ENGR4700 Thesis

Open Source Wi-Fi Tower

Designed to provide a rapidly-deployable, portable solution for elevated mesh networks

Greg Stevens, BEng (Mechanical) Hons | 15th November 2013

Flinders UNIVERSITY

Client - WiFindUs
Supervisor - Stuart Wildy
Associate - David Ilba

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Executive Summary

Background: The density of outdoor wireless mesh networks can be greatly reduced when the accesspoints (APs) are elevated to a height which avoids interference with nearby structures as well as stronger radio waves.

Purpose: The aim of the project was to research, design, construct, and analyse an open source, rapidly-deployable and portable Wi-Fi tower, designed from (1.) nationally accessible components and MakerBot Replicator 2X 3D printed parts, to (2.) fit inside a suitcase and comply with the major Australian airlines' check-in regulations, while (3.) be proven to be 'structurally sound' in accordance with relevant Australian Standards for the design and manufacture of telecommunication mast and tower structures, and to (4.) ensure that the design complies with the OH&S legislations for temporary demountable structures (TDSs) at large outdoor music festivals (OMFs).

Materials and Methods: A tower design was conceptualised through the use of the Quality Function Deployment (QFD) method, and was evaluated using Pugh's decision-matrix (PDM) methodology. A Stage 1 (S1) design was modelled in Autodesk Inventor based on the preferred concept and constructed from a combination of standard off-shelf components accessible from major Australian hardware stores and 3D printed parts from the MakerBot Replicator 2X. The S1 design was analysed using experimental methods to determine the tower's deployment times (to both assemble and disassemble), its structural stability and strength, and various geometric parameters. The mechanical material properties of the Replicator 2X's polylactic acid (PLA) printed parts were then examined through the use of an Instron tensile testing apparatus. A Stage 2 (S2) tower design was then modelled rectify problems identified during S1 and was constructed to facilitate further experimental analysis. The S2 design was analysed experimentally to determine the strength of the components, the horizontal force required to topple the tower, the natural frequency of the tower with varying mast heights, and the durability of the tower under dynamic wind loads. Theoretical analysis of the S2 design was performed using two commercial finite element solvers; ANSYS Classic was used to analyse the tower's beams and Autodesk Inventor's FEA simulation package for the custom-made parts. The simulations were computed using design loads (primarily wind loads) stipulated by the Australian Standards for mast and tower structures. Stress analyses were carried out by examining the Von-Mises, bending, and axial stresses present in the complete structure and individual parts. The displacement and first mode of vibration frequencies were also analysed using these software packages.

Conclusions: The final tower design achieved all but one of the project's goals. The design proved to be rapidly-deployable (7 minutes to setup), lightweight (dead weight 19kg, live 'water' weight 36kg), compact (total linear dimension of 140cm), maximised Wi-Fi coverage (elevated AP to 6.1m), the required factor of safety (minimum FOS of 9 for the components and 2 for the load rating) was achieved and all the tower components were deemed accessible (either through being purchasable from major hardware stores or 3D printable). Although it was permitted by the client during the project to go over the original project cost goal (to be under 250AUD) in order to achieve the project 'strength and stability' goals, this meant that the project fell just short of achieving all of its goals. However the project team concluded that the design encompassed a high degree of stability, strength and durability, and therefore proved to satisfy the Australian Standards for the design of utility poles, and telecommunication mast and tower structures.

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Disclaimer

I certify that this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any university, and that to the best of my knowledge and belief it does not contain any material previously published or written by another person, except where due reference is made in the text.

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Greg Stevens

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A special thank you goes to my supervisor Dr Stuart Wildy for his direction and input. Thank you to the project sponsor WiFindUs for offering this project and providing substantial input during the conceptualisation of the tower design and generation of the project's engineering specifications. Thank you also to my wireless mesh network consultants from the Serval Project: Dr Paul Gardner-Stephen and Ms Romana Challans. Finally, I acknowledge and appreciate the financial contributions of the Department of Further Education, Employment, Science and Technology for supporting this project through their Defence Scholarship.

Glossary of Terms

ABS	Acrylonitrile butadiene styrene
ACMA	Australian Communications & Media Authority
AEIA	Australian Entertainment Industry Association
AP	Access point
ART	Australian Radio Towers
AT&T	American Telephone & Telegraph
AUD	Australian dollar
Bunnings	Bunnings Warehouse
CASR	Civil Aviation Safety Regulations
DGR	Dangerous Goods Regulations
EHP	Environmental Health Practitioner
EIRP	Maximum equivalent isotropically radiated power
EV	Electric vehicle
FCC	Federal Communications Commission
FEA	Finite element analysis
FOS	Factor of safety
GCS	Geographic coordinate system
GLONASS	Globalnaya navigatsionnaya sputnikovaya sistema (Russian), or Global navigation satellite system (English)
GPS	Global positioning system
HDPE	High-density polyethylene
Home	Home Timber & Hardware
HSE	Health & Safety Executive
IASS	International Association for Shell & Spatial Structures
IATA	International Air Transport Association
IEEE	Institute of Electrical & Electronics Engineers
ISM	Industrial, scientific & medical radio bands
Jetstar	Jetstar Airways
LABC	Local Authority Building Control in England & Wales
LoS	Line of sight
LSB	Lightweight structural beam
Masters	Masters Home Improvement
MC	Mesh client
MG	Mesh gateway
MIMO	Multiple-input & multiple-output
MR	Mesh router
MWN	Multi-hop wireless network
NIC	Multiple network interface card
OH&S	Occupational health & safety
OMF	Outdoor music festival
PDM	Pugh’s decision-matrix
PLA	Polylactic acid
PVA	Polyvinyl alcohol
PVC-DWV	Polyvinyl chloride - drain, waste & vent
PVC-PN	Polyvinyl chloride - drain, waste & vent
Qantas	Qantas Airways
QFD	Quality function deployment
RF	Radio frequency
S1	Stage 1
S2	Stage 2
SAA	Standards Association of Australia
SCOSS	Standing Committee on Structural Safety
SME	Serval Mesh Extender
SRD	Short range device
Stratco	Stratco Australia
TDS	Temporary demountable structure
UHF	Ultra-high frequency
USD	United States dollar
UV	Ultraviolet
UV	Ultraviolet
Virgin	Virgin Australia Airlines
VoE	Voice of engineers
WLAN	Wireless local area network
WMN	Wireless mesh network


...the future of outdoor
entertainment

1. Chapter 1: Introduction

Towers and masts are structures that are built in order to fulfil the need for placing objects or persons at a certain level above the ground. Portable Wi-Fi towers support various antennas, cables and accesspoint (AP) componentry. Although the optimum design of large-scale telecommunication mast and tower structures has been studied by many researchers (Sheppared 1972), the design of portable small-scale telecommunication structures is a relatively newer field, specific to mass gathering events and thus is worthy of further study (Galeb & Khayoon 2013).

1.1. The Telecommunication Problem at Festivals

Outdoor music festivals (OMFs) are generally very congested both physically and 'telecommunication-ally', and when loud music is added to the mix this makes communication a near impossible task. The Health and Safety Executive (1999) state that *effective communication* is of 'utmost importance' when trying to ensure that OMFs run in a safe and smooth manner. To overcome this problem, OMF staff utilise radio-sets. Depending on the size of the event, there can be many radio-sets and networks operating simultaneously throughout the site (HSE 1999). Unfortunately patrons do not have this same 'radio-set luxury', and are forced to make alternative communication plans, which usually consist of meeting at specific locations at predetermined times. However, given the nature of OMFs; high crowd magnitude and density, this makes locating friends problematic and ultimately reduces the 'festival enjoyment factor'. Figure 1.1. shows the high crowd density of the world's largest OMF (185,000 attendees), which although generates a 'huge' annual revenue, has still not invested in a solution to solve the *telecommunication problem* due to the excessive cost of the current solutions (Hilliard 2013; Weverbergh 2012).

Figure 1.1. Tomorrowland: World's largest OMF (Santirso 2012)

Worldwide, communication networks cannot cope with the high crowd magnitude and density demands of large OMFs. The problem is that there's actually remarkably little spectrum available for mobile-phone use; only a few hundred MHz total in any one part of the world. Furthermore, this small spectrum is usually parcelled out among a few service providers and not typically shared unless your provider's spectrum is literally out of range, as opposed to overcrowded (Rogowsky 2012).

The reason why mobile-phones work in places like New York, Beijing and Mexico City, is because the spectrum is re-used over and over, by having multiple mobile-phone towers use the same frequencies. Unfortunately it is not as easy as simply placing two towers next to each other and re-using the frequencies. Usually in the case where two radio towers are adjacent to one another, you put channels *A*, *C*, and *E* on one and *B*, *D*, and *F* on the other, then offset the antennas by a few degrees. This configuration allows you to re-use channel *A* 'fairly cleverly', especially with sectorial antennas, which broadcast the channel in a pie-piece-shaped pattern as opposed to all directions. Sectorial antennas are essential to channel/frequency re-use, and are in turn essential to increasing bandwidth (Rogowsky 2012).

1.2. Existing Solutions

The following sections briefly outline the general and tailored OMF solutions which are currently being used to solve the OMF telecommunication problem.

1.2.1. General Solution

Although most service providers are not bothered by their lack of coverage during OMFs (due to the low feasibility of implementing high-cost solutions for one day events) some service providers offer transportable telecommunication towers for a 'hefty' cost. These transportable towers, otherwise known as micro-mobile-phone-site vehicles and trailers, as shown in Figures 1.2.a.&.b., usually have three 120° sectorial antennas, and whilst substantially increasing the bandwidth for low density crowds through 'frequency re-use', they only moderately improve bandwidth at large OMFs. As a result, although festival patrons experience some improvement, this technology is not at the stage where text messages, calls and data can be transferred without difficulty (Smith 2012).

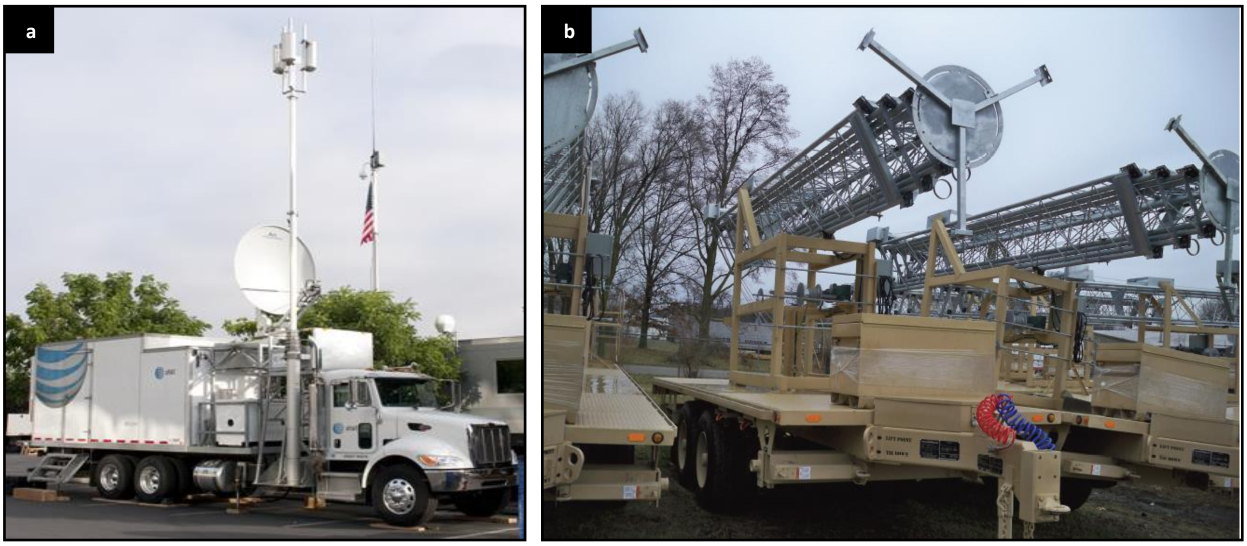


Figure 1.2.a. Micro-mobile-phone-site truck (AT&T 2010),
b. Micro-mobile-phone-site trailer (Telecom Product Profiles 2013)

Micro-mobile-phone-site trucks and trailers are not cheap to purchase either. This makes scaling very problematic given the high unit cost, as this solution would make it very expensive to service multiple stages at large OMFs. Telecom (2013), as seen in Figure 1.2.b., quoted their *micro-cell-site trailer* to be 40,000USD on the 2 July 2013. As shown in Figures 1.3.a.&.b., mobile phone antennas and microwave antennas contribute substantially to the purchase price of micro-cell-sites. Wheeler (2011), a professional mobile services developer, estimates the telecommunications componentry (baseband processors, transceivers, power supplies, amplifiers, etc) of these units to be between 20,000-50,000USD.

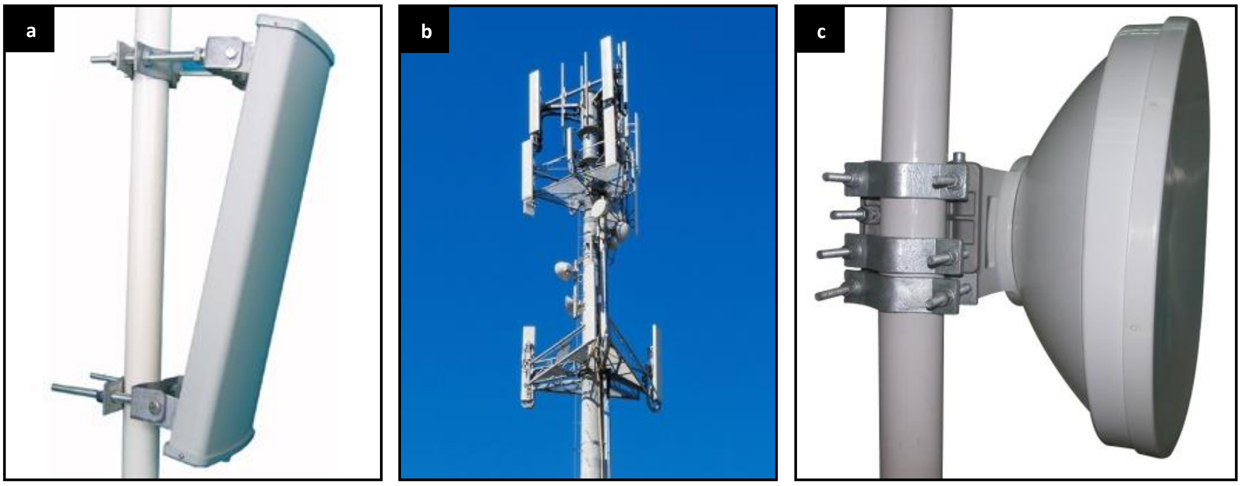


Figure 1.3.a. Mobile phone sectorial antenna (Chapman 2013), **b.** Mobile phone tower (Viking 2006), **c.** Microwave directional antenna (SafestB2B 2003)

Recently, internet providers have decided to exploit the 'poor network situation' by approaching the communication problem in a different manner. Instead of trying to improve their entire range of mobile services (i.e. voice calls, text messages, data), some have decided to focus on providing a Wi-Fi internet connection, free-of-charge for all patrons. At the 2012 WOMADelaide festival, Internode used a radio link from their base-station to provide a low bandwidth Wi-Fi service. Although this appears to be a good plan, their infrastructure could not cope with such a large number of clients. It was reported by Corey Wallis (Senior Software Engineer for the Mass Gathering Data Acquisition and Analysis project, MaGDAA, for short) on 18 March 2013 that many clients were unable to connect, let alone use the network (MaGDAA 2013)

1.2.2. Tailored Festival Solution

In July 2012, AT&T launched a 'five beam multi-sectorial antenna network system, to divide customers' signals into five 12° paths, as illustrated by the colour bands in Figure 1.4.a. The tower is mounted to a 'micro-cell-site truck', as shown in Figure 1.2.a. AT&T claim that splitting traffic into multiple segments has improved their data traffic by up to five times. However Smith (2012) reports that this is still not enough to provide a sufficient bandwidth to large OMF crowds.

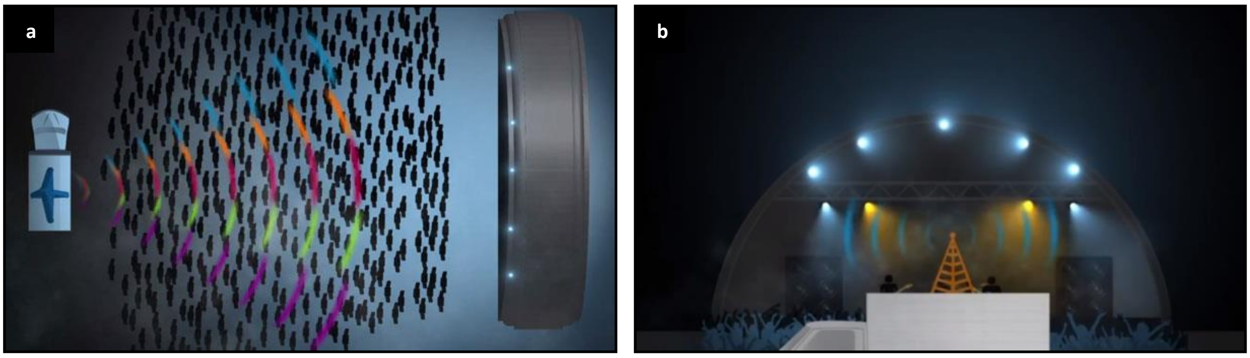


Figure 1.4.a. AT&T: Antenna coverage, **b.** AT&T: Van-tower (Smith 2012)

In April 2013, AT&T launched their 'super multi-beam antenna', as can be seen mounted to a mast on the far left of Figure 1.5. The super multi-beam antenna has 18-beams total and can handle as much as 18 times the network traffic capacity of a traditional single-beam antenna. This technology improves upon the five beam multi-sectorial antenna by expanding the same idea into two rows of nine (Franko 2013).

Figure 1.5. AT&T: Micro-mobile-phone-site at Coachella Valley Music and Arts Festival (Franko 2013)

At this stage it is useful for the reader to know that, Verizon Wireless (the largest mobile network operator in the United States) are also in the process of developing their own series of micro-cell-site vehicles designed to solne the OMF telecommunication problem (Franko 2013). Although these massive transportable telecommunication systems are being implemented at large American OMFs, it is believed by Australian telecommunication researchers that due to the extremely high cost of the systems, it will be a long time (estimate of 10 years) before the systems enter Australian OMFs (MaGDAA 2013; Serval 2013). Furthermore, although these solutions have proven to significantly increase bandwidth availability to patrons directly in front of the relevant stage area, given that most large OMFs have in excess of five stages, as shown in Figure 1.6., AT&T's solution is not a practical nor cost-effective solution to service multiple stages. Furthermore, since Australian OMFs run on successive days around the country, it would be very difficult to transport and deploy this system to and at next-day events. Given that this technology cannot be easily transported by airfreight, this solution would be a 'logistical nightmare' to achieve an efficient next-day service.

Figure 1.6. Tomorrowland: Stage layout (Digiace 2012)

1.3. The Client

The client, WiFindUs, is an Adelaide based early-stage hardware Start-up Company, developing a low-cost, rapidly-deployable and self-sufficient Wi-Fi mesh network to be used at large OMFs. WiFindUs started their project in March 2012, and are currently testing their network hardware and developing software for a mobile application and pilot study, which will be discussed in Section 1.4.3.

The WiFindUs team is made up of a group of mixed professions including: an accountant, a network engineer, a software engineer, two mechanical engineers, and an industrial designer. The team is also made up of 'veteran' OMF patrons. After attending the 2012 Adelaide Soundwave festival, the directors of the company 'joined forces' to develop a more cost-effective solution that could 'have a chance' of being deployed at Australian OMFs within the next few years. The team are energetic and have been willing to provide support wherever necessary throughout the thesis project. The knowledge and available skillset of the WiFindUs directors is summarised in Table 1.1.

Table 1.1. WiFindUs skills profile

Skills	*GS*	*MN*	*MG*	*BQ*	*TG*	*DI*
Legal & compliance		Y				
Corporate strategy	Y	Y				
Project management	Y	Y		Y		Y
Market research	Y	Y	Y	Y	Y	Y
Network development			Y		Y	
Software development			Y		Y	
Product development	Y			Y		
Structural design & analysis	Y					Y
Network operations			Y		Y	
Transport operations	Y			Y		Y
Relevant industry contacts	Y	Y		Y	Y	

It is also important to note that since March 2013, WiFindUs have been collaborating with a Flinders University research team; the Serval Project. The Serval team have developed and successfully tested a self-propagating mesh network protocol for disaster-relief and remote area connectivity. The Serval team are now in need of a compact rapidly-deployable tower for their 'Serval Mesh Extender' (SME), as will be described in Section 4.1.4.

1.4. Clients' Solution

The following sections outline the project client's solution to the previously outlined OMF telecommunication problem.

1.4.1. Vision

WiFindUs believe that internal communications are more valuable than external, and thus have derived a solution which focuses on improving internal communication channels, without internet connection. The solution is designed to streamline existing local positioning system data by integrating a basic text message service that allows patrons to coordinate meeting locations and to find their friends 'buried deep in mosh pits'. WiFindUs' long term goal is to create a 'virtual 3D festival playground', where patrons can navigate and interact with the venue and each other, *tweet status*' and *comment* on performances.

WiFindUs plan to use a wireless mesh network (WMN) similar to Carmesh's urban WMN for vehicular connectivity. Carmesh is a program created by the European Commission for Research and Innovation to focus on the delivery of advanced automotive connectivity services. Like Carmesh, WiFindUs have chosen to use this type of network because it has emerged as a highly flexible, reliable and low-cost solution for wirelessly covering large areas through multihop communications (Adelhakf 2013). Since WiFindUs will provide a localised network, without internet connectivity, this means that they will be able to maintain sufficient bandwidth through controlling their believed 'most valuable communication channel'.

Uncited research, conducted by the directors of WiFindUs has showed that the communication channel that OMF patrons 'value the most' is having the ability to organise catch-up meetings throughout the festival with friends, and to allow the 'seeker' to locate their friends. As previously stated, WiFindUs believe that this service can be best achieved through utilising the location/GPS data from each patron's phone, which 'these days' is a combination of GPS and GLONASS. The 'GPS' as we know it is often a combination of actual GPS and GLONASS, using supplementary data provided by a known server to quickly determine the satellite positions in the event that the GPS signal strength is poor.

1.4.2. Advantages

There are several advantages of using a localised, self-propagating WMN. The first and most important of which is its compact size and ability to be transported by airfreight. Next comes its ability to be rapidly-deployed throughout an entire OMF in less than one day. WMNs are also extremely cost-effective to scale, due to the associated low unit-cost and energy consumption of each accesspoint (AP). Lastly, since the proposed network is intended to work independently of infrastructure, this means that the network is quite applicable to large OMFs situated in rural and remote areas.

1.4.3. Pilot Study

In order to test the proposed WMNs capabilities, WiFindUs are developing their network for a pilot study at the 2015 Adelaide Soundwave Festival. The festival is held at Bonython Park, which is approximately 400x700m (140,000m^2), and has a set-up as shown in Figure 1.7.a.

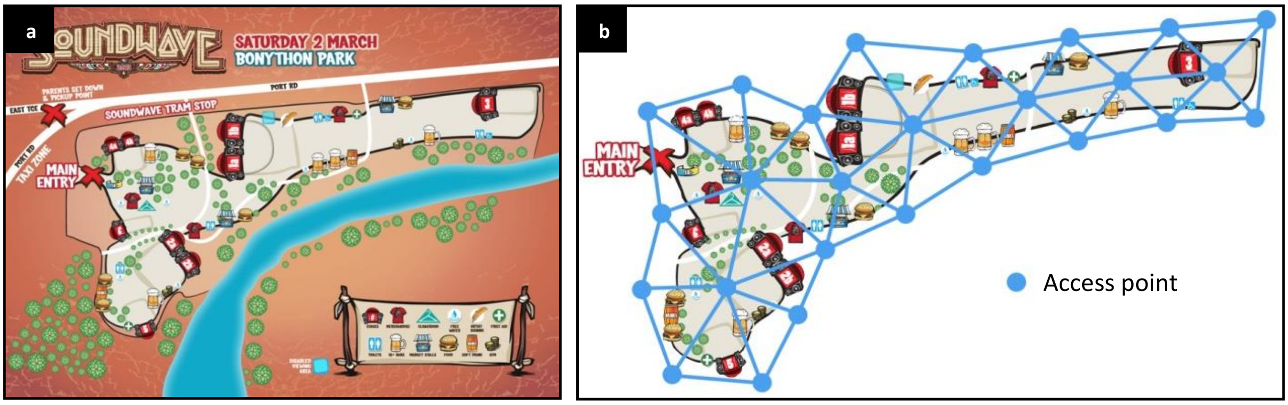


Figure 1.7.a. Adelaide Soundwave Festival map (Soundwave 2013), **b.** WiFindUs proposed WMN network topology

WiFindUs are aiming to connect 2500 clients with their WMN, which is approximately 10% of the annual Adelaide Soundwave festival attendance (Soundwave 2013). This number was deemed by WiFindUs, large enough to demonstrate their WMN's service capacity, while small enough to keep manufacturing costs to a minimum. The WiFindUs network engineer has estimated that the WMN will require between 20-30 APs. This estimation was based on each AP being able to connect with 50 clients simultaneously, with the obvious assumption that the total number of clients will not all be connected at once. The network engineer also provided an example of the envisaged WMN topology, which can be seen in Figure 1.7.b. The mechanical engineer has advised that APs will be mounted to a combination of portable towers and stage structures where possible, in order to minimise the cost of implementing the WMN.

