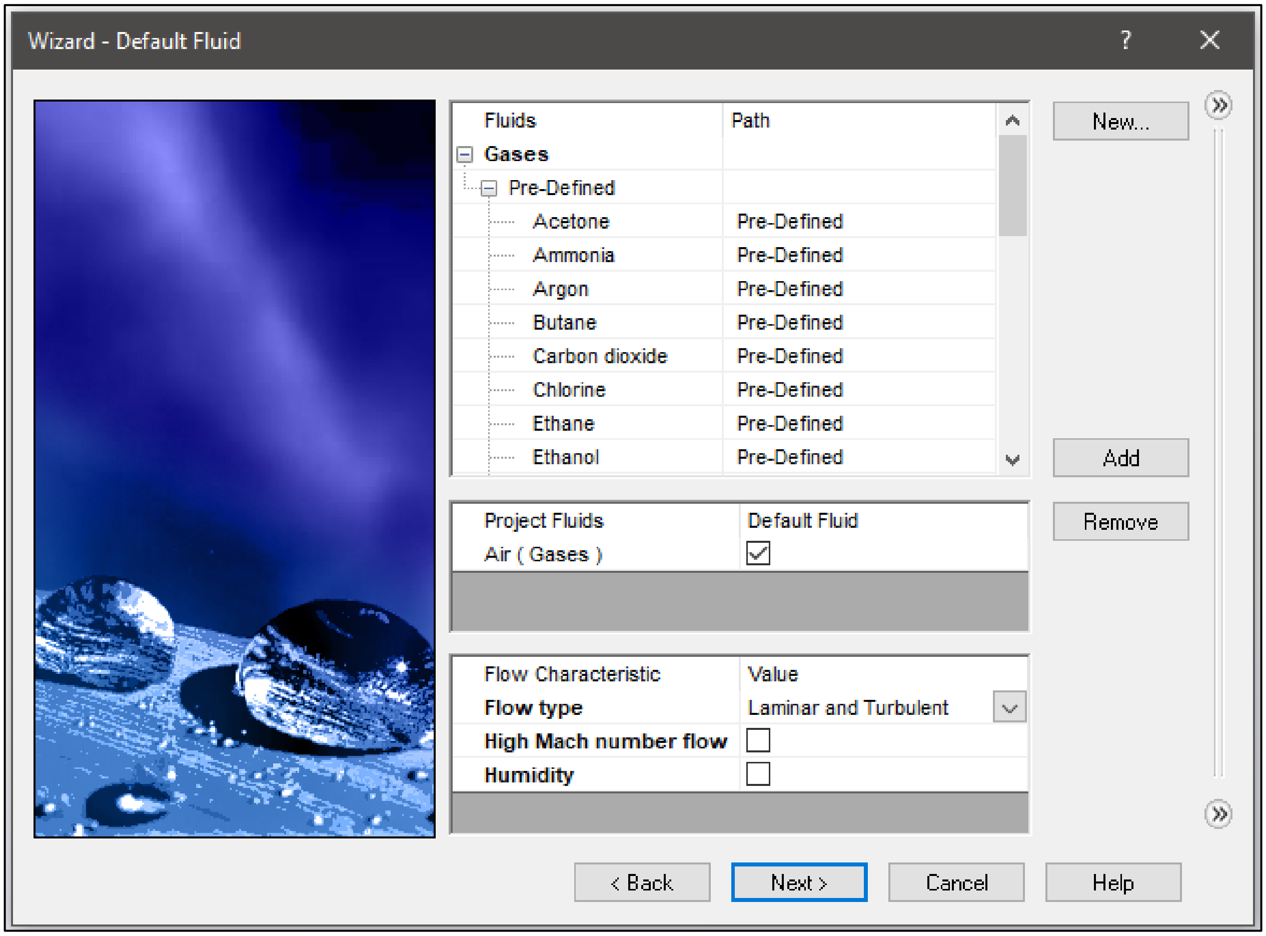


Figure 71: Wind Loading Condition - Air Gas Definition