1.5. The Project

The following sections describe the academic qualifications of the Flinders team, as well as outlining the project aim, scope, goals, objectives, and division of design and analysis tasks.

1.5.1. Flinders Team

The Flinders University, ENGR4700 Honours Thesis project team is made up of two students and one academic supervisor. Academic, Dr Stuart Wildy, has expertise in mechanical design engineering and is the leader of the Structural Analysis research group; a collaboration between Adelaide University and Flinders University. The author of this document, Greg Stevens, is a mechanical engineering student who has teamed-up with fellow mechanical student, David Ilba. Together the Flinders team are collaborating with WiFindUs to design and analyse a tower, as described in the following sections.

1.5.2. Aim & Scope

The project client requires a tower to be designed for their proposed network, which basically involves mounting and elevating their AP components. WiFindUs structured a project which requires the Flinders team to research WMNs in order to gain an appreciation of the network type. The aim is to research WMNs, so that the team understands the physical requirements of the AP hardware and can provide a recommendation for suitable AP components, before designing, constructing, analysing and refining a tower design.

WiFindUs proposed that the *thesis student's* research: WMNs, tower compliance measures, telecommunication mast and tower structures, and methods of achieving the tower's objectives. WiFindUs also summarised their requirements of the project; to design and construct a compact self-sufficient and rapidly-deployable tower that enables Wi-Fi based communications, which can be manufactured at a low-cost and has easily replaceable structural members.

1.5.3. Goals

In April 2013, the Flinders team and WiFindUs met to determine the exact goals and measurable objectives of the tower. The following section presents these goals and provides a brief outline of the rationale behind each objective.

The tower needs to be portable so that it can be carried by one person and meets all the major Australian airline's checked-baggage requirements for single items. To achieve this goal, three objectives were derived. The tower needs to be concealed in one 'carry-case'. The tower needs to have a mass less than the standard business baggage allowance (32kg), preferably less than the economy allowance (23kg), and the carry-case needs to comply with the linear geometric requirements of all Australian airlines. It is important to note that the geometric requirements were not provided by WiFindUs, and that this needed to be researched.

The tower needs to be rapidly-deployable in order for the network to be totally set-up in less than half a day. The objective is to enable 'well-trained constructors' to assemble the tower in less than 10 minutes.

The tower needs to be stable without anchors (able to freestand) so that it can stand 'freely' before guy-ropes are anchored either in ground or to surrounding structures. The objective is to ensure that the tower can resist a force applied to it at a factor of safety of two times above the maximum force identified from the Australian Standards research. The WiFindUs mechanical engineer recommended designing a water-filled ballast, similar to Figure 1.8.a., in order to increase the tower's stability.

Figure 1.8.a. Water-filled ballast example (UK Flag Company 2007), **b.** TFD enclosure example (Macedon Fencing Group 2008), **c.** Checked baggage requirements (Flight Centre 2013)

The tower needs to accommodate the Flinders team's proposed AP componentry. The objective is to fit all the components (excluding the battery) into a housing mounted to the top-most point of the tower. The housing needs to be waterproof, radio frequency transparent and stabilise all electronic components.

The tower needs to elevate the AP to a height which optimises coverage for a low-cost omni-directional antenna. The objective is to achieve a height between 6-8 metres. This elevation was deemed by the WiFindUs network engineer as a range high enough to optimise coverage, whilst flexible enough to allow the signal to successfully navigate most existing manmade structures.

The tower needs to minimise tower-tip deflection to ensure that the signal of the AP is not compromised. The objective is to achieve less than 1m horizontal displacement from the vertical axis. This displacement was deemed by Dr Paul Gardner-Stephen (telecommunications scientist) to be tolerable.

The tower needs to fit within three standard-sized temporary fence panels (TFPs), as illustrated in Figure 1.8.b. The objective is to fit the base of the tower within an equilateral triangle of sides 2.2m and allow for possible, but not reliant fixtures to the TFPs. The WiFindUs mechanical engineer advised that there is scope for fixing the structure to the TFPs to improve stability.

The tower needs to be low-cost to manufacture for obvious reasons. The objective is to manufacture the tower's structure for less than 250AUD from a combination of off-shelf hardware store purchasable parts and custom-made 3D printable parts. This amount was deemed by the WiFindUs mechanical engineer to be a reasonable target, and agreed to be a feasible amount by the WiFindUs accountant.

The tower needs to comply with deemed relevant Australian Standards for mast and tower structures. The first objective is to ensure that the structure and components have a minimum factor of safety (FOS) of two when it is being loaded as prescribed by the relevant standards. The second objective is to ensure that the structure meets its natural frequency requirement as prescribed by the standard.

The tower needs to comply with the relevant occupational health and safety (OH&S) legislations for general OMFs. The objectives for this requirement were not advised by WiFindUs and were required to be researched.

1.5.4. Division of Design & Analysis Tasks

The students of the Flinders team were allocated different members of the tower's structure in order to provide each student with multiple unique design projects. David Ilba will be conceptualising, analysing and refining the 'base/stabilisation mechanisms' and Greg Stevens will conceptualise, analyse, and refine the 'mast/ballast components'.

During the initial phases of the project the students worked together to generate engineering specifications for the tower and proposed six concepts, which in total encompass design features to satisfy all of the design objectives. Each student then designed three concepts independently, before collaborating once again to critically analyse all six concepts. For the remainder of the project the students worked independently to redesign, fabricate, and analyse their respective components. Table 1.2. outlines the components that each student worked on, and Figure 1.9. provides visual clarification of the division.

Table 1.2. Flinders team division of tasks

Classification	*David*	*Greg*
Modified off-shelf part	Composite legs	Mast
	Guy system	Ballast / case
	Tensioning mechanism	Electronics housing
Custom-made part	Leg tee-joiner	Tripod bracket
	Leg end-joiner	Mast bracket

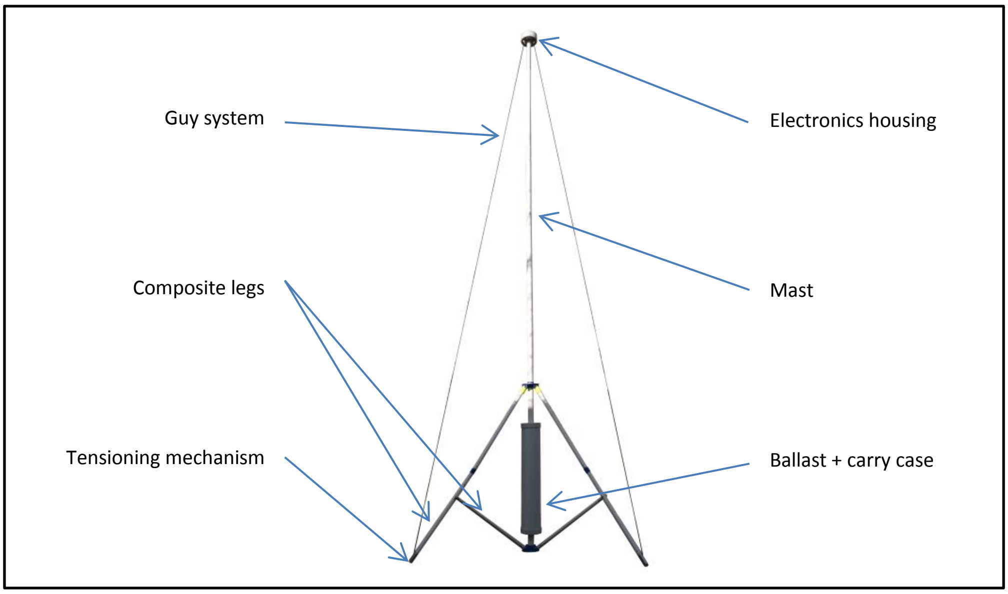


Figure 1.9. Stage 2 tower prototype

1.6. Thesis Outline

This thesis presents the design and analysis procedures undertaken in order to develop a final design for an 'open source Wi-Fi tower'. The thesis begins with a literature review in Chapter 2 that broadly examines the various small and large scale structures used in the telecommunication industry. Chapter 3 describes the towers design definition based on the project's customer requirements and engineering specifications, and concludes by presenting the preferred design concept realised through the project's conceptualisation and evaluation process. In Chapter 4 the Stage 1 (S1) design of the author's components are described and the S1 experimental analysis procedures are summarised. Chapter 5 presents a review of the MakerBot Replicator 2X 3D printing process, as well as an overview of tensile tests that were performed to determine the mechanical properties of Replicator 2X 3D printed polylactic acid (PLA) parts. In Chapter 6 the Stage 2 (S2) design of the author's components is described before the S2 experimental and theoretical analysis results are presented. These chapters are followed by a conclusion that summarises the performance of the final tower design, the project's 3D printed part successes, lessons learnt from the project, and the scope of future project work.

2. Chapter 2: Literature Review

Within the last few decades the need for tall structures has accelerated in parallel with the requirements for effective communication (Andersen 2009). The very rapid increases in telecommunication services and advancements in the field of communications technology have resulted in many different structures being designed to support a broad array of antennas (Sreevidya 2003). When it comes to the design-methods of large-scale telecommunication structures there are three common methods that exist; lattice-, solid-, and single-pole-structures (monopoles). In addition to these design-methods, there are two key telecommunication structure-types: self-supported towers and guyed-masts. However, when it comes to small-scale telecommunications structures the range of design-methods broadens and so does the range of structure-types.

The purpose of this literature review is to outline the range of design-methods and structure-types for both large-scale and small-scale telecommunication mast and tower structures. As means of ensuring that the final design conforms to industry standard practices; the large-scale telecommunication structures section focuses on reviewing structures commonly used in the telecommunication industry. In order to determine which design features best achieve the project’s design objectives; the small-scale telecommunication structures section focuses on reviewing compact structures that meet various project goals.

2.1. Large-scale Telecommunication Mast & Tower Structures

Telecommunication masts and towers are typically very tall structures relative to their cross-section. The key difference between a mast and a tower is that masts require stays (i.e. guy-ropes or guy-wires), from hereafter *guys*, to be structurally sound. There are many challenges for engineers when designing tall-and-slender structures. Many experts have stated that a guyed-mast is one of the most complicated structures to design and engineer (Andersen 2009). This is supported by the fact that there have been more documented instances of telecommunication mast collapses than tower collapses. The choice between using a mast or tower structure is usually determined by the planned location and budget of the project. Masts are more commonly used in open country regions due to low-cost and high spatial requirements, whereas towers are more prominent in urban areas due to reduced footprint requirements (Nielsen 2009).

A review of telecommunication masts and towers showed that there are three typical tower structures; lattice structures, solid structures, hollow (from here after monopole) structures, as shown in Figures 2.1.a.-.c. Lattice telecommunication structures are generally fabricated from steel angles, flats, or tubular products and come in a variety of different design configurations. While they provide a cost-effective ‘per height’ solution, they have lower structural rigidity than solid structures and thus are best suited for smaller payloads. Solid telecommunication structures on the other hand are usually fabricated from steel reinforced concrete and are less flexible in design configuration (typically of a cylindrical form). Monopoles are usually fabricated from large circular or angular sections with decreasing cross-sections telescoping up the structure. While they provide a high degree of mechanical rigidity in strong winds, considering that they are relatively expensive to build and cannot be easily transported, the remainder of this section will focus on lattice structures (ART 2013; Carl n.d.; Mer Telecom 2013). More specifically, the following sub-section will briefly describe the various lattice structures and provide examples of these types.

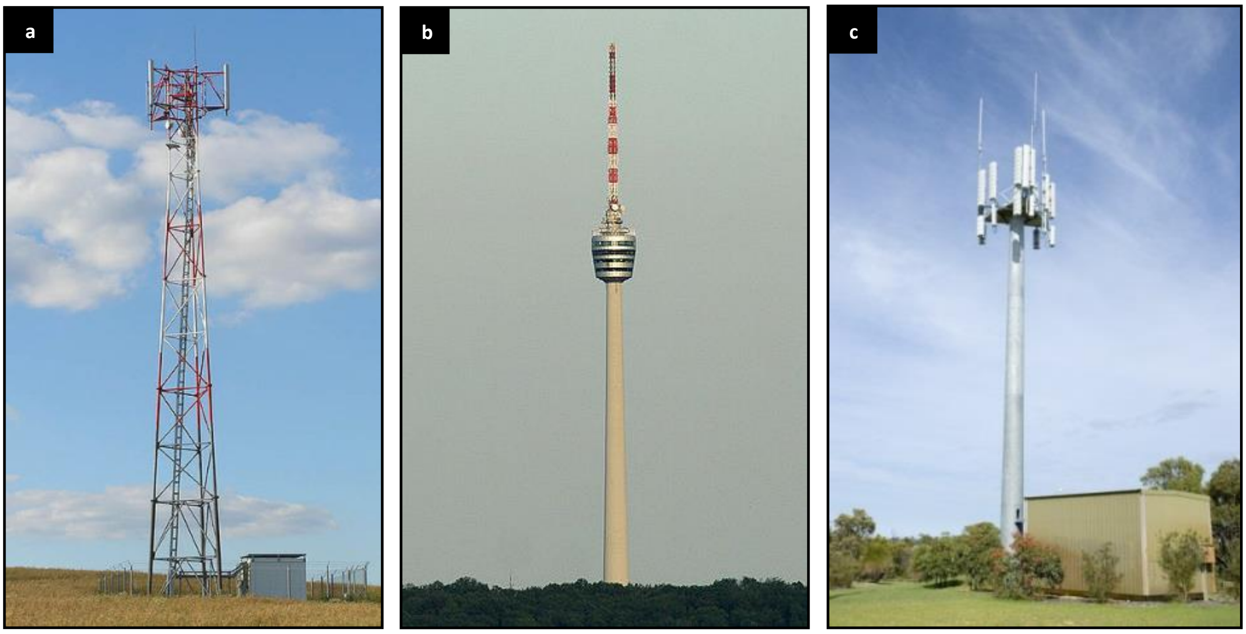


Figure 2.1.a. Lattice structure tower example (Jason 2010), **b.** Solid structure tower example (Blum 2006),
c. Monopole tower example (Perez 2012)

2.1.1. Lattice Structures

There are two common forms of lattice telecommunication structures. A lattice structured tower or otherwise known as a tower truss, is a 'self-supported' tower that stands free of guys. The other type of lattice structure is a guyed-mast, as has been previously discussed. Lattice telecommunication structures provide sufficient strength relative to the payload and environmental loads, they are more lightweight than solid structures, they have a low wind resistance, and are traditionally cheaper to manufacture than solid and monopole structures. Self-supported towers usually have triangular or square cross-sections, however it should be noted that circular cross-sections are not uncommon.

Self-supported lattice structure towers are an open and almost transparent form of construction, which makes them less visible from a distance than solid structure towers. These towers are generally constructed from flat, angular and tubular structural steels. When they are constructed of several sections which taper exponentially with height, similarly to the Eiffel Tower, the tower is said to be an 'eiffelated'. The eiffelated-design can 'almost match' the payloads of solid structure towers, and can sustain much higher loads than guyed-masts of a similar height. For these reasons, this makes self-supported towers an ideal choice when a low-cost, middle-of-the-range payload solution is desired. In contrast, while self-supported structures can range from anything up to 634m in height (Tokyo Skytree), unfortunately the maximum height of 'common-place' self-supported telecommunications structures seems to cap at approximately 150m (ART 2013; Carl n.d.; Mer Telecom 2013), which is significantly less than guyed-masts. Figures 2.2.a.&.c. respectively show the design of a typical square and triangular cross-section self-supported telecommunication towers.

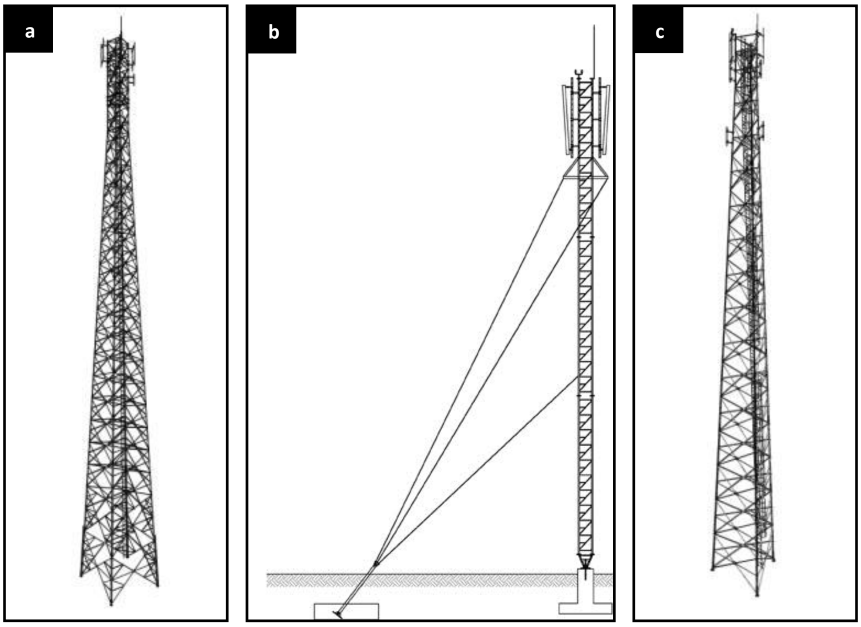


Figure 2.2.a. Self-support tower with a square cross-section (Mer Telecom 2013),
b. Guyed-mast with a square lattice structure (Mer Telecom 2013),
c. Self-support tower with a triangular cross-section (Mer Telecom 2013),

Guyed-masts are traditionally parallel-sided and are also usually constructed from triangular cross-sections. While they have a lower structural rigidity than self-supported towers, their cost and maximum height performances are greater. In additional to typically being constructed from flat and angular profiled members, guyed-masts are also constructed from structural grades of steel tube profiles. This construction type has the advantage of allowing cables and other components to be protected from the weather inside the tube, which subsequently improves the aesthetics of the structure. Guyed-masts are capable of achieving significantly greater maximum heights than self-support towers, ranging from anything up to approximately 300m depending on the manufacture (ART 2013; Carl n.d.; Mer Telecom 2013).

2.1.2. Summary of Lattice Structured Tower Designs

This section has merely been provided to briefly summarise the various lattice structured tower designs. Table 2.1. outlines some of the tallest large-scale telecommunication masts and towers that have been built with a lattice structured design and have been well documented.

Table 2.1. Well documented lattice structures

Lattice Type	*Structure Example*	
Height: 250m **Classification:** Guyed-mast **Beam-type (majority):** Tubular & flat steel **Stay-type:** Guy-wire **Cross-section:** Triangular		Rugby Radio Station (Man 2005)
Height: ~200m **Classification:** Pyramid-like-tower **Beam-type (majority):** Tubular, flat & angular steel **Cross-section:** Square		Penza TV Tower (Shelyapin 2011)
Height: 324m **Classification:** Eiffelated-tower **Beam-type (majority):** Flat & angular steel **Cross-section:** Square		Eiffel Tower (Benh 2009)
Height: ~332m **Classification:** Eiffelated-tower **Beam-type (majority):** Tubular & angular steel **Cross-section:** Square		Tokyo Tower (Keiows 2011)
Height: 624m **Classification:** Pyramid-like-tower **Beam-type (majority):** Tubular & angular steel **Cross-section:** Triangular to Circular		Tokyo Sky Tree (Kakidai 2012)

2.2. Small-scale Telecommunication Mast & Tower Structures

This section focuses on reviewing compact structures that meet various project goals in order to determine which design features best achieve the various performance objectives. The reviewed performance objectives include: structure height, mass of complete system, time to setup (deployment), and cost of the unit.

2.2.1. Lightweight Units

Although lattice mast and towers have traditionally been manufactured from various steels, today we are seeing an increase in the number of towers being manufactured from fibreglass, carbon fibre, aluminium and other composite materials because of their lightweight characteristics. This increase is largely due to the fact that advancements have been made in manufacturing composite material structures, which has ultimately reduced the cost of manufacturing these structures. Another contributing factor is the ease of transport and erection associated with lightweight structures, relative to steel structures (Aravinthan et al. 2008; Clarke 1996).

Fibre composite structures also have the advantage of being ‘flexible in design’; whereby composite materials are usually selected to ‘best suit’ the intended application. In 2008, Aravinthan et al. designed and developed an advanced composite windmill structure, as part of a study to determine the challenges that engineers face when designing and developing fibre composite structures. The study found that while composite materials have huge potential, structural design engineers face huge challenges when using them for mast and tower structures. Currently there are no specific Australian design standards or guidelines, and there is limited documentation available to review the performance of such materials (Aravinthan et al. 2008). Furthermore, many manufacturers have limited experience in a wide range of composite structures, which has also proven to be a hindrance. Aravinthan et al. (2008) believe that forming an alliance with the manufacturer is essential to designing a successful structure and gaining approval by regulatory authorities, such as the LABC.

Although many compact telecommunication tower structures claimed to be lightweight, there was really only one mast found that was specifically designed to be lightweight. The *GeoStrut* (company and product name) telescopic mast is an excellent example of a lightweight guy-mast that has been achieved through utilising composite materials. As per the words of GeoStrut; “the GeoStrut telescoping guyed-mast provides an affordable carbon-fibre option for rapid deployment and mobile situations. GeoStrut’s unique, patent-pending, open lattice design is engineered for peak strength to weight performance” (GeoStrut 2013). As shown in Figure 2.3.b., the *GST05* would be GeoStrut’s solution to WiFindUs’ proposed application, predominantly based on mast height. Table 2.2. outlines how the GST05 performs in the key areas of WiFindUs’ proposed tower.

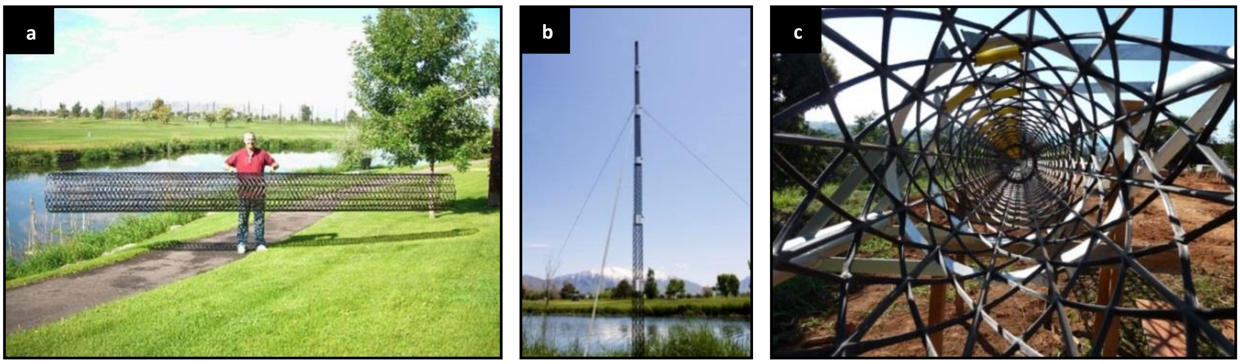


Figure 2.3.a. GST40 mast section, **b.** GST05 erected, **c.** GST40 cross-section (GeoStrut 2013)

Table 2.2. Performance of lightweight unit (GeoStrut 2013)

Characteristic	*GeoStrut Unit (GST05)*
Height (m)	5
Mass (kg)	18
Set-up (mins)	10
Cost (AUD)	3250

*table notes: data taken from GeoStrut (2013)

Although the *GeoStrut* has been claimed by the company to be an affordable option, the cost of this solution is estimated to be far in excess of WiFindUs' budget. Furthermore, the *GeoStrut* requires guy-wires to be structurally sound, and therefore does not meet client's tower requirement for being structurally sound without an anchorage mechanism.

2.2.2. Freestanding Units

Another key project goal is to design a tower which has the ability to 'free-stand free of guys and anchors'. While there were many small-scale towers identified which met this objective, none of them met all the other project objectives. As shown in Figure 2.4.a.&.b., and outlined in Table 2.3. even the most appropriate freestanding towers were too heavy, too large, and too expensive for the purposes of the project. Of these two units, the VMCT13 has the best overall performance as a freestanding tower.

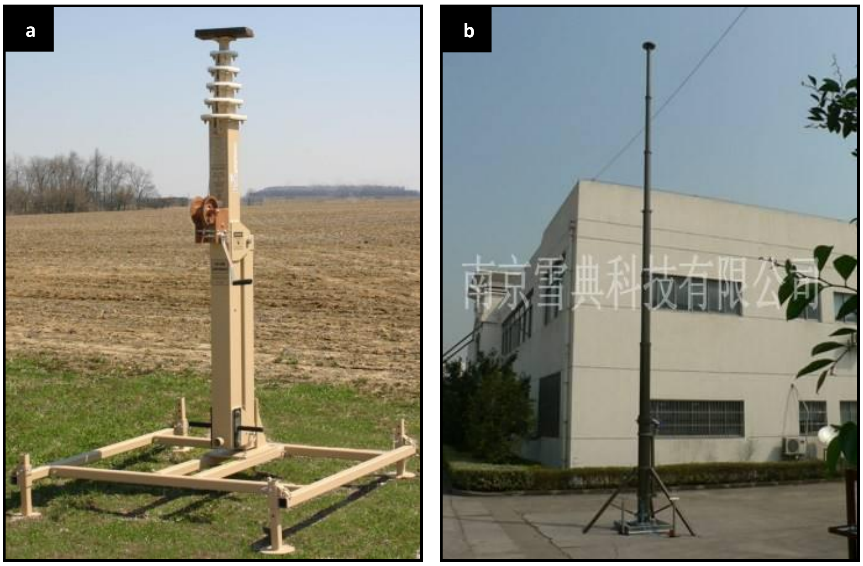


Figure 2.4.a. Floatograph unit (EM50): Freestanding telecommunication tower (Floatograph Technologies 2013), **b.** NXL unit (VMCT13): Freestanding telecommunication tower (NXL 2012)

Table 2.3. Performance of freestanding units

Characteristic	*Floatograph Unit (EM50)*	*NXL Unit (VMCT13)*
Height (m)	15	13
Mass (kg)	unspecified	120kg
Set-up (mins)	unspecified	unspecified
Cost (AUD)	3800	1600

*table notes: Data taken from (AP Landing 2010; ART 2013; Floatograph Technologies 2013)
Costs were converted from USD to AUD on 22 October 2013

2.2.3. Rapidly-deployable Units

Through reviewing many rapidly-deployable masts and towers, it was realised that the majority of the existing market is made up of guyed-masts fixed to trailers. Since the structure can stand-alone they are classified as towers. As shown in Figures 2.5.a.&.b. many of the trailer-based masts are significantly oversized for the purposes of the project. In addition to the trailer-based masts, a tow-bra-based design was found with similar performance to the trailers.

Unfortunately, in a similar manner to freestanding towers, all the reviewed rapidly-deployable units are too heavy, too large, and too expensive. Table 2.4. outlines the performance of the rapidly-deployable units seen in Figures 2.5.a.-.c. Of these three units, the HDCA15 has the best overall performance as a rapidly-deployable unit.

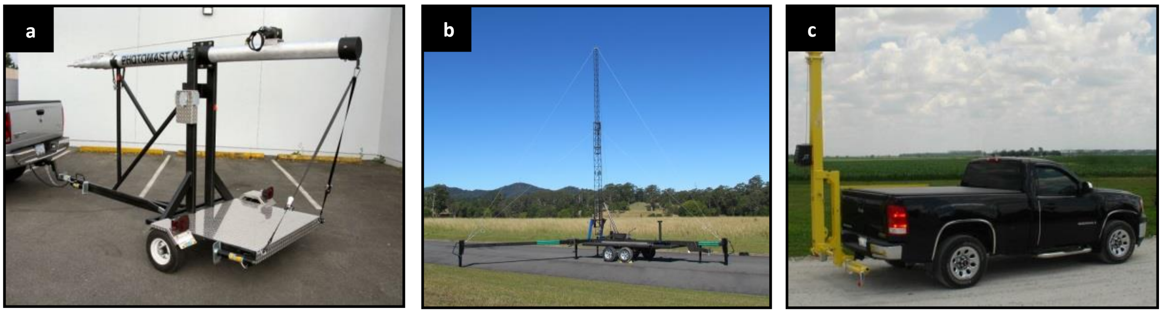


Figure 2.5.a. AP Landing unit (HDCA15): Rapidly-deployable telecommunication mast (AP Landing 2010),
b. ART unit (RDTM30): Rapidly-deployable telecommunication mast (ART 2013),
c. Floatograph (EM10T): Rapidly-deployable telecommunication mast (Floatograph Technologies 2013)

Table 2.4. Performance of rapidly-deployable units

Characteristic	*AP Landing Unit (HDCA15)*	*ART Unit (RDTM30)*	*Floatograph Unit (EM10T)*
Height (m)	15	30	10
Mass (kg)	unspecified	unspecified	unspecified
Set-up (mins)	30	60	unspecified
Cost (AUD)	7800	12900	3500

*table notes: Data taken from (AP Landing 2010; ART 2013; Floatograph 2013)
Costs were converted from USD to AUD on 22 October 2013

2.2.4. Portable Units

A review of portable telecommunication masts and towers showed that most of the designs are very similar. As shown in Figure 2.6.a., most units are guyed-tent-pole-like systems with aluminium mast sections and guy-ropes (not guy wires). Although this design meets most of the project objectives, since they are unable to free-stand they are unfortunately still not completely suitable. Further research found a freestanding portable structure, as shown in Figure…………, however the tower proved to be too expensive and short for the purposes of the project. Table 2.5. outlines the performance of these portable units. Of the two units, the PTM15 has the best overall performance as a portable unit.

Figure 2.6.a. Go Vertical unit (PTM15): Portable telecommunication mast (Go Vertical 2013),
b. Super Antenna unit (PT3): Portable telecommunication mast (Super Antenna 2013)

Table 2.5. Performance of portable units

Characteristic	*Go Vertical Unit (PTM15)*	*Super Antenna Unit (PT3)*
Height (m)	8	5
Mass (kg)	15	unspecified
Set-up (mins)	20	5
Cost (AUD)	230	785

*table notes: Data taken from (Go Vertical 2013; Super Antenna 2013)
Costs were converted from USD to AUD on 22 October 2013

2.2.5. Low-cost Units

Although many compact telecommunication tower structures claimed to be low-cost, apart from the Go Vertical unit (PTM15) which cost 230AUD, there was really only one mast that was classified as being low-cost according to the project goal (250AUD). In 2011, a team of structural engineers from a United States Air Force (USAF) squadron constructed a 6.7m guyed-mast, from PVC pipe and poly-chord rope, as shown in Figure 2.7. The structure was designed to be used as a telecommunication mast to supplement Civil Air Patrol (CAP) communications in southern Texas. The design brief was to fabricate a low-cost, telecommunications mast that can extend to at least 6m, and can be built entirely from local hardware store supplies (Carrales 2011). This design project appears to not only fulfil the low-cost performance objective, but also seems to have the best overall performance of all the structures reviewed in this section. Table 2.6. outlines the performance of this structure.

Figure 2.7. USAF unit: Low-cost mast (Carrales 2011)

Table 2.6. Performance of low-cost unit

Characteristic	*USAF Unit (LC)*
Height (m)	6.7
Mass (kg)	unspecified
Set-up (mins)	30
Cost (AUD)	163

*table notes: Data taken from (Carrales 2011)
Costs were converted from USD to AUD on 22 October 2013

2.3. Telecommunication Structure Design Principles

Telecommunication masts and tower structures have been studied by many researchers over the years, and with continuous break-throughs in various technologies, this area of study continues to be the focus of many research efforts (Galeb et al. 2013). Sheppard (1972) developed a dynamic programming method to determine the minimum cost for a structurally sound transmission tower. Green (1985) studied the minimum weight sizing of guyed antenna towers, and noted the difficulties with using non-linear structural analysis techniques. Jalkanen (2007) studied tubular truss optimisation (based on topology, shape and size) using heuristic multipurpose algorithms, and examined the conflict between mass and stress. Galeb et al. (2013) optimised the design of standard transmission towers subjected to wind, seismic and self-weight loads, and investigated the optimal design based on the Hooke and Jeeves method. At this stage it should be noted that there is an abundance of literature available on this methodology if the reader wishes to review this methodology.

There are a number of factors that structural design engineers need to consider before starting the analysis and detailed design of telecommunication mast and tower structures. Ulrik Andersen, the Chairman of International Association for Shell and Spatial Structures (IASS) Working Group discusses the unfortunate common problem within the telecommunication mast and tower manufacturing industry, of clients contracting engineers who do not completely understand all the design aspects of these structures. The IASS have outlined a checklist for structural design engineers to review before designing a structure of this type (Andersen 2009). For the purposes of the thesis, the following lists items from this checklist which were deemed relevant to the proposed tower:

- Mean antenna height
- Directions for the various directional antennas
- Wind drag of the structure itself without ice and with ice if feasible
- Size, weight and disposition of all feeders and cables
- The need for all-weather access to some of the antennas
- Besides the known antenna configuration the possible future extension should be defined
- The degree of security required
- The available ground area and access to the site
- The geological nature of the site
- The cost of the structure
- The cost and implications of future maintenance or structural replacement
- Any special planning considerations imposed by statutory bodies
- The aesthetic appearance of the structure

When it comes to designing the actual structure, Freeman (2007) provides a comprehensive guide to the specific requirements of the antenna type selection and position. 2EN (2012) have documented the design of their lattice tower and provide a detailed description and recommendation for how to apply the boundary and loading conditions during FEA simulations of lattice mast and tower structures.

2.4. Summary

This literature review has looked at the various large and small-scale mast and tower structures that are currently utilised by the telecommunication industry. The section on large-scale telecommunication structures touched on the various design-methods and structure-types of mast and towers (i.e. lattice-, solid-, monopole-structures), before providing a detailed discussion on lattice structures. This helped the project team become aware of the types of structures that are acceptable within the telecommunication industry.

The section on small-scale telecommunication structures looked at lightweight, freestanding, rapidly-deployable, portable, and low-cost mast and tower units. This found that carbon fibre and aluminium is predominantly being used for structural members of masts and towers in order to make them lightweight. It also found that both freestanding and rapidly-deployable units are too expensive, heavy and large for the purposes of the project. However reviewing these structure-types did present a few design-methods which would help achieve their respective project goal. Researching portable units found that they are mostly dependent on guys, and when not, they are too expensive. Lastly, researching low-cost units showed that there is a 'gap in the market' for a low-cost (less than 250AUD) freestanding telecommunication tower if the project team is willing to use PVC for the structural members.

While the literature review showed that there is an abundance of literature on the optimisation of large-scale traditional telecommunication mast and tower structures, when it comes to small-scale telecommunication structures there is a shortage of literature. In fact, most of the existing literature comes from the product manufacturers and therefore has a strong bias towards the performance of their products.

The following chapters aim to address this gap in research by providing a detailed definition of the engineering requirements for designing small-scaled telecommunication structures. This will include: a review of the relevant Australian Standards for these structures, as well as a detailed discussion on the analytical procedures and documentation required in order to achieve certification (by an external structural engineer) of a tower design to be used in the public domain.

3. Chapter 3. Design Definition & Conceptualisation

Before starting the analysis and detailed design of telecommunication mast and tower structures, it is very important for engineers to establish the basic requirements for the structure (Andersen 2009). This section provides an overview of the customer requirements and engineering specifications that were used to aid with the conceptualisation and evaluation of the tower through the use of the Quality Functional Deployment (QFD) method, and Pugh's decision-matrix methodology. Key specifications highlighted through QFD were used to create six unique concepts, which together reflect an array of solutions for each of the most important customer requirements. The chapter concludes with a detailed description of the 'preferred design' as determined through Pugh's methodology.

3.1. Customer Requirements

Ensuring that a product's customer requirements are met is essential to the development of a quality product. The following sections identify and discuss the key customer requirements for the project, which have been identified as significant in the performance of the proposed tower structure. While a detailing of the complete customer requirements will take place in Section 3.3., the following sub-sections will enlighten the reader on the rationale behind some the project's key design decisions. The following sub-sections provide discussions on: accessible components, lightweight beams, outdoor designs, and radio frequency transparent housings.

3.1.1. Accessible Components

High accessibility of replacement parts is a core performance objective of the tower. It has been advised by the client that the majority of the off-shelf components, need to be purchasable from all the major Australian hardware stores. Although plumbing stores, steel suppliers, fastener stores etc. could potentially supply the required components, since it was deemed that they are 'unable to provide the majority' of the required components unlike traditional hardware stores, these stores were neglected from the following review. Furthermore, since 3D printing technology has become affordable (~3000AUD) to 'middle class hobbyists' and Flinders University have two such printers to which students have access , 3D printing has been classed as an accessible method of manufacturing any custom-made parts required for the project. This section aims to provide an overview of the various structural hollow-section beams that are purchasable from major Australian hardware stores, as well as briefly discuss why 3D printing technology has become 'accessible to the masses'.

A review of the 'mainstream Australian hardware stores' was performed to identify parts which could be utilised as hollow-section beams for the tower structure. For the purpose of the review, in order to be classified as a *mainstream Australian hardware store*, multiple retail outlets need to be located in each of the major capital cities where the Soundwaves festivals play (i.e. Brisbane, Melbourne, Perth, Adelaide, Sydney). The following stores met this classification: Bunnings, Home, Masters, Mitre10, and Stratco. Table 3.1. outlines the standard range of products that can be purchased from these hardware stores and used as hollow-section beams. The review highlighted that all stores stock standard steel hollow-section (i.e. CHS, RHS and SHS), as well as copper-, HDPE- and PVC pipe.

Table 3.1. Hollow-section beams (Bunnings 2013; Home 2013; Masters 2013; Mitre10 2013, Stratco 2013)

Company	Pipe / CHS					RHS / SHS			Extruded					Folded		
	Polyethylene (HDPE)	*Polyvinyl Chloride (PVC-DWV)*	*Polyvinyl Chloride (PVC-PN)*	*Galvanised Steel*	*Copper*	*Galvanised Steel*	*Painted Steel*	*Stainless Steel*	*Circular-section*	*Square-section*	*C-section*	*I-section*	*Other 'structural' section*	*C-section*	*S-section*	*Other 'structural' section*
Bunnings	X	X	X	X	X	X	X		X	X	X		X	X		
Home	X	X	X	X	X	X	X			X						
Masters	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Mitre10	X	X	X	X	X	X	X			X	X		X			
Stratco	X	X	X	X	X	X	X	X		X	X		X	X	X	X

With short manufacturing cycle, low manufacturing costs, and a plethora of manufacturers adopting this technology, 3D printing has emerged as a key 'accessible manufacturing process' (Zhu et al. 2013). Today 3D printing methods or otherwise known as additive manufacturing methods, are commonly used to create prototypes and are even used to print/fabricate commercial products. Molina et al. (2012) describe 3D printing as a technology which has huge potential to dramatically increase the performance of components due to the low-cost and accessible nature of the process.

The 3D printing industry has come a long way, particularly in the last decade. Recently multi-material 3D printing, utilising flexible elastomers and stronger rigid plastic has become possible (Molina et al. 2012). Considering the increasing accessibility of this technology and the fact that multi-material 3D printing has the potential to create components with high structural rigidity, it was decided by the project team that this process should be utilised to manufacture custom-made parts.

Given that Flinders University have two 3D printers, for the purpose of the thesis, this manufacturing process has been regarded as being 'highly accessible'. The specific 3D printers that the Flinders University own are manufactured by MakerBot, and named *Replicator 2/2X Experimental 3D Printer*, as shown in Figure 3.1.a. These printers are capable of printing parts (28.4x15.5x15.2cm - 6691cm^3) from thermoplastic filaments, such as acrylonitrile butadiene styrene (ABS) or polyvinyl alcohol (PVA) for a cost of $48/kg (MakerBot 2013).

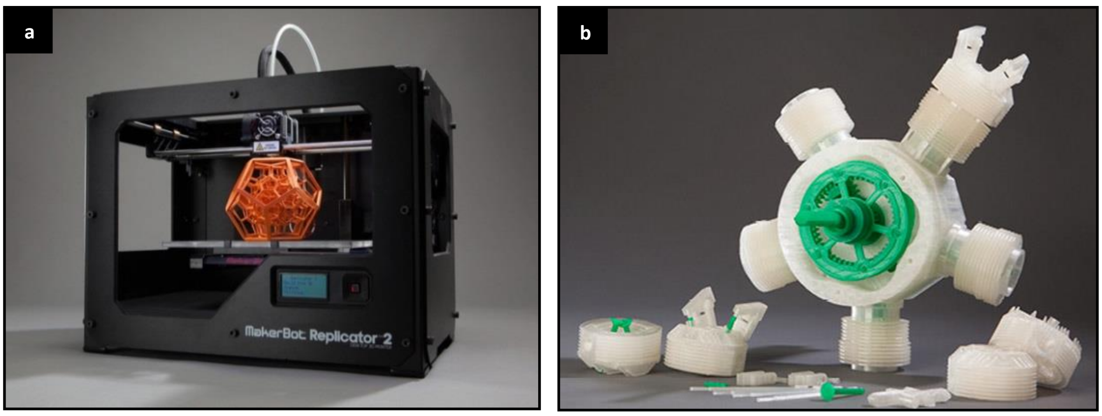


Figure 3.1.a. MakerBot: *Replicator2*, **b.** MakerBot: *Replicator2X* co-printed part (MakerBot 2013a)

Although the *Replicator2* can only print with one filament at a time, the *Replicator2X* has an additional print head which provides users with the opportunity to co-print with different plastics. As previously discussed, this creates the unique ability to print 'structural sections' of a part with a high stiffness plastic to increase the strength and rigidity of the part, while printing 'less important sections' with a more sustainable plastic.

Willans (2013) validates the quality of the MakerBot '2 series' by discussing the manufacturers collaboration with *giant* mobile phone manufacturer, Nokia. Nokia provided MakerBot with the specifications for their *Lumia* 820 and *Lumia* 520 covers, so that MakerBot can provide Nokia customers with 'generic case files' to be adapted and printed by the customers.

3.1.2. Lightweight Beams

In order to minimise the total weight of the tower, the structure needs to be manufactured from lightweight beams. While the most obvious solution is to use hollow-section beams manufactured from lighter materials (i.e. alloys, composites, plastics), it is important that the beam selection does not compromise the structural integrity of the tower. A review of lightweight beams revealed that there are two common methods used to achieve 'structurally sound' lightweight beams. The first method involves the use of 'internal supports' and the second utilises composite materials.

There are two common processes used to manufacture internally supported beams. The first and typically preferred method is 'extrusion forming', a process used to create objects with a fixed cross-sectional profile. Oberg et al. (2000) describes this process as a material being pushed or drawn through a die of desired cross-section. The main advantage of this process over other manufacturing processes is its ability to create complex cross-sections since the material only encounters compressive and shear stresses, which therefore permits the use of brittle materials. Extrusion forming is also highly regarded for the excellent surface finish which it is capable of achieving.

The second common process used to manufacture internally supported beams is 'material folding'. This method basically increases the beam's strength and rigidity through folding the sheet material at different angles to each other, thus increasing the cross-sectional stiffness of the structure. In 1997, Perkins et al. patented a 'lightweight structural beam' (LSB), as shown in Figures 3.2.a.&.b. Perkin's design is formed from a single sheet of cardboard and a series of folds. A number of folds are pre-scored on the sheet of cardboard, forming a diagonal panel, a securable panel on one side of the diagonal panel, and a plurality of structural panels on the other side of the panel. The beam is assembled by folding the structural panel in a second direction using a rolling action, thus simplifying the assembly of the beam. The beam has double-walled sides that provide strength in the vertical direction. The beam is provided with interlocking tabs which prevent the beam from dissembling and avoids the need for adhesives (Perkins et al. 1997).

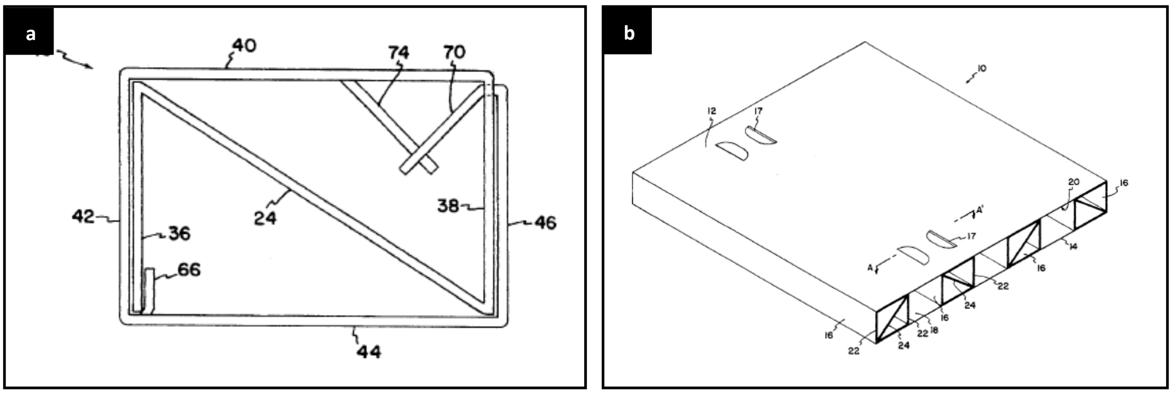


Figure 3.2.a. Folded LSB cross-section, **b.** Folded LSB isometric (Perkins et al. 1997)

As already presented, the second common method of creating a structurally sound lightweight beam is to use composite materials. Composite materials, shortened to composites, are materials made from two or more constituent materials with significantly different physical or chemical properties, that when combined, produce a material with characteristics different from the individual components (Autar 2005). It is important to realise that the individual components remain separate and distinct within the finished structure.

Although composite beams are widely used in many structures today, for a long time after their benefits were realised, they could not penetrate the market due to their high-cost of manufacture. While the automotive industry is not especially relevant to this project, there is value in reviewing the evolution of composite beams in this industry, since 'in general' this industry is at the forefront of new technologies.

Composite beams made their first major appearance in the automotive industry in the 1980s (Autar 2005). In 1989, Wycech et al. patented a 'lightweight composite automotive door beam and manufacturing method', as shown in Figure 3.3. The lightweight, composite beam for reinforcing a vehicle door was comprised of an open channel-shaped metal member having a longitudinal cavity filled with a reinforcing polymeric material, which can be a thermoset or thermoplastic resin-based material.

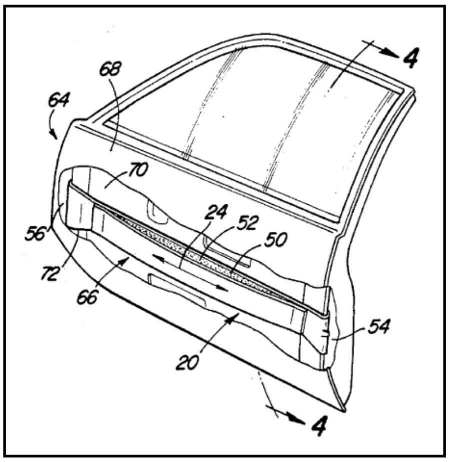


Figure 3.3. Composite LSB isometric (Wycech et al. 1989)

Due to the increasing demands of the automotive industry, in 2003 Wycech et al. started utilising structural foam as a reinforcing medium for automotive hollow-sections instead of thermoplastics. Wycech et al. (2003) later found that by not filling a section solid, but rather using a local reinforcement, and laminating a section by use of a polymer layer captured between an inner layer, this optimises strength and weight performances.

In 2013, Kim et al. released a lightweight composite beam onto the market consisting of aluminium space frame (ASF) with carbon fibre reinforced plastic (CFRP). This beam was designed to act as a lightweight vehicle body structure for electric vehicles (EVs). This design also proved to reinforce the EVs structural members, which subsequently obtained a high score for the 'crash worthiness' standard test category (Kim et al. 2013).

3.1.3. Outdoors Design

In order to maximise the durability of the tower, the structure needs be resistant to, or minimally impacted by environmental factors. Given that the tower will be deployed in Australia, the three key 'climatic factors' are rainfall, sunlight and wind loads. As discussed in Section 3.2.2., the wind loads will be accounted for in accordance with the relevant Australian Standards. A brief review was undertaken to understand the extent to which rainfall and sunlight can degrade the structural properties of the materials identified as potential hollow-section beams from Section 3.1.1.

The two obvious degradation mechanisms realised from reviewing the accessible beams were: corrosion of steels and ultraviolet (UV) radiation deterioration of plastics and timbers. In colloquial usage, the term *rust* is applied to red oxides, formed by the reaction of iron and oxygen in the presence of water or air moisture. Given sufficient time, oxygen, and water, any iron mass will eventually convert entirely to rust and disintegrate (Gräfen et al. 2000). To ensure that the tower does not rust, the obvious solution is to use alloys, plastics or timbers instead of steel beams. Alternatively, the tower could be manufactured from steels with protective coatings. Gräfen et al. (2000) discusses the process of rust and provides many ways to reduce corrosion. It is recommended that the reader consults this text if they wish to expand their knowledge of this degradation mechanism. It should also be noted that there is an abundance of literature on corrosion of various grades of steel.

The second degradation mechanism which needs to be accounted for is UV radiation. Most plastic materials are not UV stable to start with, other than 'acrylic' which is invisible to UV (Hess 2013). All other plastics need 'stabilisers' to give it protection from the UV segment of the sun's spectrum. Many plastic materials, if given the proper additives, can be used in direct sunlight for 10-15 years (City Plastics 2010).

When UV attack occurs, plastics generally tend to have a colour shift, become chalky on the surface, and crack in weaker regions. There are a number of methods used in industry to reduce this problem. The addition of carbon black to the polymer will usually absorb most UV radiation. Chemical inhibitors are available for certain plastics, which improve the UV resistance. Paint (acrylic-based) and silicone coatings can also be used to completely cover exposed surfaces to sunlight (Hess 2013).

It is important to select plastics according to the intended use, especially when the application involves exposure to UV radiation. High-density polyethylene (HDPE) is widely regarded as being one of the best materials for long-term outdoor use, if given the proper additives (Hess 2013). However if the application is 'more mechanical-based', then Hess (2013) recommends the use of ABS, acetal, polycarbonate, PVC or noryl. Table 3.2. was generated to outline the suitability of using the 'accessible plastics', identified in Section 3.1.1. for structural beams. This table was based on a reputable Adelaide plastics manufacturer's recommendation.

Table 3.2. Summary of the suitability of using accessible plastics for structural beams (City Plastics 2010)

Material	*UV Comments*	*Manufacturers Comments*
Acrylonitrile Butadiene Styrene (ABS)	ABS is not suitable for outdoor applications because of its poor UV resistance	UV stabilised material can be manufactured, subject to minimum quantities of about 1000 kg
High-density Polyethylene (HDPE)	Un-pigmented (natural) HDPE will degrade upon exposure to sunlight. However when carbon stabilisers are added, HDPE becomes arguably the most UV stable plastic available	UV stabilised HDPE is available
Polyvinyl Chloride (PVC)	Standard PVC is better under UV than most plastics, then when stabilisers are added, PVC becomes one of the most UV stable plastics available	UV stabilised PVC is available

3.1.4. Radio Frequency Transparent Housing

The last, but definitely not least important customer requirement requires the 'electronics housing' material to be radio frequency (RF) transparent, for obvious reasons.

Objects can exhibit a wide range of behaviour characteristics in relation to RF that is depend on their material composition. An object can be RF transparent, RF reflecting, or RF absorbing. Most objects exhibit some combination of the three. There are two common material types with regards to RF transparency however; metallic types and liquid types (Sweeney 2005). Metallic items are the most likely to be RF reflecting. Metallic housings generally either shield or detune antennas from their resonance frequency, and ultimately can block the signal from entering or exiting the housing. Liquid materials are the most likely to be RF absorbing. They tend to reduce the strength of the original signal by absorbing or dissipating the power, which ultimately 'eat ups' the potential energy that antennas require to function properly (Sweeney 2005). Table 3.3. shows the behaviours of different types of materials and their effects on RF communications.

Table 3.3. Material effects on RF communications (Sweeney 2005)

Material Composition	*Effects on RF Signal*
Corrugated cardboard	Absorption from moisture
Conductive liquids	Absorption
Glass	Attenuation (weakening)
Groups of cans	Multiple propagation effects; reflections
Human body / animals	Absorption; detuning; reflection
Metals	Reflections
Plastics	Detuning (dielectric effect)

This brief review has shown that plastics are definitely a better choice for the electronics housing than metals. However, it is advised that a simple RF transparency test is performed on the proposed housing to ensure that the material choice has a negligible effect on the quality of the Wi-Fi radio signal. Cactus Intertie Systems (2013) recommend placing a sample of the material in a microwave oven (since they operate at approximately 2.4GHz) along with a cup of water, to test the RF transparency of the material. When the water starts boiling, carefully check the temperature of the plastic sample. If the plastic burns your hand, the material is 'not very RF transparent', whereas if it is only slightly warm or still cool then it is considered as being RF transparent (Cactus Intertie Systems 2013).

3.1.5. Recommendation for Tower Structure

This brief review of material requirements has indicated that plastic components should be used for the majority of the structure; due to their high accessibility, ability to be protected from environmental factors, and ability to allow a Wi-Fi signal to pass through better than many other materials. It is recommended that PVC is utilised for the structural beams instead of HDPE, due to its higher structural rigidity. It was deemed appropriate to complete a quick review of the most accessible PVC brands, since the mechanical properties of these brands needed to be reviewed during the next phase of the project. Table 3.4. outlines the brands of PVC that each of the major Australian hardware stores stock.

Table 3.4. PVC brand accessibility (Bunnings 2013; Home 2013; Masters; Stratco 2013)

Store	*Brands*
Bunnings	Holman, Vinidex, Iplex
Home	Vinidex
Masters	Holman, Vinidex
Mitre10	Vinidex, Iplex
Stratco	Vinidex

3.2. Engineering Specifications

In order to ensure that the product's customer requirements are met, it is essential to develop quality engineering specifications. For the project this meant that the Australian Standards were used to generate various 'loading scenarios', so that a stress analysis could be performed on the overall structure and individual parts. It also meant that outdoor music festival (OMF) OH&S legislations were reviewed in regard to the engineering documentation requirements for the tower, and to help develop OH&S specifications for the tower. A brief review of the Australian Communication and Media (ACMA) Wi-Fi requirements was undertaken to determine operational frequency targets for the accesspoint electronics, and lastly the regulations of all the major Australian airlines were reviewed to generate specifications for the 'packaged tower'.

3.2.1. Australian Standards Review

A detailed review of the Australian Standards was undertaken in order to ensure that the tower complies with all the relevant standards. This included reviewing any standard which mentioned: design or analysis of telecommunication towers, masts, portable structures, rapidly-deployable units or erection techniques, freestanding units, light poles, and Wi-Fi device mounts.

3.2.1.1. Reviewed Standards

Although some standards initially appeared to hold relevance through their title, upon closer examination, many proved to be irrelevant to the proposed tower structure. Table 3.5. provides an overview of the Australian Standards that were reviewed, and Appendix D provides a more detailed description of the scope of these standards. It should be noted that there were no Australian Standards found specific to Wi-Fi structures, nor portable structures.

Table 3.5. Reviewed Australian Standards

Standard	*Title*
AS1170.1	SAA Loading Code, Part 1 - Dead and Live Loads
AS1170.2	SAA Loading Code, Part 2 - Wind Forces
AS1417	Receiving Antennas for Radio and Television in the Frequency Range 30 MHz to 1 GHz Construction
AS1798	Lighting poles and bracket arms - Preferred dimensions
AS2550	Cranes Hoists and Winches - Safe Use Self-Erecting Tower Cranes
AS3995	Design of Steel Lattice Towers and Masts
AS4268	Radio Equipment and Systems - Short Range Devices
AS4676	Structural Design Requirements for Utility Services Poles

3.2.1.2. Validation of Review

In order to ensure that all possible Australian Standards had been reviewed, the author cross-referenced the relevant standards with a reputable Australian telecommunication tower manufacturer and installer. Although research highlighted that there are many telecommunication tower manufacturers and installers in Australia, it appears that Australian Radio Towers (ART) are one of the most reputable companies. ART started manufacturing masts and towers in 1973, and have installed over 4000 units since then (ART 2013). Furthermore, ART claim to have installed masts from just about every manufacturer in Australia, which has led to a comprehensive understanding of the requirements for designing, manufacturing, and installing many different styles of masts and towers. ART also claim that they design and engineer their masts and towers to comply with the latest Australian Standards and have their designs independently reviewed by specialist structural engineers to the Australian design codes as outlined in Table 3.6.

Table 3.6. Australian Standards that ART masts and towers comply with

Standard	*Title*
AS1170.1	SAA Loading Code, Part 1 - Dead and Live Loads
AS1170.2	SAA Loading Code, Part 2 - Wind Forces
AS1891	Industrial Fall Arrest Systems and Devices
AS3995	Design of Steel Lattice Towers and Masts
AS3600	SAA Concrete Structural Code
AS4100	SAA Steel Structures Code

3.2.1.3. Summary of Relevant Standards

There were several Australian Standards to which the tower needs to comply. These standards are outlined in Table 3.7. For a more detailed description of the scope of the standards please consult Appendix D It is important to realise that standards: AS1891, AS3600, AS4100, were omitted from the review, since the proposed tower will need to utilise light-weight materials and will not be climbed upon.

Table 3.7. Relevant Australian Standards

Standard	*Title*
AS1170.1	SAA Loading Code, Part 1 - Dead and Live Loads
AS1170.2	SAA Loading Code, Part 2 - Wind Forces
AS3995	Design of Steel Lattice Towers and Masts
AS4268	Radio Equipment and Systems - Short Range Devices
AS4676	Structural Design Requirements for Utility Services Poles

3.2.2. Structural Requirements

Through reviewing the relevant Australian Standards for mast and tower structures, the design load requirements, several static and dynamic analysis methods, and performance targets were realised. These methods and targets have provided a guide for the structural requirements of the tower. As discussed in Section 3.2.1.3. there were five Australian Standards deemed to be relevant to the design of the proposed tower. The applicable sections of these standards relate to wind load and first mode natural frequency analysis.

Through a more detailed review of the relevant standards, various ‘overlaps’ and design assumptions were realised. It was discovered that the design and live loads from AS3995 were referenced from AS1170.1, and that the wind load requirements from AS3995 were referenced from AS1170.2. Furthermore, in order to use these standards to develop engineering specifications, it needs to be assumed that the tower has an equilateral-triangle or square plan lattice structure, with circular or square members. It also needs to be assumed that the force coefficient shall be constant for any inclination of the wind-to-beam-face. These assumptions permit the use of the wind load tables from both standards. For the purpose of simplifying discussions, AS3995 will be the only standard referenced from now onwards.

AS3995 (1994) describes situations where a tower requires structural analysis and prescribes methods for performing the analysis. General freestanding lattice towers shall be analysed using first-order linear elastic methods. For the analysis of lattice masts supported by guys, the non-linear properties of the guys and other second order effects shall be taken into account (AS3995 1994).

The following sections detail procedures for the determination of design loads as well as how to analysis masts and lattice towers. AS4676 is used to determine the design load requirements, whilst AS3995 is used to determine the magnitude of the loads (i.e. AS1170.1 for dead loads, and AS1170.2 for wind loads). The ‘static analysis’ procedure is used from AS3995 to analyse the structural requirements. Furthermore, since masts and towers vary in sensitivity to wind action, dynamic analysis shall be undertaken for those masts and towers having a first mode natural frequency less than 1Hz. For structures with a first mode natural frequency greater than or equal to 1Hz, only static analysis is required (AS3995).

3.2.2.1. Design Load Requirements

The structural design requirements for utility services poles, AS4676 sets out general requirements for structural design and minimum design loads applicable to pole structures supporting equipment for communication through the atmosphere. The design of a utility services pole and its component parts shall take into account, as appropriate, the limit states of stability, strength, serviceability and durability. The design for stability, strength and serviceability of utility services poles and their component parts shall take account of the effects arising directly from the following loads, as appropriate:

a) Dead loads
b) Snow and ice loads
c) Wind loads
d) Earthquake loads

e) Live loads and maintenance loads
f) Aerial cable loads

Once the design loads have been determined, AS4676 recommends testing the 'design action effect' (bending moment, shear, torsion, deflection, rotation). The standard also provides some examples on how to setup experimental tests for each of the limit states.

3.2.2.2. Static Analysis

The predominant loads of mast and tower structures are natural loads, such as, wind and ice induced loads (Andersen 2009). In order to simplify the static analysis of the structure several loads were neglected. Ice loads were neglected because the towers will only be used during Australian summers (thus no ice). In addition, both earthquake and incidental loads were neglected from the analysis to reduce the scope of the project.

Although dead loads (i.e. self-weight) are easy to calculate, wind loads are quite the opposite. Wind possesses kinetic energy by virtue of its velocity and mass, which is transformed into potential energy of pressure when a structure obstructs the path of wind. Natural wind itself is neither steady nor uniform; it varies along the dimensions of the structures as well as with time (Galeb & Khayoon 2013). The following describes how wind loads were calculated for the tower in accordance with AS3995.

To calculate the design wind loads, the 'drag force' equation is used. The design drag force, F_d, shall be calculated using Equation 1. (AS3995 - Equation 3.5.5.):

$$F_d = C_d A_z q_z \qquad (1)$$

where,
F_d is the drag force acting parallel to the wind-stream - N
z is the height of the centroid of the tower section above ground level - m
C_d is the drag force coefficient - constant
A_z is the area at height z of members in the front face, projected normal to that face - m^2
q_z is the free stream gust dynamic wind pressure at height z - kPa

The drag force coefficient, C_d, shall be determined from Table 3.8. depending on the 'actual solidity of front face', which is in other words, the solid area divided by the total enclosed area. To both ease calculations and ensure that the tower can withstand the highest wind loads in Australia; the maximum drag force coefficient of 1.8 was used.

Table 3.8. Drag force coefficients for equilateral-triangle plan lattice towers with circular members (AS3995 - Table 3.5.3.)

Actual solidity of front face (δ)	Drag force coefficient (C_d)	
	Parts of tower in sub-critical flow $bV < 3$ m²/s (all wind directions)	Parts of tower in super-critical flow $bV \geq 6$ m²/s (all wind directions)
0.05	1.8	1.1
0.1	1.7	1.1
0.2	1.6	1.1
0.3	1.5	1.1
0.4	1.5	1.1
≥0.5	1.4	1.2

*table notes: interpolation is permitted
δ is the actual solidity ratio
b is the average member diameter

Due to variation of wind speeds with height, terrain and averaging time. AS3995 describes a reference dynamic wind pressure. The free-stream gust dynamic wind pressure, q_z, shall be calculated using Equation 2:

$$q_z = 0.6 \times 10^{-3} V_z^2 \qquad (2)$$

where, q_z is the free-stream gust dynamic wind pressure at height z - kPa
V_z is the design gust wind speed at height z - m/s

The design gust wind speed, V_z, shall be calculated using Equation 3.

$$V_z = V M_{(z,cat)} M_t M_d \qquad (3)$$

where, V is the basic wind speed, V_u, for ultimate limit state, V_s, for serviceability limit state - m/s
z is the height of the centroid of the tower section above ground level - m
$M_{(z,cat)}$ is the gust wind speed multiplier for a terrain category at height z - constant
M_t is the topographic multiplier for gust wind speeds - constant
M_d is the wind direction multiplier - constant

The basic wind speed is obtained from Figure 3.4. depending on the region in which the tower will be deployed. To both ease calculations and ensure that the tower can withstand the highest wind loads in Australia; maximum wind speed of 85m/s was used.

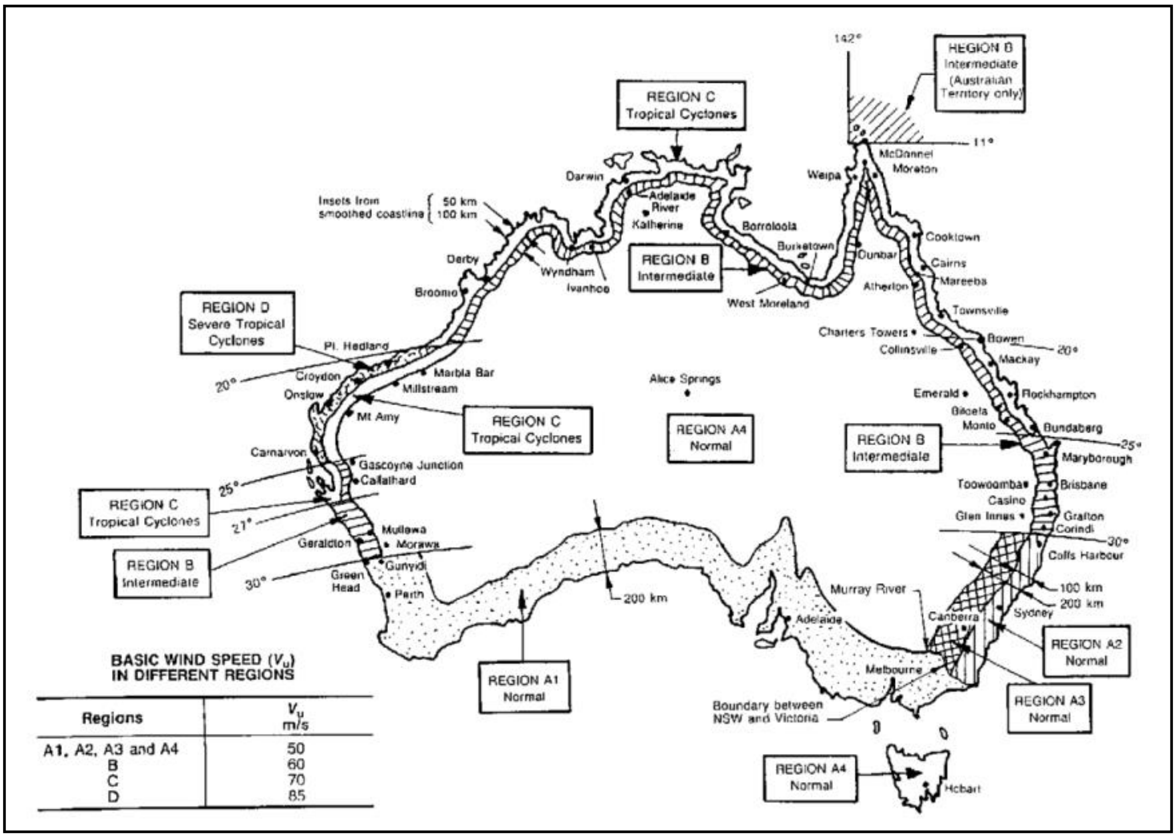


Figure 3.4. Basic wind speeds (*V*): Boundaries of various wind speed regions in Australia (AS3995 Figure 4.2.2.)

The gust wind speed multiplier, $M_{(z,cat)}$, for a terrain category is obtained from Table 3.9. depending on the height of the centroid of the tower section above ground level, as shown in Figure 3.5. Considering that the centroid of tower will be below 5m, and to ease calculations and ensure that the tower can withstand the highest wind loads in Australia; a gust wind speed terrain multiplier of 1 was used.

Table 3.9. Terrain height multiplier for gust wind speeds for ultimate limit state design for regions C & D (AS3995 Table 2.2.3.2.)

Height (z)	Terrain height multiplier ($M_{(z,cat)}$)	
m	Terrain Categories 1 and 2	Terrain Categories 3 and 4
≤3	0.90	0.80
5	0.95	0.80
10	1.00	0.89
15	1.07	0.95
20	1.13	1.05
30	1.20	1.15
40	1.25	1.25
50	1.29	1.29
75	1.35	1.35
≥100	1.40	1.40

*table notes: interpolation is permitted

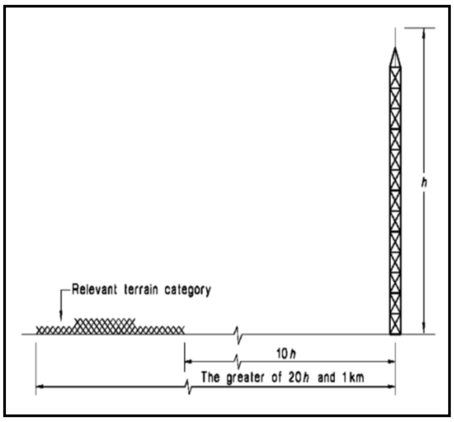


Figure 3.5. Terrain multiplier ($M_{(z,cat)}$): Terrain category selection (AS3995 Figure 2.2.3.1.)

The topographic multiplier, M_t, shall be calculated for sites at or near the crest of a hill, ridge or escarpment using Equation 4, as shown in Figures 3.6.a.&b.

$$M_t = 1 + \frac{H\left(1 - \frac{|x|}{4L_g}\right)}{3.5(z + L_g)} \qquad (4)$$

where, H is the height of the hill, ridge or escarpment - m
x is the horizontal distance from the structure to the crest of a hill or a ridge - m
L_g is the length to determine the multiplier ($0.4H$ or $0.35L_u$), whichever is greater - m
L_u is the horizontal distance upwind from the crest of a hill, ridge or escarpment to a level half the height below the crest - m
z is the height of the centroid of the tower section above ground level - m

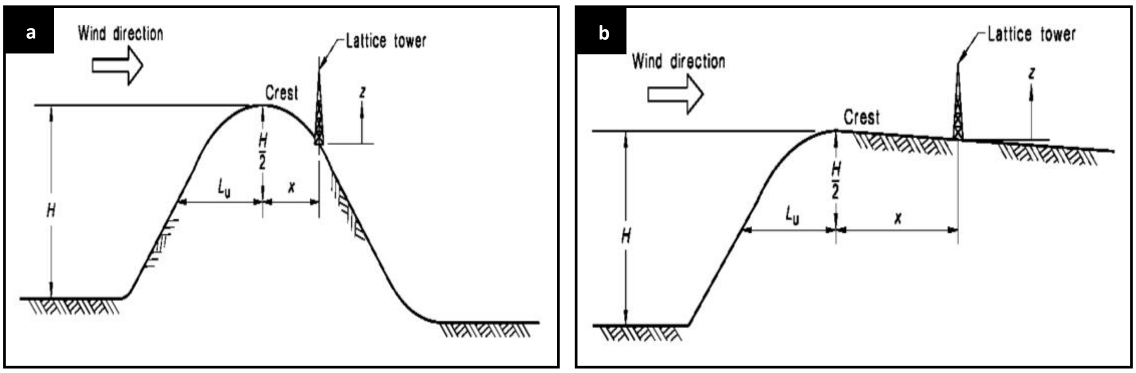


Figure 3.6.a. Topographic multiplier (M_t), Wind direction multiplier (M_d): Hills and ridges (AS3995 Figure 2.2.4.1.),
b. Topographic multiplier (M_t), Wind direction multiplier (M_d): Escarpments (AS3995 Figure 2.2.4.1.)

The wind direction multiplier, M_d, is obtained from Table 3.10., as shown in Figures 3.6.a.&b., obviously depending on the wind direction. To ease calculations and ensure that the tower can withstand the highest wind loads in Australia; the maximum wind direction multiplier of 1 was used.

Table 3.10. Wind direction multiplier (AS3995 Table 2.2.5.)

Wind direction	Wind direction multiplier (M_d)			
	Region A1	Region A2	Region A3	Regions A4, B, C and D
NE	0.80	0.80	0.80	0.95
E	0.80	0.80	0.80	0.95
SE	0.80	0.95	0.80	0.95
S	0.85	0.90	0.80	0.95
SW	0.95	0.95	0.85	0.95
W	1.00	1.00	0.90	0.95
NW	0.95	0.95	1.00	0.95
N	0.90	0.80	0.85	0.95

Once the wind loads have been determined, the proposed tower structure needs to be analysed using the first-order linear elastic method (AS3995 1994). Given that many finite element analysis (FEA) commercial software packages are constructed based-on first-order linear elastic models, for simplicity these packages can be utilised. It is important to note that the design wind loads can be either 'distributed over the height' of the tower (for a more exact approach), or simply 'applied at the centroid' of the tower (to ease calculations).

3.2.2.3. Dynamic Analysis

Dynamic analysis shall be undertaken for those masts and towers having a first mode natural frequency less than 1Hz. An accurate method of estimating the natural frequencies of vibration of a lattice tower is to obtain a flexibility matrix, then perform an eigenvalue calculation in conjunction with its mass matrix. This process gives not only the first mode frequency but also the frequencies of all other modes (AS3995 1994). It is important to note that all the mode frequencies can also be easily found using commercial FEA solvers. Furthermore, AS3995 (1994) also outlines an alternative 'hand calculation' approach to estimate the first mode of vibration. For freestanding lattice towers, the first mode natural sway frequency, *n*, may be calculated from Equation 5.

$$n = \frac{1500w_a}{h^2} \qquad (5)$$

where, w_a is the average width of the structure, in metres
h is the height of the structure above ground, in metres.

3.2.3. Electronic Requirements

Through reviewing the relevant Australian Standards for Wi-Fi mast and tower components, one standard was found that states the limits and methods of measurement for short range devices (SRDs). AS4268 (2008) specifies the minimum performance and methods of measurement for SRDs supplied for use under the Australian Radiocommunications (low Interference Potential Devices) Class Licence 2000 and the Radiocommunications (Radio-controlled Models) Class 2002. This standard was deemed highly relevant since it obviously specifies the performance requirements for APs.

Radioactive networks (2011) an engineering consultancy based in Sydney, specialising in wireless communications, states that AS4268 is the industry standard for Wi-Fi technology compliance. They explain that under a class licence all users operate in the same spectrum segment on a shared basis and are subject to the same conditions. A class licence governs the frequencies that may be used, commonly prescribes equipment standards, and may specify other technical and operational parameters. Class licences do not have to be applied for, and no licence fees are payable. Radioactive Networks (2010) describe how spread spectrum devices are defined in the class licence as radiocommunications devices that employ direct sequence spread spectrum modulation techniques, frequency hopping spread spectrum modulation techniques, or both, to transmit information.

The Australian Communications and Media Authority (ACMA) clarify the 'interference management' scheme for spread spectrum and digital modulation devices operating under the class licence. Basically, they must not cause interference to other radio communications services and will not be afforded protection from interference caused by other radio communications services. Furthermore, when operating in bands designated for industrial, scientific and medical (ISM) applications, protection from interference which may be caused by ISM applications (such as microwave ovens) will not be afforded. Table 3.11. outlines frequency bands and power limits for spread spectrum and digital modulation devices. Since the SRD that the client proposes to use will be operating at a frequency band of 2400-2483.5MHz, the AP must consume no more than 500mW of equivalent isotropically radiated power (EIRP) when a minimum of 15 hopping frequencies are used, or no more than 4W of EIRP when a minimum of 75 hopping frequencies are used.

Table 3.11. Frequency bands and power limits for spread spectrum and digital modulation devices (ACMA 2010)

Device	*Frequency band (MHz)*	*Maximum equivalent isotropically radiated power (EIRP)*
Frequency hopping transmitters and digital modulation transmitters	915-928	1W (frequency hopping transmitters must use a minimum of 20 hopping frequencies)
Frequency hopping transmitters	2400-2483.5	500mW (a minimum of 15 hopping frequencies must be used)
Frequency hopping transmitters and digital modulation transmitters	2400-2483.5	4W (frequency hopping transmitters must use a minimum of 75 hopping frequencies)
Frequency hopping transmitters and digital modulation transmitters	5725-5850	4W (frequency hopping transmitters must use a minimum of 75 hopping frequencies)

3.2.4. OH&S Legislations

Outdoor music festivals (OMFs) are complex events to organise with many exceeding the population of a small city (Earl 2006). Poor behaviour and judgement associated with drug and alcohol consumption while attending OMFs has forced event organisers to demand higher standards for temporary demountable structure (TDS) construction contractors and other vendors during OMFs (Milsten et al. 2002). Given the high complexity and population of these events, this demands a high standard for the OH&S procedures observed during the running, setting-up, and packing-up of large OMFs.

A literature review has revealed that there are a few key texts which Australian OMF event organisers reference to ensure that their event addresses all relevant OH&S legislations. In 1999, the British Health & Safety Executive (HSE) published a text, 'The Event Safety Guide', that appears to be the standard for planning and managing health and safety at OMFs (Earl 2006). This text provides detailed information regarding design requirements for TDS's at these events. An overview of the design requirements will be provided later in this section. The second key text that OMF event organisers refer to, is the 'Employer Guide to OH&S in The Entertainment Industry', which was published by the Australian Entertainment Industry Association (AEIA) in 2004 (Earl 2006). This text provides event organisers and entertainment industry workers with an understanding of the legal responsibilities under OH&S legislation. It also provides a practical guide in how to manage risks to the health and safety of persons working in the industry, and to members of the public (including festival patrons) who would be affected by entertainment activities (AEIA 2004).

Although OMFs are not limited by the same physical constraints of indoor events, the majority of OMFs have limited permanent facilities existing on the sites (HSE 1999). Technologies that have the potential to increase the efficiency of communication mediums are encourage at OMFs, especially if they are supported by a body of health practitioners. Stoneham et al. (2003) discuss the idea of how improving telecommunication infrastructure will allow festival patrons to communicate 'more freely' and ultimately improve the safety of OMFs. Earl (2006) discusses how environmental health practitioners (EHPs) working within local government authorities are 'key players' in regulating the OH&S of

OMFs. Earl suggests that by engaging with EHPs during the planning of OMFs, this will help ensure that the event meets OH&S legislations.

All TDS's must be accounted for in the layout of OMFs. HSE (1999) state that contractors and vendors must declare the geometric and structural details of any 'large structures' that they wish to utilise within the public domain at OMFs. These structures need to be accounted for in the event organiser's 'structural layout plan'. Figure 3.7. shows an example of the types of structures the event organisers need to account for.

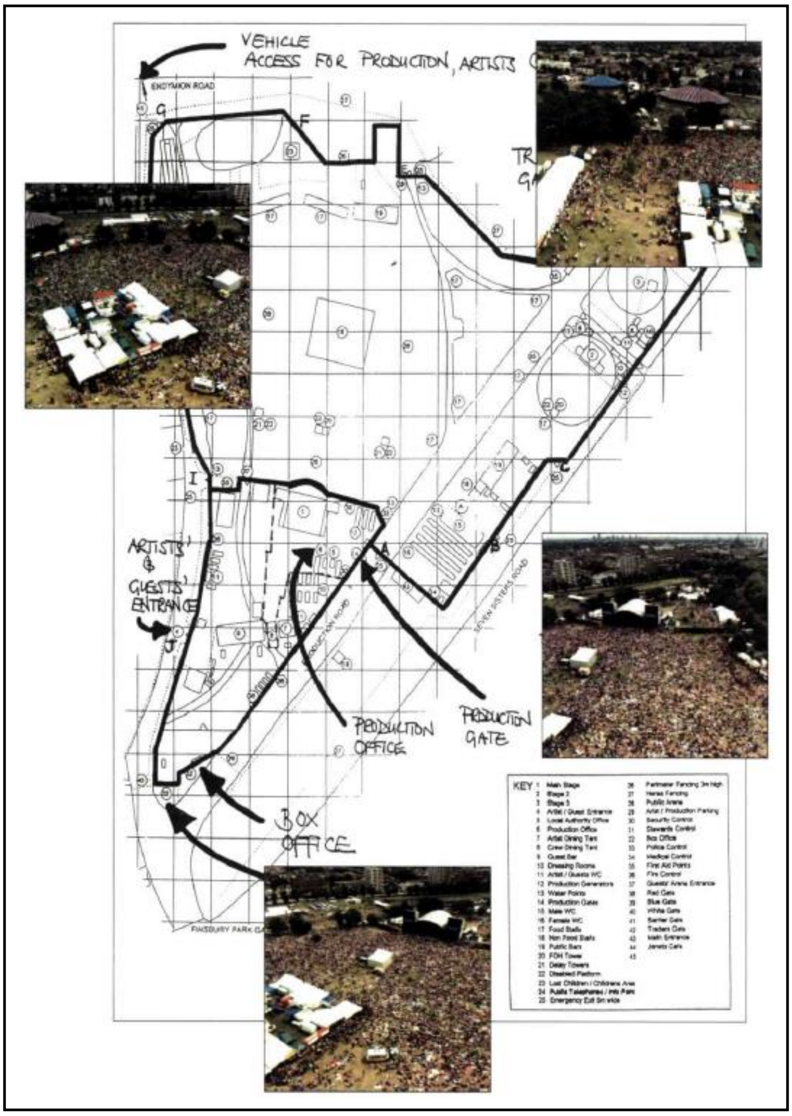


Figure 3.7. Example OMF structural layout plan HSE 1999)

The failure of any TDS, no matter how small, in a crowded, confined space could have devastating effects. There have been recent collapses of temporary stage structures in the USA and in Europe during entertainment events, as shown in Figure 3.8. These have resulted in fatalities and numerous injuries. Although reasons why the failures occurred have not yet been published, wind has been reported as a contributory cause (SCOSS 2012). It is therefore essential to design and erect structures to suit the specific intended purpose, and to recognise that the key to the safety of these structures is largely dependent on the structural design and materials selection (HSE 1999). All TDS's must possess adequate strength and stability in service and during construction. The HSE have endorsed the Standing Committee on Structural Safety (SCOSS) guide on TDS's, which provides guidance on the design, procurement and use of TDS's.

Figure 3.8. The Indiana State fair stage collapse (Foley 2011)

The SCOSS (2012) guide describes how TDS contractors should be able to prove to the OMF engineer that their TDS has been specifically designed to accommodate all vertical loads, including self-weight, lights, and sound equipment and snow (if applicable). It should also be capable of withstanding agreed wind loads applied to the structure, equipment, and any roofing or side cladding (i.e. advertising banners). SCOSS also advise that each TDS needs to meet the Local Authority Building Control in England & Wales (LABC) on-site 'TDS checklist'. Appendix B outlines a checklist that the LABC have created for OMF engineers to use to review TDS's upon being completely setup. In addition, Appendix C summarises the 'essential documents' that HSE (1999) advise OMF event organisers to collect from TDS construction contractors, prior to the event.

3.2.5. Airline Regulations

In order to ensure that the tower meets all major Australian airline checked baggage requirements, the major airlines were reviewed to determine what the specific requirements and regulations are for each of them. In 2011, the Oneworld Alliance considered there to be five major operable airlines in Australia (Oneworld 2011). Oneworld Alliance is one of the world's three largest global airline alliances, which as of October 2012, operated 12.2% of the global airways seat capacity (Gulliver 2012). These five major airlines are outlined in Table 3.12. with a brief description of the respective airline. The airlines were reviewed to ensure that the tower carry-case (i.e. tower in a baggage-state) will comply with each airline's relevant regulations.

Table 3.12. Major Australian airlines

Airline	*IATA Designator*	*Description*
Qantas Airways	QF	Australia's largest airline - 65% market share (Qantas 2012)
Virgin Australia Airlines	DJ	Australia's second-largest airline
Jetstar Airways	JQ	Low-fare carrier A subsidiary of Qantas Airways
Tigerair	TT	Low-fare carrier A joint venture between Singapore Airlines and Virgin Australia Airlines
Airnorth	TL	A regional airline based in Darwin

Through reviewing the 'checked baggage allowance' and 'dangerous goods' regulatory documents from each of the major Australian airlines, it was realised that there are three main regulations with which the tower carry-case will need to comply. The first airline requirement is with regards to the total mass of the checked baggage. As outlined in Table 3.13., there are two main baggage allowances for mass; business class and economy class. To comply with all the airlines, the tower carry-case would need to weigh less than 20kg. However a more realistic target is for the tower carry-case to weigh less than 32kg, since this would ensure that it could be transported as checked baggage with Australia's two largest airlines. In addition, it was realised that having the 'total linear dimensions' less than 140cm will ensure the carry-case complies with another of the checked baggage requirements.

Table 3.13. Major Australian airline baggage allowances (Qantas 2013; Virgin 2013; Jetstar 2013; Tigerair 2013; Airnorth 2013)

Allowance Type	*Qantas*	*Virgin*	*Jetstar*	*Tigerair*	*Airnorth*
Economy Mass Allowance (kg)	23	23	15	10	13
Business Mass Allowance (kg)	32	32	30	25	20
Total Linear Dimensions = length + width + height (cm)	140	140	140	140	140

The third airline requirement for the tower carry-case is specific to lithium ion batteries. All Australian airlines are only permitted to transport items governed by the International Air Transport Association's (IATA) Dangerous Goods Regulations (DGRs) and the Civil Aviation Safety Regulations (CASRs). These regulations stipulate 'dangerous goods' as being items that may endanger the safety of an aircraft or persons on board the aircraft (IATA 2013). While there are many items on the dangerous goods list (see Figure 3.9.), the items of interest to the project are 'lithium ion batteries'.

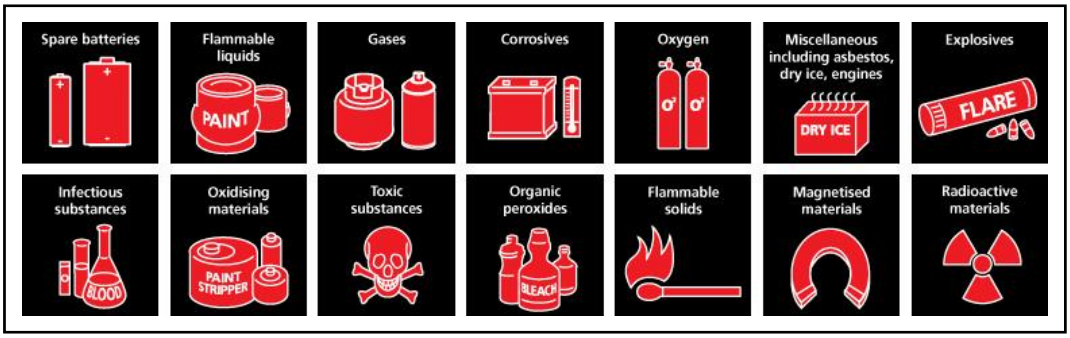


Figure 3.9. Major Australian airline dangerous goods (Qantas 2013)

To comply with the DGRs for lithium ion battery powered equipment and spare batteries, there are two requirements. For spare lithium ion batteries with a Watt-hour rating exceeding 100Wh, but not exceeding 160Wh (i.e. consumer electronic devices), these batteries must be individually protected to prevent short circuits. The customer is only permitted to check-in a maximum of two spare batteries. Furthermore, if the customer wishes to use the battery powered piece of equipment on-board, the battery must remain in the piece of equipment at all times (IATA 2013). A review of the all the major Australian airlines checked baggage regulatory policies proved that all airlines make reference to IATA's DGRs (Airnorth 2013; Jetstar 2013; Qantas 2013; Tigerair 2013; Virgin 2013).

3.3. Quality Functional Deployment

Understanding the design problem is an essential foundation for designing a quality product (Ullman 2010). Despite all efforts, many product development projects fail and lead to the introduction of products that do not meet customers' expectations (Matzler et al. 1998). A structured planning process that systematically incorporates the voice of the customer into product design, Quality Function Deployment (QFD) has proven itself a highly effective development tool for creating globally competitive products in software, hardware, services, and many other industries (Cohen 1995). Quality function deployment (QFD) is a "method to transform user demands into design quality, to deploy the functions forming quality, and to deploy methods for achieving the design quality into subsystems and component parts, and ultimately to specific elements of the manufacturing process" (Akao 1994). QFD has been practiced by leading companies around the world since 1966 (Akao et al. 2003). Although there are many techniques to generate engineering specifications, QFD is still one of the best and currently most popular methods (Ullman 2010).

QFD employs a series of matrices to quantify customer requirements, product ratings and technical descriptors. By identifying the correlation factors among all these requirements, the importance weights of each technical detail can be calculated through a simple algorithm. One major approach to implement the QFD process is through the House of Quality, which will be discussed in more detail in the following section (Yang 2013).

The House of Quality is a plan of four stages in which a QFD team translates customer requirements into product characteristics, product characteristics into part characteristics, part characteristics into process targets, and finally process targets into production targets. Further refinement can be done by putting the output of the first matrix into the input part of the second, and so on (Yang 2013). Ullman (2010) breaks these four stages into 8 steps, as shown in Figure 3.10. For a more extensive explanation of the House of Quality, consult Cohen (1995).

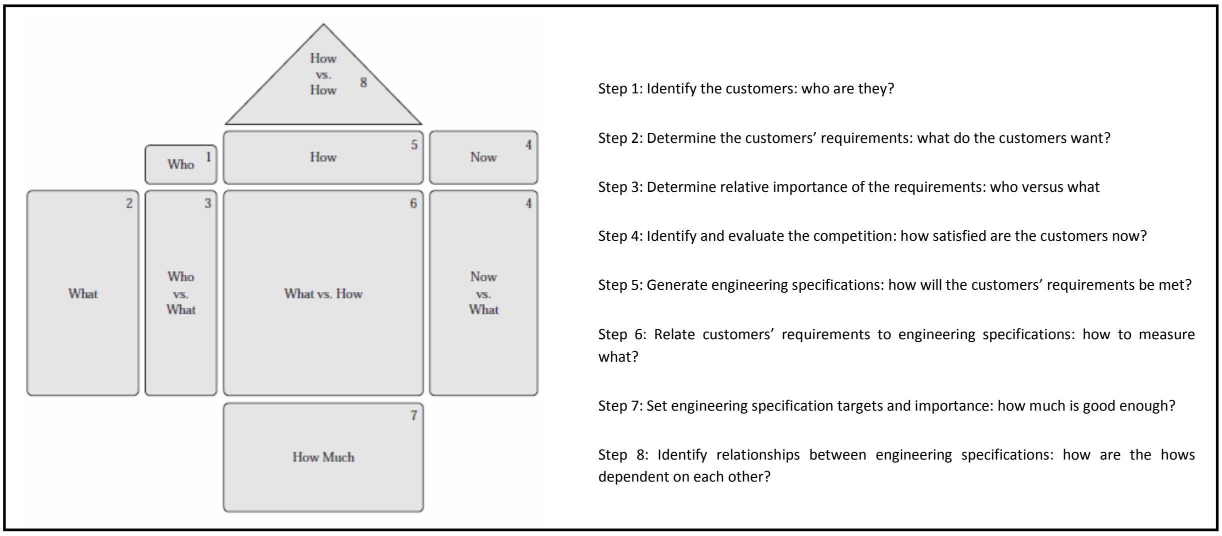


Figure 3.10. Typical structure of a House of Quality (Ullman 2010)

Through meeting with the WiFindUs and Serval teams, as well as festival representatives, the Flinders team was able to realise the complete customer requirements of the tower. These requirements were used to develop engineering specifications through the House of Quality method, which helped realise the importance of each of these specifications. As shown in Table 3.14., the most important specifications have the highest 'voice of engineers' (VoE) score, and are highlighted red. Targets were then set for all the engineering specifications based on 'deemed reasonable' and 'ensuring compliance' rationales. This process involved setting a goal with which the customers would be delighted (the target) and a baseline that the customers would deem as being acceptable (the threshold). It should be noted that Step 8 was purposely neglected from this evaluation, as many of the relationships between the engineering specifications were deemed intangible, and the Flinders team believed they could monitor the 'relevant relations'.

Table 3.14. Project House of Quality

	Who			How																																					
				Main Structure												Standards				Manufacture				Deployment								Transportation				Others					
				Housing							Frame						AS		Festival						Assembly				Disassembly				Portable										
What	WiFindUs	Serval	Festival	Waterproofness of housing	Number of component fixtures	Volume of housing	Temperature of electronics	RF transparency of housing	Height of Wi-Fi components	Material product life	Height of mast	Triangular footing span	Area of individual footing	Weight of ballast	Number of Guy ropes	1st mode of vibration	Wind loading	Radiation	Beamwidth of antenna	Percentage of off-shelf components	Number of manufacturing steps	Yield stress	Length of section	Workers required to assemble	Time to assemble	Force to assemble	Number of ballasts	Time to disassemble	Number of Steps to disassemble	Time to dispose of ballast	Quantity of content recycled	Number of people required to carry	Weight of suitcase	Size of suitcase (L+W+H)	Number of packages	Number of parts	Cost of unit	Number of joints	Ratio of yield /max operating stress	Surface finish	Time to clean
				↑	↑	↑	↓	↑	↑	↑	↑	↓	↑	↑	↓	↑	↑	-	↑	↑	↓	↑	↑	↓	↓	↑	↓	↓	↓	↓	↑	↓	↓	↓	↓	↓	↓	↓	↑	↑	↓
				m	#	cm3	°C	%	m	yr	m	m	m2	kg	#	Hz	m/s	GHz	°	%	#	MPa	m	#	min	N	#	min	#	min	%	#	kg	cm	#	#	$	#	:	%	min
Shelter components	4	4	1	9			3																													1					
Stabilise components	3	2	1		3							9	3				3																								
Accommodate components	2	2	1			9																																			
Minimise operating temperatures	3	3	1				9																																		
Minimise radio signal attenuation	4	4	1					9	9		3					1																									
Maximise longevity of parts	3	5	1							9																															
Maximise coverage	5	5	4						3		9								9																						
Minimise footing area	5	1	3									9		9													3										3					
Stable on all surfaces	4	3	3									9	9	3			3																						1			
No permanent fixtures	5	5	5											9	9																										
Comply AS tower design	4	4	5													9	9	3																							
Comply AS tower set-up	4	4	5														9																								
Comply OH&S legislations	5	1	5									9						9																							
Flexible set-up	5	2	5																9						9			9													
Minimise fabrication processes	5	5	1																	9	3		3														3		3			
Use in-house facilities	3	5	1																	9	9																3		3			
Minimise fixtures	5	5	1						3													9	9										9	9		3	9	3			
Minimise labour	5	3	1							3											9		9													3	9	3			
Minimise steps to assemble	5	5	1																					9			3									3	9	3			
Quick to assemble	5	5	1																						9	1	3	9								3		3			
Easy to assemble	4	5	1																					9	9	9	1	9								1		1			
Easy to stabilise	4	4	1																								9														
Quick to disassemble	4	5	4																						9		3	9	9							3		3			
Easy to disassemble	4	1	1																						9		1	9	9							1		1			
Easy to dispose ballast	3	4	4																								3			9	9		3	3							
Sustainable ballast	2	3	5																												9										
Good ergonomics	2	4	1																													9	9	9	3						
Minimise weight	5	4	1																			1		3			3						9			1		1			
Minimise size	5	4	1																			3					3							9		1		3			
Minimise transport cost	4	5	1																														9	9	9	1		1			
Minimise parts	5	4	1									3											3	9			3									9		9			
Minimise unit cost	5	5	1																	9																1	9	3			
Minimise maintenance	2	5	1							9		3								9																1		9			
High factor of safety	3	3	5													3	3					3																	9		
Good aesthetics	1	1	1																																	1		1		9	
Easy to clean	1	1	5																												3					1		1			9
WiFindUs	Absolute Importance			36	9	18	39	36	66	60	57	174	45	102	45	49	102	57	90	135	87	74	120	141	198	41	155	198	72	27	48	18	153	153	42	191	180	212	27	9	9
	Relative Importance			1.1	0.27	0.55	1.19	1.1	2.02	1.83	1.74	5.31	1.37	3.11	1.37	1.5	3.11	1.74	2.75	4.12	2.66	2.26	3.66	4.31	6.05	1.25	4.73	6.05	2.2	0.82	1.47	0.55	4.67	4.67	1.28	5.83	5.5	6.47	0.82	0.27	0.27
	VoE Score			3	1	1	3	3	3	3	3	9	3	3	3	3	3	3	3	3	3	3	3	3	9	3	9	9	3	3	3	1	9	9	3	9	9	9	3	1	1
Serval	Absolute Importance			36	6	18	39	36	66	99	57	90	33	63	45	49	96	21	63	180	87	70	99	138	162	50	138	162	54	36	66	36	174	174	57	173	162	227	27	9	9
	Relative Importance			1.16	0.19	0.58	1.26	1.16	2.12	3.19	1.83	2.9	1.06	2.03	1.45	1.58	3.09	0.68	2.03	5.79	2.8	2.25	3.19	4.44	5.21	1.61	4.44	5.21	1.74	1.16	2.12	1.16	5.6	5.6	1.83	5.57	5.21	7.31	0.87	0.29	0.29
	VoE Score			3	1	1	3	3	3	3	3	3	3	3	3	3	3	1	3	9	3	3	3	3	9	3	3	9	3	3	3	3	9	9	3	9	9	9	3	1	1
Festival	Absolute Importance			9	3	9	12	9	24	21	39	114	30	81	45	61	117	60	81	36	21	28	24	30	108	10	59	108	45	36	96	9	48	48	12	62	36	67	45	9	45
	Relative Importance			0.53	0.18	0.53	0.71	0.53	1.41	1.24	2.3	6.72	1.77	4.77	2.65	3.59	6.89	3.54	4.77	2.12	1.24	1.65	1.41	1.77	6.36	0.59	3.48	6.36	2.65	2.12	5.66	0.53	2.83	2.83	0.71	3.65	2.12	3.95	2.65	0.53	2.65
	VoE Score			1	1	1	1	1	3	3	3	9	3	9	3	3	9	3	9	3	3	3	3	3	9	1	3	9	3	3	9	1	3	3	1	3	3	3	3	1	3
Target (Delighted)				1	4	2000	25	100	8	5	8	2	0.04	5	0	5	100	2.4	360	100	6	200	0.8	1	5	50	1	5	5	5	100	1	20	120	1	10	150	5	3	100	2
Threshold (Disgusted)				0.3	10	4000	38	85	4	1	4	2.4	0.16	10	1	1	85	2.48	180	80	12	50	1	2	15	100	3	15	10	10	50	2	32	140	2	15	200	10	1	50	5

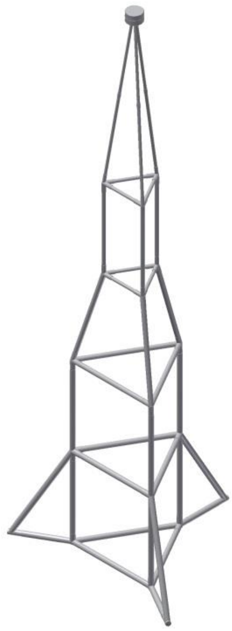
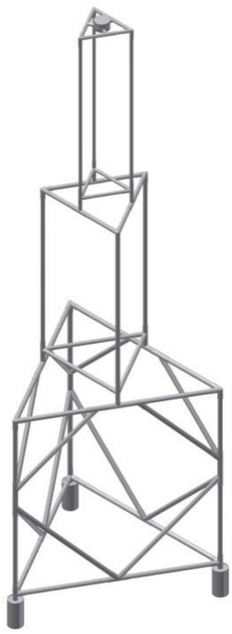
Through evaluating the VoE scores of all three customers, the engineering specifications which had two or more customers scoring a high VoE were determined to be the most important. These engineering specifications include:

1. Triangular footing span of tower fits within three standard fence panels
2. Time to assemble tower is less than 15mins
3. Time to disassemble tower is less than 15mins
4. Weight of tower suitcase is less than 32kg
5. Size of tower suitcase (L+W+H) is less than 140cm
6. Number of unique parts is less than 15
7. Cost of unit is less than $250
8. Number of unique joints is less than 10

3.4. Conceptualisation

Six unique concepts were generated that together reflect an array of different solutions for each of the most important engineering specifications. The design of these concepts was inspired by the 'small-scale telecommunication mast and towers' findings that were reviewed in Chapter 2. These six concepts were modelled in Autodesk Inventor so that FEA simulations could be performed based-on the design wind loads. The results from these simulations were then used to critically analyse the structural performance of each concept. Table 3.15. provides a summary of the tower design generated from the conceptualisation process.

Table 3.15. Summary of concepts

Concept Reference		
C1	**C2**	**C3**
		
C4	**C5**	**C6**
		

3.5. Concept Evaluation

There are several methods used in industry to help analyse the performance of various concepts against each other. Ullman (2010) describes Benjamin Franklin's decision-making method in which he itemises the pros and cons for each concept and then uses a process of elimination to decide which concept to select. While this methodology is acceptable for evaluating concepts one at a time, a more complex analysis method is required when there are multiple concepts involved with a mixture of qualitative and quantitative evaluations to be performed.

The decision-matrix method, or Pugh's method, is fairly simple and has proven effective for comparing alternative concepts (Ullman 2010). In essence, the method provides a means of scoring each alternative concept relative to the others in its ability to meet the engineering specifications generated from the House of Quality (Pugh 1991). Pugh's decision-matrix method is an iterative evaluation method that tests the completeness and understanding of criteria, rapidly identifies the strongest alternatives, and helps foster new alternatives (Ullman 2010). As shown in Figure 3.11. there are six steps to this method.

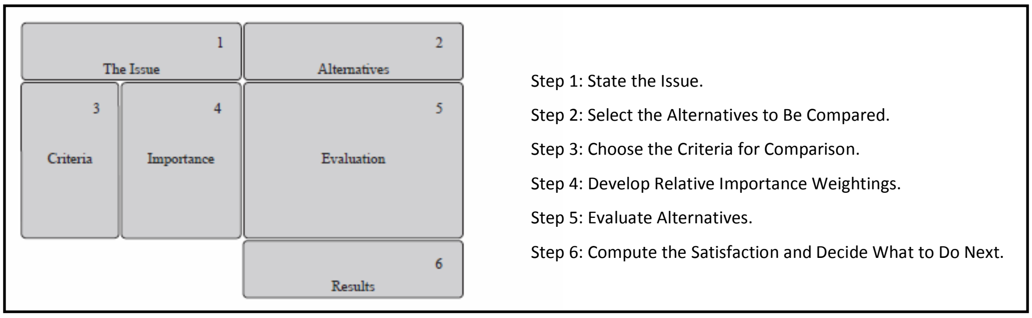


Figure 3.11. Typical structure of Pugh's decision-matrix (Ullman 2010)

The first stage of the concept evaluation was to perform a critical analysis using FEA data from the Autodesk Inventor package. Table 3.16. outlines how the concepts performed in the FEA simulations. These performances were then used to evaluate the engineering specification performance of the concepts using Pugh's decision-matrix methodology, as seen in Table 3.17. It is important to note that the evaluation of the concepts, C2-C6, have been ranked against a datum, in C1.

Table 3.16. Initial design phase: Performance evaluation of concepts using FEA simulations

Performance Criteria	*C1*	*C2*	*C3*	*C4*	*C5*	*C6*	*Best Perform.*
Mass (kg)	95.89	11.53	21.26	40.70	16.53	38.70	C2
Frequency (Hz)	1.09	0.48	2.99	0.14	0.50	1.00	C3
Stress (MPa) - Direct. 1	1.83	0.73	1.55	1.20	9.68	1.69	C2
Stress (MPa) - Direct. 2	1.47	0.59	1.10	0.96	10.31	1.42	C2
Deflection (mm) - Direct. 1	27.28	22.79	8.66	3.76	78.29	1.53	C6
Deflection (mm) - Direct. 2	27.28	22.79	8.66	3.76	78.29	1.53	C6

Table 3.17. Initial design phase: Performance evaluation of concepts using decision-matrix methodology

Engineering Specifications	*Importance Weighting*				*Alternatives*					
	WiFindUs	Serval	Festival	Ave.	C1	C2	C3	C4	C5	C6
Waterproofness of housing	3	3	3	3.0		0	0	0	0	0
Number of component fixtures	1	1	1	1.0		0	-1	-1	0	-1
Volume of housing	1	1	1	1.0	**D**	-1	-1	-1	-1	-1
Temperature of electronics	3	3	1	2.3	**A**	0	0	0	0	0
RF transparency of housing	3	3	1	2.3	**T**	0	0	0	0	0
Height of Wi-Fi components	3	3	3	3.0	**U**	0	0	0	0	0
Material product life	3	3	3	3.0	**M**	1	1	1	1	1
Height of mast	3	3	3	3.0		0	0	0	0	0
Triangular footing span	9	3	9	7.0		0	0	0	0	0
Number of footings	3	3	3	3.0	**D**	1	0	1	0	0
Weight of ballast	3	3	9	5.0	**A**	-1	-1	-1	-1	-1
Number of guy ropes	3	3	3	3.0	**T**	0	0	0	0	0
1st mode of vibration	3	3	3	3.0	**U**	-1	1	-1	-1	-1
Wind loading	3	3	9	5.0	**M**	1	1	1	-1	1
Radiation limit	3	1	3	2.3		0	0	0	0	0
Beamwidth of antenna	3	3	9	5.0		0	0	0	0	0
Percentage of off-shelf components	3	9	3	5.0	**D**	1	-1	-1	0	-1
Number of manufacturing steps	3	3	3	3.0	**A**	1	-1	-1	1	-1
Yield stress	3	3	3	3.0	**T**	-1	-1	-1	-1	-1
Length of section	3	3	3	3.0	**U**	0	0	0	0	0

Workers required to assemble	3	3	3	3.0	**M**	0	-1	-1	0	-1
Time: to assemble	9	9	9	9.0		-1	-1	-1	-1	-1
Force to assemble	3	3	1	2.3		1	1	1	1	1
Number of ballasts	9	3	3	5.0	**D**	0	-1	0	-1	-1
Time to disassemble	9	9	9	9.0	**A**	0	-1	-1	-1	-1
Number of Steps to disassemble	3	3	3	3.0	**T**	0	-1	-1	0	-1
Time to dispose of ballast	3	3	3	3.0	**U**	1	1	1	1	1
Quantity of content recycled	3	3	9	5.0	**M**	-1	-1	-1	-1	-1
Number of people required to carry	1	3	1	1.7		1	-1	-1	1	-1
Weight of suitcase	9	9	3	7.0		1	1	1	1	1
Size of suitcase (L+W+H)	9	9	3	7.0	**D**	1	-1	-1	1	-1
Number of packages	3	3	1	2.3	**A**	0	-1	-1	0	-1
Number of parts	9	9	3	7.0	**T**	1	-1	-1	1	-1
Cost of unit	9	9	3	7.0	**U**	1	-1	-1	1	-1
Number of joints	9	9	3	7.0	**M**	1	-1	-1	1	-1
Ratio of yield / max operating stress	3	3	3	3.0		1	1	1	-1	1
Surface finish	1	1	1	1.0		1	1	1	1	1
Time to clean	1	1	3	1.7		0	-1	-1	0	-1
				Total	0	9	-11	-11	1	-13
				Weighted Total	***0***	***39***	***-58***	***-56***	***1***	***-64***

3.6. Preferred Design

Examination of the concept evaluation shows that C2 performed the best and C6 performed the worst. It can also be seen that C2 performed substantially better than the second placed concept, C1. As a result, the Flinders team decided that C2 was the preferred design from the conceptualisation process. The structural design of C2 was used to guide the design of the custom-made parts, as well as to aid with the selection of structural members during Stage 1 of the tower design.

4. Chapter 4: Stage 1 Design & Analysis

In seeking to develop a product which fulfils both the project's customer requirements and engineering specifications, countless design variations and thus performance analysis retests are often required. For this reason it is good practice to break the design and analysis phases into several stages. The aim of Stage 1 (S1) of the tower design and analysis was to turn the conceptual CAD design generated from Chapter 3 into a physical prototype to prove that the 'preferred design' can fulfil the project requirements. Chapter 4 presents the S1 tower and author's components design as well as the various tests that were undertaken. The key performance indicators that the prototype was tested for include: structural stability and strength, deployment times (both assembly and disassembly), and basic geometry checks such as, height, footing plan, and packaged checked-baggage-state. It is important to note that Section 4.1. aims to provide a general design description of the tower; it is realised by the author that the description is not detailed enough to be used as an open source instruction guide for fabricating and deploying the tower.

4.1. S1 Tower Design

The Stage 1 tower prototype was constructed as per the design of Concept 2 (C2) from Chapter 3. This required some refinement of the individual components design, which will be discussed in the following sections. As shown in Figure 4.1.a., the original tower design did not have any guy-ropes. However during the construction phase it was realised that guy-ropes are necessary in order to make this design both structurally stable and durable. Figure 4.1.b. shows the fully-assembled S1 tower prototype.

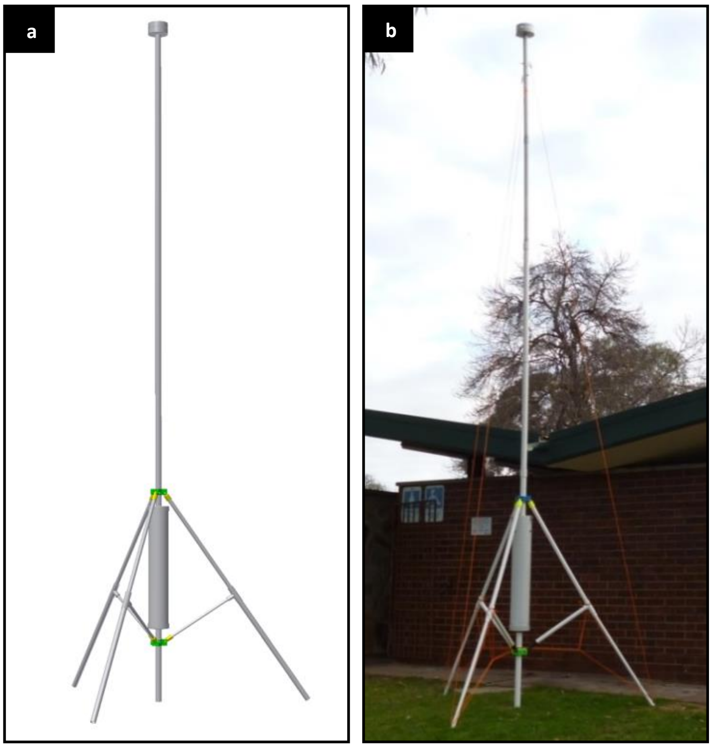


Figure 4.1.a. C2 CAD model, **b.** S1 tower prototype

4.1.1. Ballast

The ballast has several requirements which have contributed to its multi-functional design. Firstly, the ballast needs to be fillable with either water or sand. Secondly the ballast needs to act as a 'hard' carry-case to protect the tower components during transit, and thirdly, as the name suggests, it needs to act as a ballast for the tower.

In keeping with the 'open source accessible design' theme of the project, 150mm PVC-DWV pipe was selected as the main component of the ballast system. Not only can a 1m section of 150mm PVC-DWV pipe hold both water and sand well, it can also neatly fit seven 40mm PVC sections inside it for transportation. The ballast can hold approximately 17.6L of water and this provides approximately 173N of 'live-weight' force. In order to suspend the ballast between the two sets of tripod legs, a 40mm PVC 'load-supporting leg' was designed to fasten to the bottom of the ballast with a 25mm PVC bush/cap/socket arrangement. To strengthen the load-supporting leg, a double thickness of 40mm PVC-DWV- and 40mm PVC-PN pipe (ideal friction fit) were glued together using PVC primer and cement. Lastly, it is important to note that the centroid of the ballast is located at a height of 1.2m from the ground. This height was obviously not optimal for the ballast, but quite optimal for leg lengths.

Figure 4.2.a. S1 ballast: Removing cover, **b.** S1 ballast: Fastening load-supporting leg, **a.** S1 ballast: Filling ballast

4.1.2. Mast

The core design requirement for the mast was to elevate the Wi-Fi accesspoint componentry to a height greater than 6m. In addition, the mast needs to anchor on the inside of the ballast, possess minimal tower-tip deflection in winds, and be structurally stable during various impact loads. Since it was decided by the Flinders team that the mast required the highest degree of axial stiffness, the mast was designed from the largest standard PVC pipe diameter possible in order to reduce bending. This meant that a combination of 40mm PVC-DWV and 40mm PVC-PN was used: 4 of 750x40mm PVC-DWV pipes and 4 of 750x40mm PVC-PN pipes. To join the 750mm section, standard 40mm PVC couplers were used, as can be seen in Figures 4.3.a.&.b. Lastly, the mast was centralised to the inside of the ballast through the re-use of the 25mm PVC cap, used for securing the load-supporting leg.

Figure 4.3.a. S1 mast: Detail of mast coupling, **b.** S1 mast: Joining the mast, **c.** S1 mast: Erecting the mast

4.1.3. Tripod Bracket

There were two key design requirements of the tripod bracket; to act as a 'structurally sound' pin-joint for the tripod legs, and to facilitate adjustable leg height through permitting vertical translation along the mast and load-supporting leg. It was decided by the Flinders team that this part needed to be custom-made. At this stage, since the mechanical properties of the 'accessible' MakerBot Replicator 2X 3D printed parts were unknown, the tripod bracket was designed to maximise structural strength and durability. This meant that the part was designed with 'excessively thick' pin-joint support struts and was printed with 100% infill. Furthermore, as can be seen in Figures 4.4.b.&.c., the part was printed from both ABS and PLA so that the structural strength and durability could be assessed during S1 of the tower's experimental analysis methods.

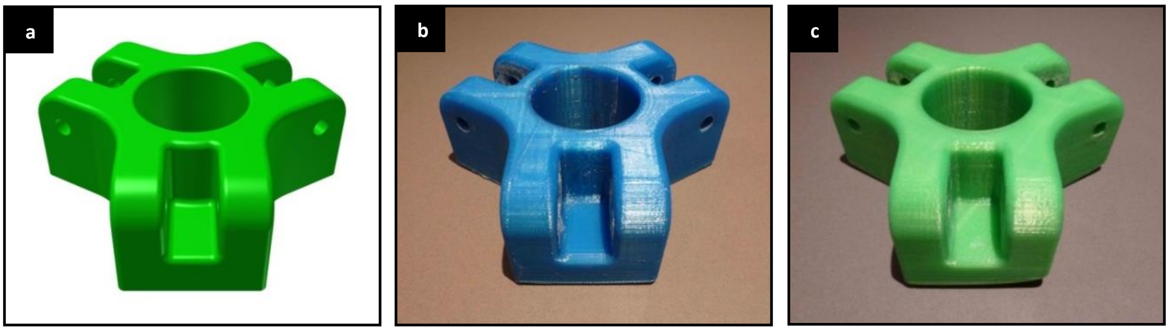


Figure 4.4.a. S1 tripod bracket: CAD model, **b.** S1 bracket: PLA printed, **c.** S1 bracket: ABS printed bracket

4.1.4. Wi-Fi Accesspoint

The design requirement for Stage 1 was to work with the client's network engineer to select hardware which could fulfil the needs of the client's proposed mesh network, while maintaining a compact nature. In order to gain appreciation of mesh networks, an extended literature review was completed. If the reader is interested in this review, please consult Appendix A. As part of designing the Wi-Fi accesspoint (AP), the Flinders team collaborated with Serval, as was discussed in Section 1.3. Serval disclosed the details of their 'Serval Mesh Extender' (SME), a long range (3km) Wi-Fi accesspoint, to help with the Flinders team's Stage 1 design. The design involves a LIfeP04 battery providing power to an embedded Wi-Fi router, which is connected to a passive USB hub in order to facilitate the use of a UHF radio modem and external storage device. Figure 4.5.a. shows the wiring of the S1 Wi-Fi AP components, and Figure 4.6.b. shows a schematic of the S1 Wi-Fi AP components

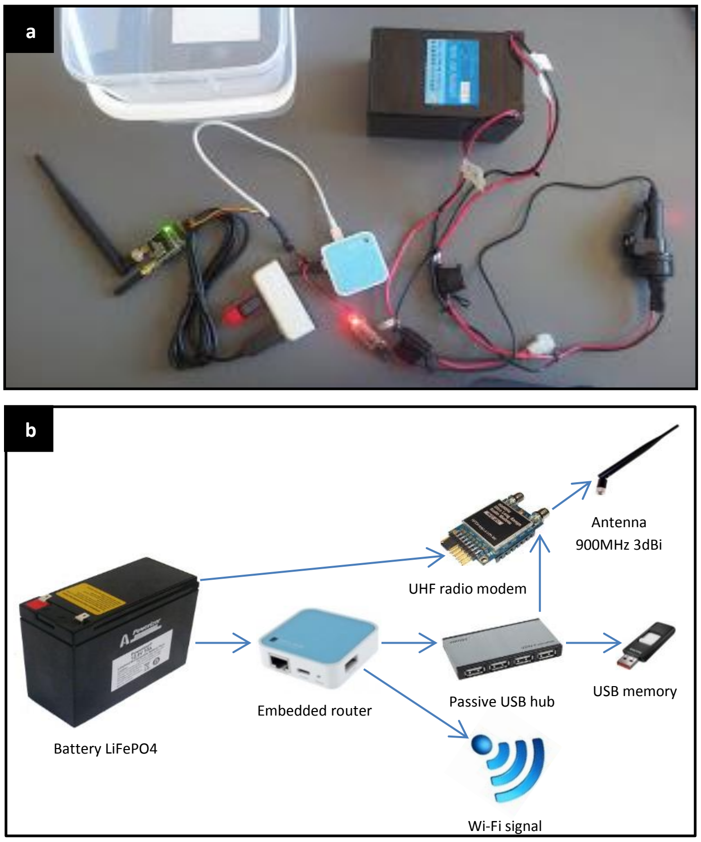


Figure 4.5.a. S1 Wi-Fi AP: Wiring of components, **b.** S1 Wi-Fi AP: Schematic of components
(Battery Space 2013; RFDesign 2012; TP-Link 2011; Vakoss 2013)

4.1.5. Electronics Housing

The primary design requirement for the electronics housing is to contain and protect the components of the Wi-Fi accesspoint. The secondary requirement for the housing is to act as a lid to the carry-case (i.e. lid for the ballast), as seen in Figure 4.6.b. To achieve these requirements while still providing a low-cost solution and fitting with the accessible components objective, two 150mm PVC pipe caps were utilised. These caps, located end-on-end have sufficient space to store all the components except for the battery (which will be located on the ground), and are more than capable of protecting the components from moisture and ultraviolet (UV) light. The housing is attached to the carry-case with two stainless steel latches and is attached to the top of the mast with a 25mm PVC threaded adapter fitting. The housing was attached to the carry-case with two stainless steel latches. Although not shown in Figures 4.6.a.&.c., ventilation and power lead holes were drilled on the underside of the housing. In addition, a hole was drilled on the round face to serve as a UHF radio modem antenna 'access port'. To hold the two halves of the housing together, standard electric tape was used since it provides a low-cost, water resistant solution.

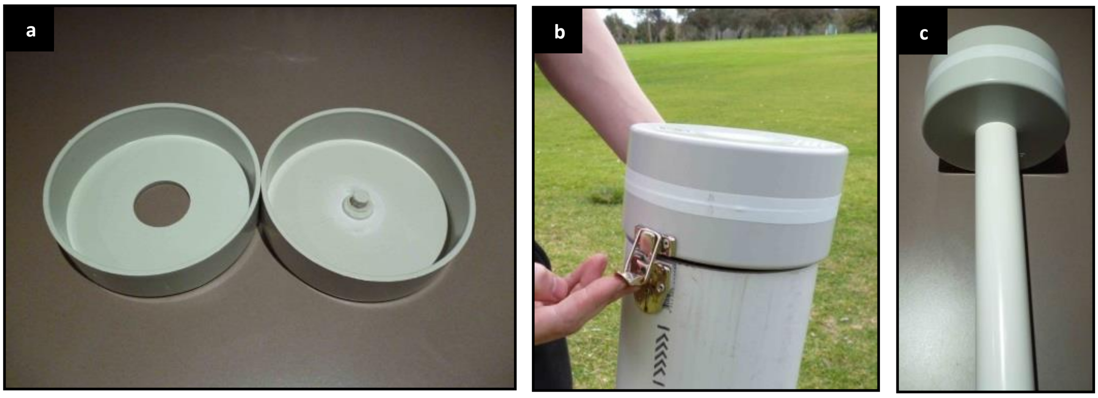


Figure 4.6.a. S1 electronics housing: Opened, **b.** S1 housing: Acting as lid, **c.** S1 housing: Detail of mast connection

4.1.6. Soft Carry-case

There are three key design requirements for the soft carry-case. The first is to provide an ergonomic means of carrying the tower in its packaged-state. The second is to act as a bag to store all the tower components together as a single item, and the third is to ensure that the total linear dimension of the bag are under 140cm. This was achieved by sewing a 'sleeping bag like' case (i.e. one opening with a single tightening cord) from denim and attaching a shoulder strap to each end of the bag. The design of the soft carry-case can be seen in Figures 4.7.a.&.b.

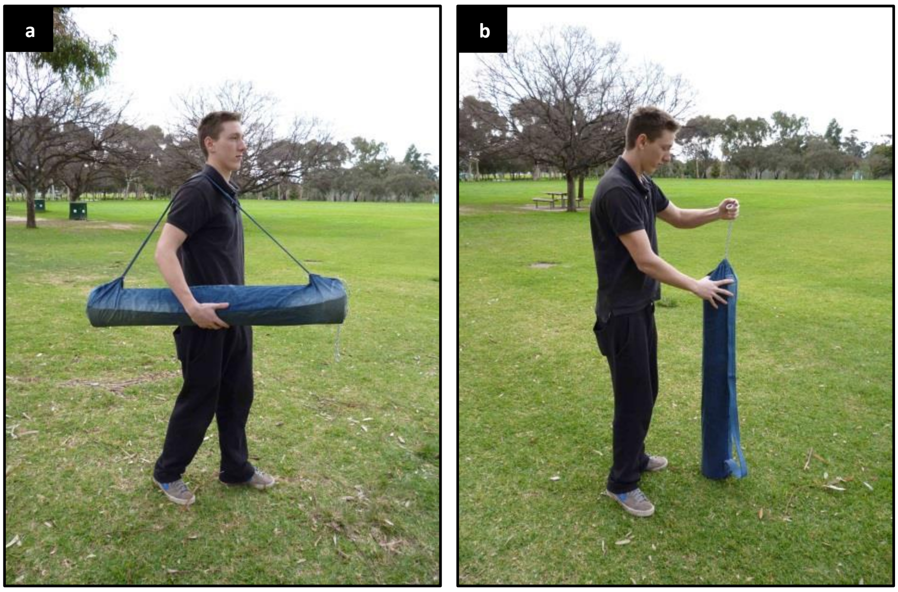


Figure 4.7.a. S1 soft carry-case: Detail of carrying position, **b.** S1 soft carry-case: Detail of carrying opening/closing mechanism

4.1.7. Other Parts

In closing this section it is important to point out that the other Flinders team student, David Ilba, was responsible for designing and analysing the tripod legs, leg joiners and guy-system.

4.2. S1 Experimental Analysis

Experimental analysis was undertaken to facilitate a performance review of the Stage 1 tower design. The key performance indicators that the prototype was tested for include: structural stability and strength, deployment times, and basic geometry checks.

4.2.1. Deployment Times

The aim of the 'deployment times' test was to determine realistic duration in which 'well trained' constructors could assemble and disassemble the tower. The S1 tower was assembled and disassembled multiple times by the constructors, until they considered themselves to be well trained. The analysis found that the constructors were able to assemble the tower following the sequence shown in Figure 4.8. in approximately eight minutes, and were able to disassemble it in 5mins.

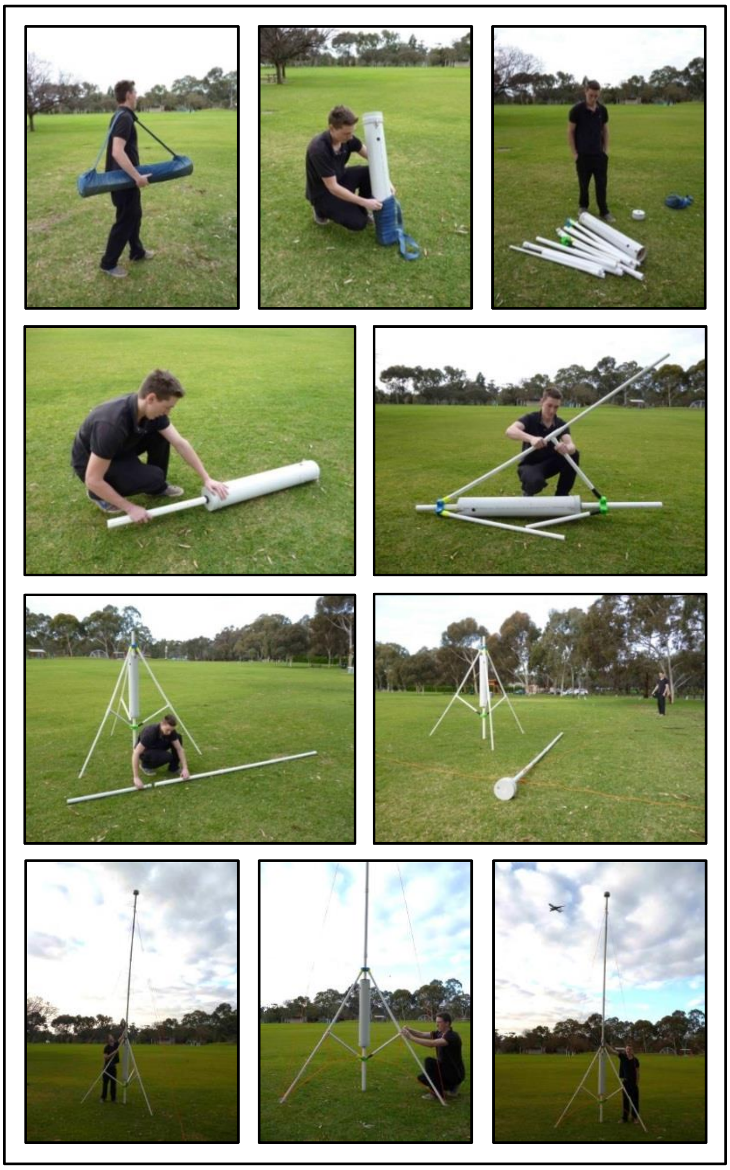


Figure 4.8. S1 tower: Assembly procedure

4.2.2. Structural Stability & Strength

The aim for the ‘structural stability and strength’ test was to determine whether the tower could maintain stability and to be free-of-failure after sustaining varying impact loads. Once erected, all the Flinders team members applied impact loads to the structure with varying magnitudes and locations. It was estimated by the team that the loads would have ranged from 1-50N. The analysis found that while the impact loads initially excited the tower, after short periods the vibrations would cease. It was realised that the tower had both sufficient strength to endure impacts and also a large enough footing plan and structural design to ensure that the tower was structurally stable.

Figure 4.9. S1 tower: Impact test load example

4.2.3. Geometry Checks

The aim of the ‘geometric checks’ performance analysis was to determine whether the tower met its broad array of geometric design constraints. The first check, as shown in Figure 4.10.a., involved positioning the S1 tower next to the tallest manmade structure in Bonython Park to check that it had adequate clearance. This check verified that manmade structures would minimally obstruct the Wi-Fi signal from an AP located at the top of the tower, and ultimately showed that the tower design met its height specification. The second check, as shown in Figure 4.10.b., involved packaging the tower into its carry-case and measuring its total linear dimensions to check whether it met the checked-baggage specification (140cm). Unfortunately the check showed that the design did not meet this requirement, since its total linear dimensions were approximately 150cm. Lastly, the third check, as shown in Figure 4.10.c., involved getting permission from a construction site, to use their temporary fence panels (TFPs) to check whether the tower’s footing plan fitted inside three standard TFPs. This check showed that the tower design met the footing plan specification.

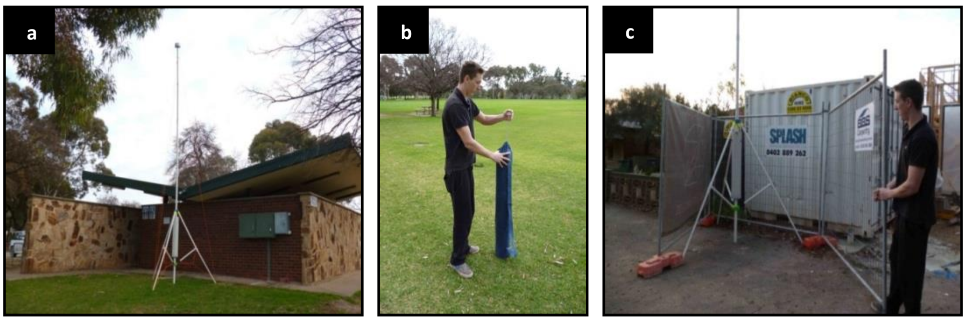


Figure 4.10.a. S1 tower: Height relativity check, **b.** S1 tower: Checked-baggage check, **c.** S1 tower: Footing plan check

4.3. S1 Performance Review

A performance review was undertaken to help analyse the 'relative performance' of the tower design compared with existing competitor products. This involved initially costing the tower and compiling data obtained from experimental tests to determine if the project goals had been achieved, before providing a brief competitor product comparison to see if the project was on the 'right track'.

4.3.1. Prototype Costs

While compiling the costs of the major Australian hardware store's off-shelf parts simply required time and effort, developing 'accurate costs' for the 'free' custom-made 3D printed parts was more challenging. The reason for this was because, as shown in Figure 4.11., as the infill percentage changes (see Chapter 5 for more discussion), the mass of the part changes linearly but the printing time changes non-linearly. This is obviously to do with the printer's tool-path drivers, however further investigation is outside the scope of the project. To overcome this problem a basic 'MakerBot replicator 2X 3D printing cost calculator' was developed which uses the cost of plastic per kg (48AUD/kg) and a fixed machine amortisation rate per cycle (1% of machine cost – approximately 29AUD; includes programing and part loading/unloading). Equation 6 summarises this calculator, and was used to generate the costs of the custom-made parts.

$$Part\ Calculator\ =\ (weight\ of\ plastic\ \times\ cost\ per\ weight) +\ 1\%\ machine\ amortisation\ per\ cyc. \qquad (6)$$

Figure 4.11.a. 100% infill, **b.** 50% infill, **c.** 25% infill, **d.** 10% infill (3D Printing Systems 2013)

Table 4.1. summarises the S1 prototype costs and is based on more detailed cost breakdowns, which can be seen in Appendix F. Unfortunately this shows that the S1 tower does not meet its low-cost specification. It should be noted that these are retail costs and that the overall cost of the tower will drop substantially if the product was to be commercialised and thus costed on wholesale prices. However, since the aim of the project is to develop an open source tower designed from accessible components, retail prices will remain relevant for the remainder of the thesis.

Table 4.1. Summary of S1 prototype costs

Type	*Classification*	*Cost (AUD)*
Structural	Custom-made parts	78.90
	Off-shelf parts	231.72
Electronics	Wi-Fi accesspoint parts	353.05
	Total	***663.67***

4.3.2. Project Goals

The most important goals, as determined from the Quality Functional deployment method, were reviewed to ensure that the project was on track for achieving a successful outcome. Although as shown in Table 4.2., the majority of the engineering specifications were achieved, several were not. The total linear dimensions of the carry-case exceeded their specification of 140cm, and the low-cost target of 250AUD was exceeded. This highlighted the need for the Flinders team to pay close attention to these specifications during Stage 2 of the tower design and analysis. It is also important to note that the 'factor of safety' specification was not confirmed, and needs further review during Stage 2.

Table 4.2. Summary of S1 project goal performances

Requirement	***Specification***	***Performance***	***Result***
Lightweight	Weight of tower suitcase < 32kg	22kg	Spec. achieved
Compact	Total linear dimensions < 140cm	150cm	Spec. not achieved
Rapidly-deployable	Time to assemble tower < 15mins	8mins	Spec. achieved
Low-cost	Tower cost < 250AUD	310AUD	Spec. not achieved
Maximise Wi-Fi coverage	Extend to height > 6m	6.5m	Spec. achieved
Maximise factor of safety	FOS > 2	?	Needs further review
Maximise replacement part accessibility	No. off-shelf comp. > No. custom comp.	True	Spec. achieved
Minimise tower-tip deflection	Horizontal displacement < 1m	0.7m	Spec. achieved
Minimise footing area	Footing area < 2.2m equilateral triangle	2.1m	Spec. achieved
Minimise parts	No. unique parts < 15	8	Spec. achieved
Minimise joints	No. unique joints < 10	6	Spec. achieved

4.3.3. Competitor Product Comparison

The performance of the S1 tower was compared to structures which the literature reviewed revealed to be the benchmark. As can be seen in Table 4.3., the S1 tower proved to be lighter than the 'lightweight' GST05, substantially cheaper and lighter than the 'freestanding' VMCT13, quicker to setup than the 'rapidly-deployable' HDCA15, slightly heavier yet quicker to setup that the 'portable' PTM15, but unfortunately significantly more expensive than the 'low-cost' LC67. Although the S1 tower did not perform better in all categories than its competitors, the Flinders team believe that this tower design is 'on track' to positioning itself well in the telecommunication mast and tower product industry.

Table 4.3. S1 tower performance comparison with competitor products

Performance Characteristic	***Flinders Team (S1Tower)***	***GeoStrut (GST05)***	***NXL (VMCT13)***	***AP Landing (HDCA15)***	***Go Vertical (PTM15)***	***USAF (LC67)***
						
Best perform.	-	Lightweight	Freestanding	Rapid.-deploy.	Portable	Low-cost
Height (m)	6.5	5	13	15	8	6.7
Mass (kg)	16	18	120kg	unspecified	15	unspecified
Set-up (mins)	8	10	unspecified	30	20	30
Cost (AUD)	310	unspecified	1600	7800	230	163

*table notes: set-up times are based on different 'constructor abilities'

4.4. Areas for Redesign

At the completion of Stage 1 of the tower design and analysis the Flinders team met to discuss potential areas for performance improvement. The redesign areas specific to the author's project tasks include:

- Ballast – redesign to:
    - Lower centre of gravity
- Mast – redesign to:
    - Improve structural rigidity
    - Lengthen
- Tripod bracket – redesign to:
    - Facilitate lengthening of mast
    - Improve ease of packaging
- Wi-Fi accesspoint – redesign to:
    - Reduce cost
- Electronics housing – redesign to:
    - Cater for proposed structural guy-rope connections on underside of housing

5. Chapter 5: 3D Printer Review

This chapter presents an investigation into the performance of the Replicator 2X 3D printer which was released to the domestic market as a 'hobbyist printer' in early 2012. The replicator 2X was deemed in Chapter 3. to be an accessible 3D printing technology due to its low purchase cost, and the fact that Flinders University students have access to two of these units. Essentially this chapter will outline the characteristics of the two printable thermoplastics; acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). It will then provide a brief discussion of the strength versus weight trade-off, before concluding with a summary of a materials test undertaken to determine the mechanical properties of these plastics in their printed form.

To investigate various properties of the Replicator 2X, both a review of product data sheets, as well as several interviews with industry experts were undertaken. Mr David Brown, the owner of 3D Prototypes and Models provided much insight on the structural strength of various infill percentages, and Ms Kimika Faint, from Adelaide's Fab Lab was also able to help with the strength versus weight optimisation problem as well as provide further insight into printing resolutions.

5.1. Characteristics of ABS & PLA

ABS has excellent mechanical properties, however it also has a tendency to *curl* and *shrink* during the 3D printing process. PLA on the other hand is a renewable bio-plastic that sticks to the platform reliably with practically no curling or shrinking, and according to MakerBot (2013a) uses 32% less energy when printing as opposed to ABS filament.

ABS filament is made of a combination of acrylonitrile, butadiene and styrene. The three plastics can be mixed in different proportions to formulate ABS intended for different uses. ABS is tough and somewhat flexible. ABS becomes softer with increased temperatures, but at the extrusion temperatures used in a MakerBot it remains fairly viscous. ABS can also withstand heat well enough that MakerBot (2013b) claim they use it to make the plastic components of the Replicator 2X's extruders.

PLA filament is a biodegradable plastic with properties that make it very suitable for 3D printing. Research has shown that many hobbyists prefer using PLA because it does not give off unpleasant fumes. PLA has a low rate of thermal expansion, and therefore it does not warp as much as ABS. PLA is harder and slightly more brittle than ABS, and is more likely to break than bend. In contrast PLA stays flexible for a short while as it cools, which contributes to its better 'printer bed adherence' property. Table 5.1. summarises the differences in characteristics between ABS and PLA.

Table 5.1. Summary of ABS vs PLA characteristics

ABS	PLA
Stronger	Faster to print
More flexible	More precise
Easier to machine	More consistent
Higher temperature resistance	Wide range of colours & translucencies
Requires heated print bed	Sweet printing odour
Petroleum printing odour	

5.2. Optimisation of Strength vs Weight

Understanding the printing process is essential to gaining an appreciation for the 'strength versus weight' optimisation problem. The Replicator 2X begins printing an object by putting down several solid layers (the floor). It then starts each new layer of an object by printing a number (as determined by the user) of outlines of that layer, which are referred to as shells. If there is more than one shell, the additional shells will be nested inside the first one. Everything that is not a shell, floor, or roof is then filled with an internal lattice called infill, as shown in Figure 5.1. which provides the object with an internal support structure. A hollow object with no internal support structure will have an infill of 0%, and a completely solid object will have an infill of 100%. The number of shells can be chosen and they will print as concentric perimeters on each layer. It is important to realise that a greater number of shells and higher percentage infill will result in stronger but heavier parts. Lastly it should be noted that the programmable 'layer height' determines the thinness of each printed layer of the object being printed. It is often treated as a measure of resolution in 3D printing, which affects resolution only on the Z-axis (vertical axis). Thinner layers will result in a smoother surface, but will also increase print times. The Replicator 2X has a Z-resolution range of 100-300 microns (MakerBot 2013b). Given the project's low-cost requirement, the Flinders team decided that a resolution of 300 microns is acceptable.

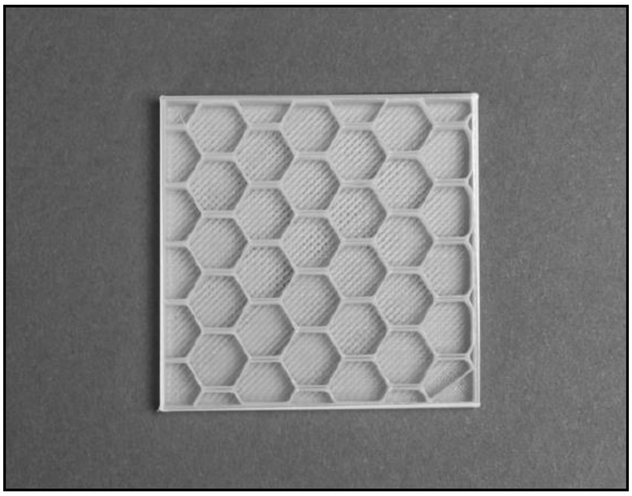


Figure 5.1. MakerBot: 20mm calibration box (MakerBot 2013b)

It was confirmed by Ms Kimika Faint from Fab Lab Adelaide (2013, pers. comm. 10 October) that there is a negligible difference in material strength between 100 and 300 micron printed parts. Furthermore, Ms Faint advised that a 50% infill actually provides the maximum strength for this 'type' of 3D printing at a Z-resolution of 300 microns. Mr Daniel Brown from 3D Prototypes & Models (2013, pers. comm. 15 October) confirmed this by stating that 3D printers using fused deposition modelling (FDM) technology achieved maximum strength at 50% infill. Mr Brown also stated that many of his clients found that 15% infill was surprisingly strong and sufficient for their needs, and at 50% infill injection moulded should be considered as an alternative. He also stated that whilst 50% is the strongest infill it does take three times longer to print, and he believes that it is certainly not three times stronger than 15% infill. When asked how to achieve the optimal strength to weight ratio Mr Brown recommended using four shells at 15% infill or three shells at 20%, which he believed would provide just as much strength as one shell at 50% infill. Taking all these discussions into consideration, as well as wanting to determine the load bearing capabilities of the plastic, the Flinders team members decided to print their respective parts during Stage 2 with both: 4 shells - 50% infill, and 4 shells - 100% infill. This decision ensured that the custom-made parts would be as strong as the 3D printing process permits.

5.3. Experimental Testing of 3D Print Samples

During Stage 1 of the design and analysis of the tower it was realised that the parts printed by the Replicator 2X have anisotropic material properties. Furthermore, a brief literature review revealed that there is a gap in the field of 'known mechanical properties' of the Replicator 2X printed parts. In order to determine the mechanical properties of the parts the Flinders team decided to utilise the Instron tensile testing apparatus which was available at Flinders University to experimentally analyse these properties. Since it became apparent that ABS is a stronger plastic than PLA, the team decided to test dog-bone specimens of PLA to determine the 'worst case' mechanical properties of parts printed by the Replicator 2X. In addition, the team tested a variety of specimens that had been printed with different layups to determine which print layups had the lowest mechanical properties. The various layups specimens are shown in Figure 5.2., and include: 45 degree angular thickness printed specimens (6of), 45 degree angular width printed specimens (6of), vertically printed specimens (6of) and horizontally printed specimens (5of).

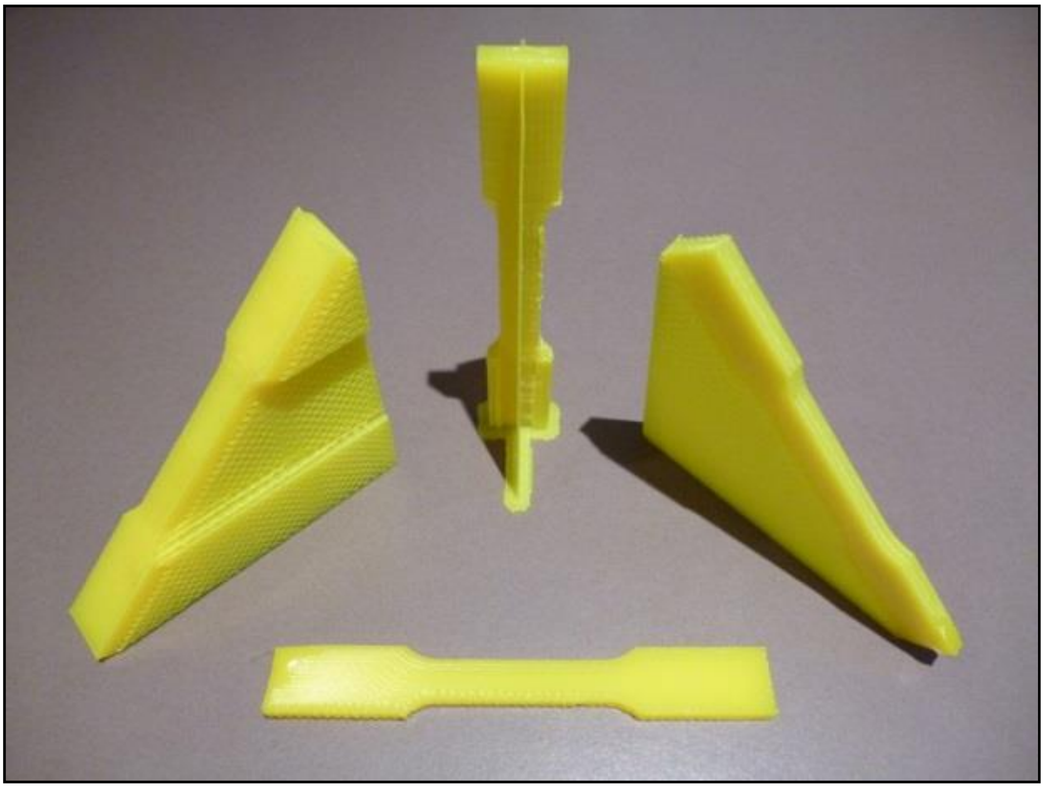


Figure 5.2.Left. Angular thickness printed specimen, **Right.** Angular width printed specimen, **Mid.-top.** Vertically printed specimen, **Mid.-bottom.** Horizontally printed specimen

5.3.1. Methods

The PLA dog-bone specimens were inserted into the Instron, as shown in Figure 5.3.a. An extensometer was then clamped to the specimens to track the displacement during each test. The Instron was controlled by desktop computer software, which simultaneously logged incremental force and displacement results. Before each test the specimen's cross-section was measured so that the stress could be calculated during the test and in combination with the extensometer, the specimen's Young's modulus (elastic modulus) could be determined.

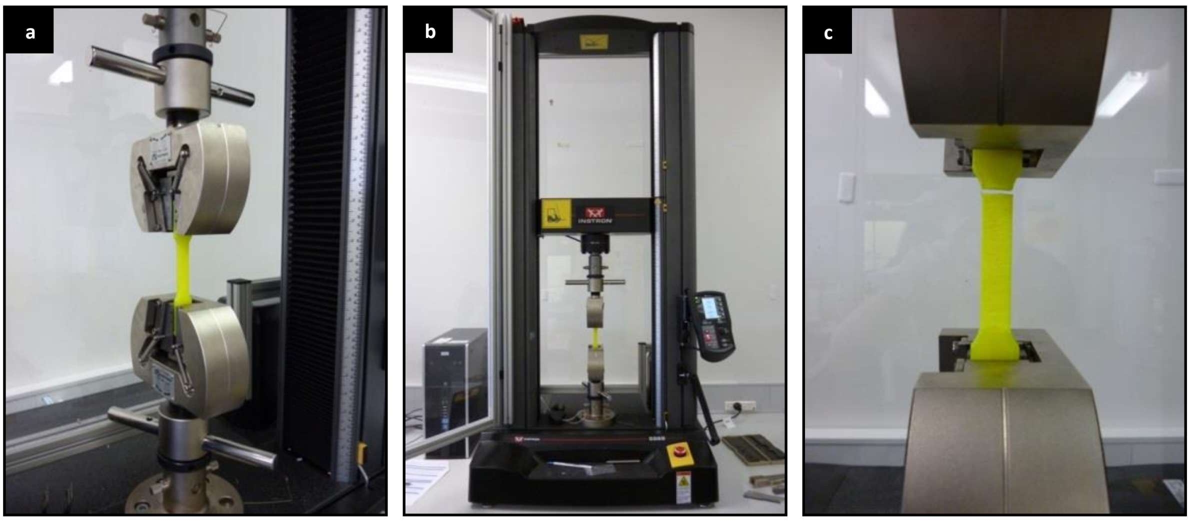


Figure 5.3.a. Inserting the specimen into the Instron, **b.** Instron test apparatus, **c.** Example of specimen failure

The test specimens were loaded until they broke. During the test however, the extensometer was removed at approximately 2% strain to ensure that it was not damaged during the fracture phase. In Figure 5.4. it can be seen where the extensometer was removed, as shown by the instantaneous fall in tensile stress. After each test the data was logged by the Instron's software, and this data was then used to determine the mechanical properties of the PLA specimen.

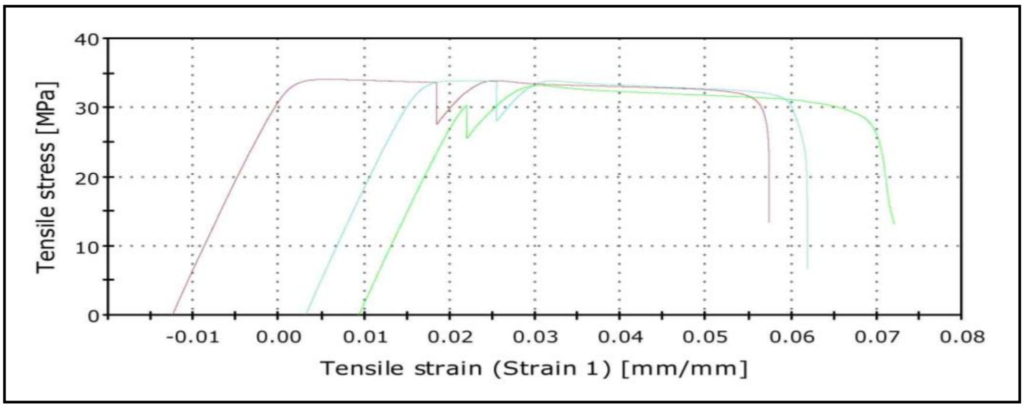


Figure 5.4. Tensile tests results: 45 degree angular thickness specimens

5.3.2. Observations

Several observations were made upon inspection of the failed specimens. From Figures 5.5.a.-.d. it can be seen that the horizontally and vertically printed specimens failed at random locations, whilst the angular specimens seemed to mostly fail near the clamping region of the specimens. It was also realised that the vertical specimens failed along a layer of the plastic, whilst the angular specimens failed over several layers. As a result the project team concluded that the direction of print layup does not necessarily indicate regions of lower mechanical properties, and that further testing was required to gain a better understanding of PLA's anisotropic properties.

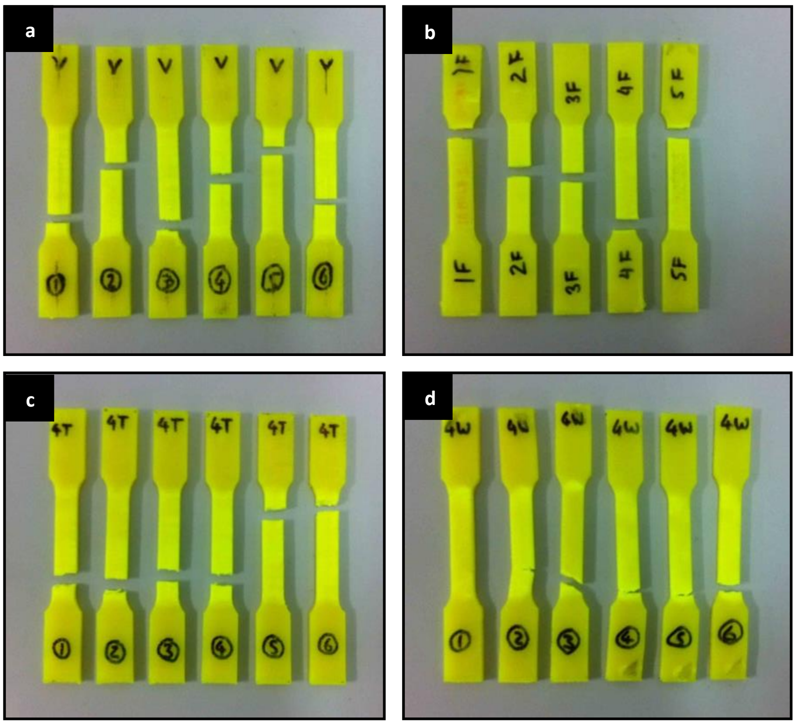


Figure 5.5.a. Vertically printed specimens, **b.** Horizontally printed specimens, **c.** Angular thickness printed specimens, **d.** Angular width printed specimens

5.3.3. Results

The Instron experimental test results showed that the horizontally printed PLA specimens have the highest average yield stress (38MPa), while the 45 degree angular width printed specimens had the lowest (32.6MPa). It is believed that this is due to the fact that the horizontal specimen's layers run parallel to the tensile load thus providing the most resistance, whereas the angular width specimen's layers run perpendicular to the load thus providing less resistance.

It is interesting to note the results of the Young's modulus, where the horizontally printed specimens have the lowest average modulus (2.47GPa), and the 45 degree angular width specimens have the highest (2.71GPa). Given that both the angular specimens have higher Young's moduli than the others this suggest that angular printed layups provide more stiffness than perpendicular and parallel printed layups. Figure 5.6. and Figure 5.7. summarise the averages of the test results with one standard deviation of a normal distribution marked as well. For more detailed test results, please consult Appendix H. It should be noted that, since a material property study was not initially planned for the project, nor is it a core project objective, this section has merely provided a general overview of the mechanical properties of Replicator 2X 3D printed parts.

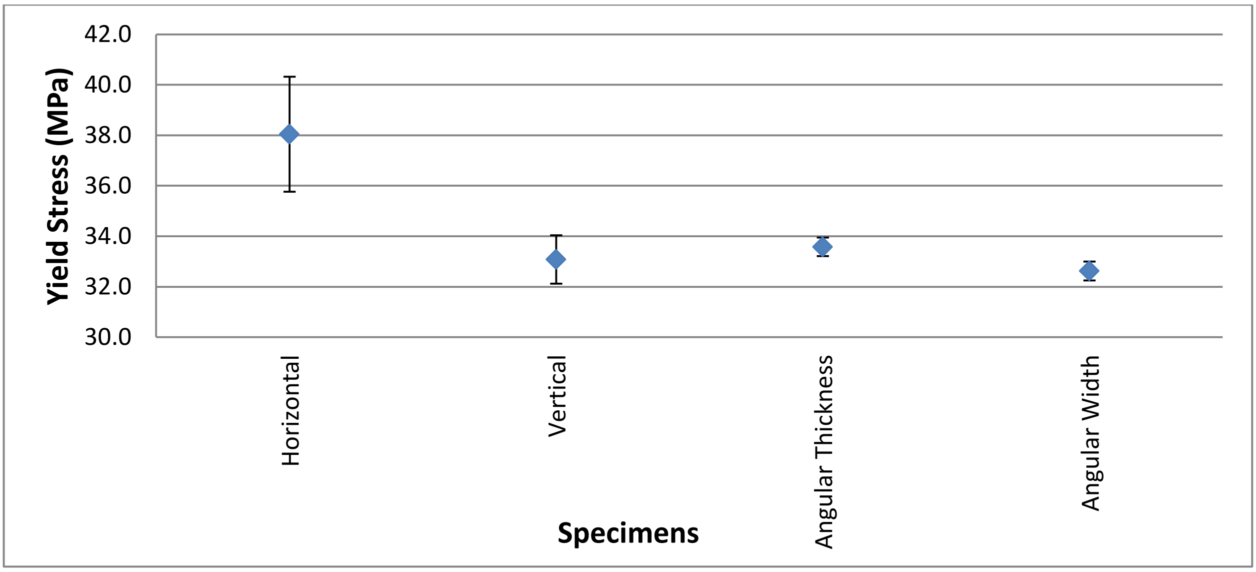


Figure 5.6. Tensile yield stress of 3D printed tensile test specimens with different print layups. The mean yield stress of the different tensile specimens is indicated by the diamond and the error bars indicate one standard deviation of the data.

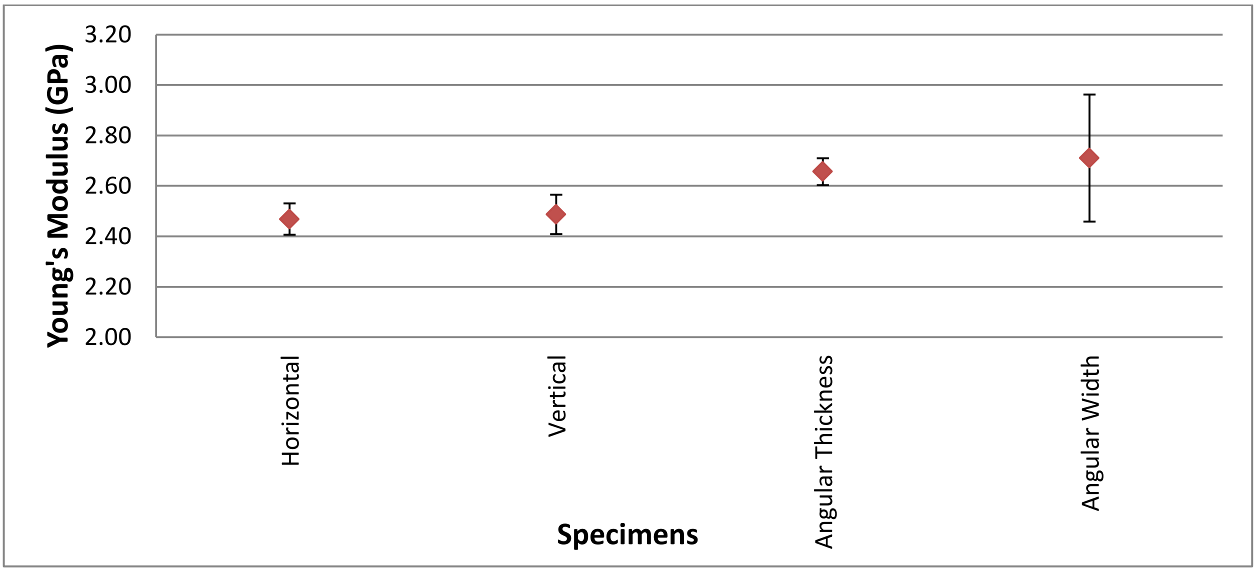


Figure 5.7. Young's Modulus of 3D printed tensile test specimens with different print layups. The mean Young's Modulus of the different tensile specimens is indicated by the diamond and the error bars indicate one standard deviation of the data.

6. Chapter 6: Stage 2 Design & Analysis

It is often the case that various design stages reveal new functional requirements for parts after they have already been 'fully' designed. Chapter 6 will not only present how design issues identified from Stage 1 (S1) were solved by redesigning the tower's parts during Stage 2 (S2) with Autodesk Inventor, but it will also present the details of the theoretical and experimental analysis measures undertaken to ensure the tower successfully meets the project's goals. Experimental analysis of the S2 tower and components was performed; to determine the strength of the tripod bracket as well as the mast and electronics housing, to identify the load required to topple the tower, to analyse the change in natural frequency of the tower under varying guy-rope tensions, and to assess the durability of the tower. Theoretical analysis was undertaken to; determine the axial, bending and Von-Mises stresses present in all the author's manufactured components under theoretically calculated loads, to analyse the first mode of vibration of the structure, and to determine whether there is any displacement experienced by the components which will affect the performance of the tower (i.e. displacements which contribute to a tower-tip displacement greater than 1m from the mast's vertical axis). It is important to note that Section 6.1. aims to provide a general design description of the tower; it is realised by the author that the description is not detailed enough to be used as an open source instruction guide for fabricating and deploying the tower.

6.1. S2 Tower Design

Once the required design refinements had been made to the individual components, the S2 tower prototype was constructed as per the Flinders team's final design. The refinements made during S2 included: lowering the ballast, repositioning the top guy connection-point from the mast to the electronics housing, strengthening of the mast and legs, upgrading of the carry-case to a canvas bag, and the removal of material from the tripod bracket to facilitate mast and leg section extensions.

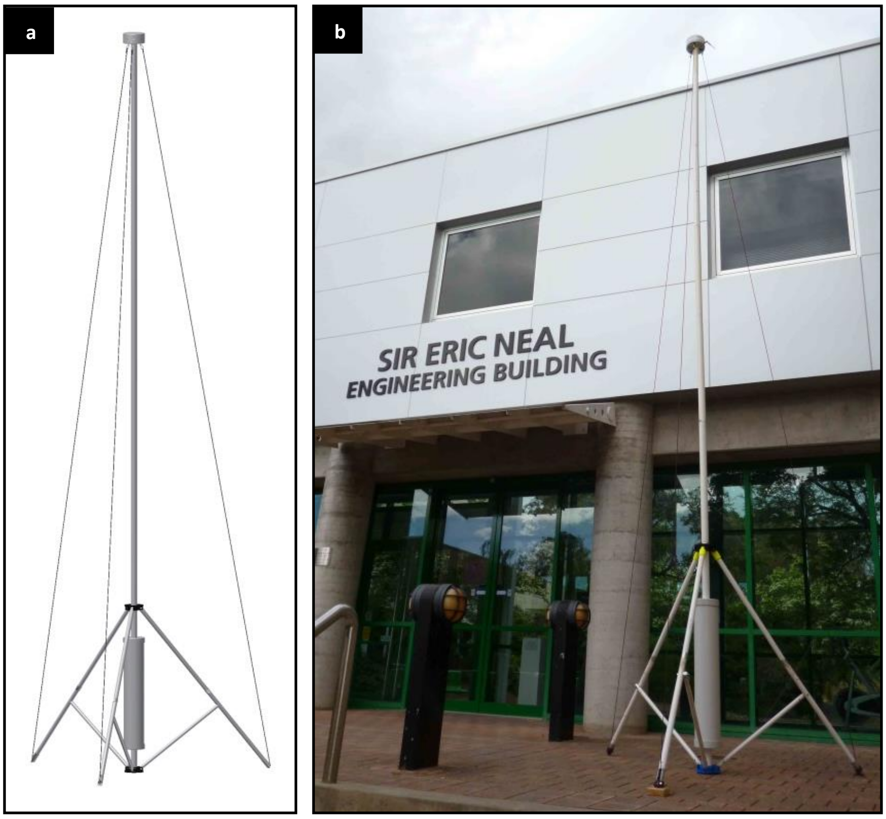


Figure 6.1.a. S2 CAD model, **b.** S2 tower prototype

6.1.1. Ballast

The ‘live-load’ ballast design remained relatively unchanged during S2 of the project. The main component of the system is still made from 150mm PVC-DWV pipe with two 150mm PVC caps instead of just the one. The additional cap was included to aid with centralising the mast at the top of the ballast, as can be seen in Figure 6.3.c. The load-supporting leg was again made from a glued combination of 40mm PVC-DWV and 40mm PVC-PN pipe sections, but was shortened in order to lower the ballast’s centre of gravity. The load-supporting leg pipes were also staggered, as can be seen in Figure 6.2.c., to ensure that the transfer of load from the ballast was being evenly distributed on both the DWV and PN pipes. In order to fit both the ballast and electronics housing into the ‘soft’ carry-case, as shown in Figure 6.8.d., it was necessary to reduce the length of the ballast from 1m to 980mm. Reducing the length by 20mm had a negligible effect on the weight generated by the ballast (changed from 173N to 170N). However it is important to note that lowering the ballast’s centre of gravity from 1.2m above the ground to 650mm significantly increased the stability of the structure.

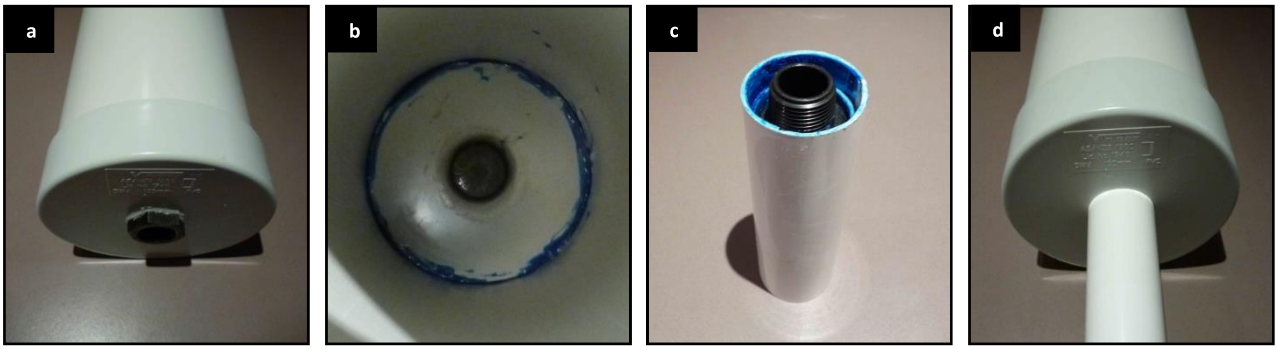


Figure 6.2.a. S2 ballast: External detail of bottom cap, **b.** S2 ballast: Internal detail of bottom cap, **c.** S2 ballast: Load-supporting leg, **d.** S2 ballast: External detail of bottom cap joint

6.1.2. Mast

Considering that the S1 mast ‘coupling arrangement’ design proved to have too much sway (due to excessive joint movement between the couplers and mast sections) to be considered as a rigid structure, the mast required a major redesign. Instead of using the coupling arrangement, as shown in Figure 6.3.a., the mast was modified to a ‘composite arrangement’ of PN and DWV PVC pipes. This modification utilised the small tolerance between the outside of the DWV pipe and the inside of the PN pipe to create a mast that is both quicker to assemble and disassemble, as well as more compact and elegant as a design solution. The composite arrangement allowed the mast to be designed so that the DWV and PN pipe section could simply stack on top of one another in an alternative ‘half-section-at-a-time’ manner, which meant that no couplers were required. Figure 6.3.b. shows the composite arrangement of the S2 mast design.

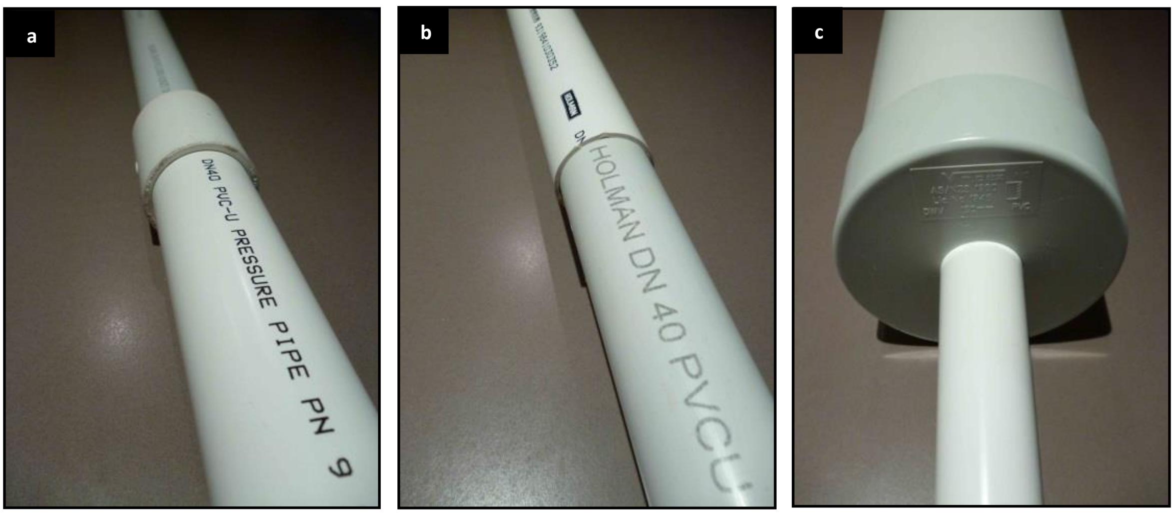


Figure 6.3.a. S1 mast: Detail of coupling arrangement, **b.** S2 mast: Detail of composite arrangement, **c.** S2 mast: Detail of top cap joint

6.1.3. Tripod Bracket

The tripod bracket was the most extensively redesigned part during S2. A substantial amount of material was removed from the region near the central collar in order to facilitate the penetration of the mast and leg sections into the bracket during its packaged-state. Given that sections were penetrating the bracket, it seemed worthwhile to redesign the bracket in such a way that it could aid with the tower packaging process. For this reason, additional circular-continuation sections were added to the part, as can be seen in Figures 6.4.a.-.c. This redesign proved to significantly simplify the 'constructors' task of having to hold the sections in position while the other constructor inserts the top tripod into the bottom one. It is also important to note that the removal of material from the discussed regions did not reduce the structural rigidity of the bracket. The final tripod brackets were fabricated from black PLA to maximise UV stability and were printed with four shells at 50% and 100% infill to investigate the strength of these two different 3D print configurations.

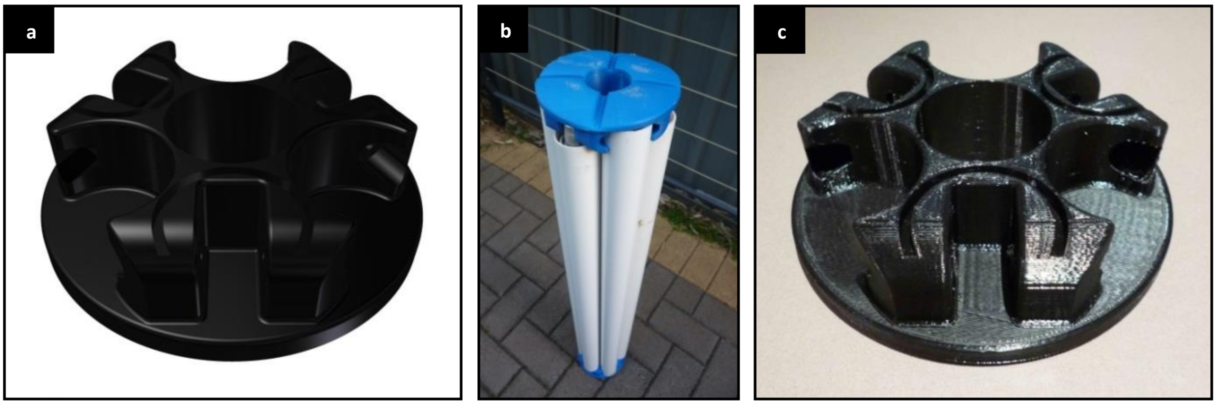


Figure 6.4.a. S2 tripod bracket: CAD model, **b.** S2 bracket: Packaged-state, **c.**S2 bracket: PLA printed

6.1.4. Wi-Fi Accesspoint

During S2 the Wi-Fi accesspoint (AP) componentry was also significantly modified in order to both reduce the cost of the unit and to increase available random-access memory (RAM). This involved swapping the embedded Wi-Fi router for a Raspberry Pi single-board computer and a Wi-Fi network adapter to increase the RAM, and swapping the UHF radio modem with a second Wi-Fi network adapter to reduce the cost of the accesspoint. Figure 6.5. shows a schematic of the new unit.

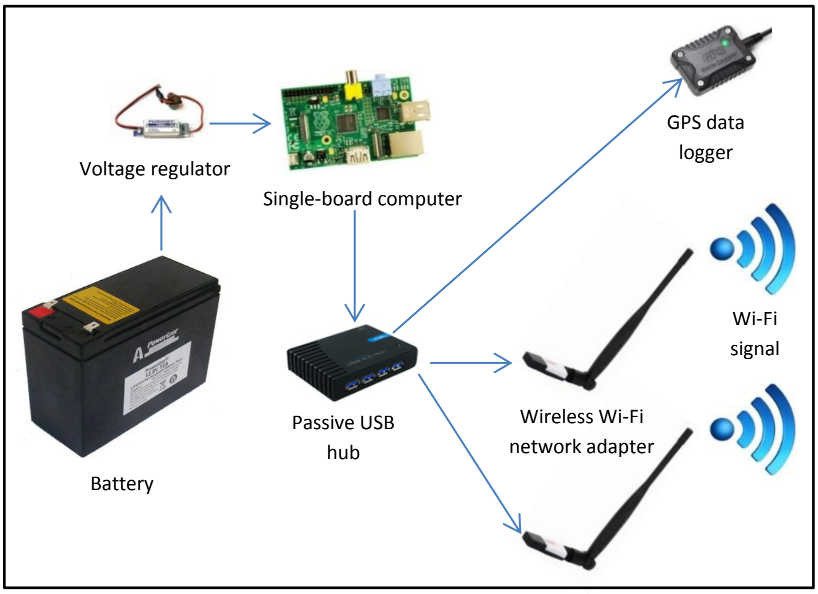


Figure 6.5. Schematic of S2 accesspoint electronics (Battery Space 2013; Columbus 2013; Comfast 2013; Element14 2013; Turnigy 2013; Zipp 2013)

6.1.5. Electronics Housing

Apart from repositioning various holes due to the reconfiguration of the electronics, the primary redesign aspect for the electronics housing during S2 was to include structural connection-points for the guy-ropes. In order to accommodate structural connection-points whilst limiting alterations to the natural structure of the 150mm PVS caps, a custom-made 3D printed insert was designed to fit inside the housing and provide structural pivot locations for the three 3mm stainless steel hinging-connectors (made from mild steel in the prototype). Figure 6.7.b. shows how the 3D printed part fits inside the housing, and Figure 6.6.a. shows how the steel hinging-connectors pivot inside the new part. The housing is attached to the top of the mast with a 25mm PVC threaded adapter fitting, as can be seen in Figure 6.6.b.

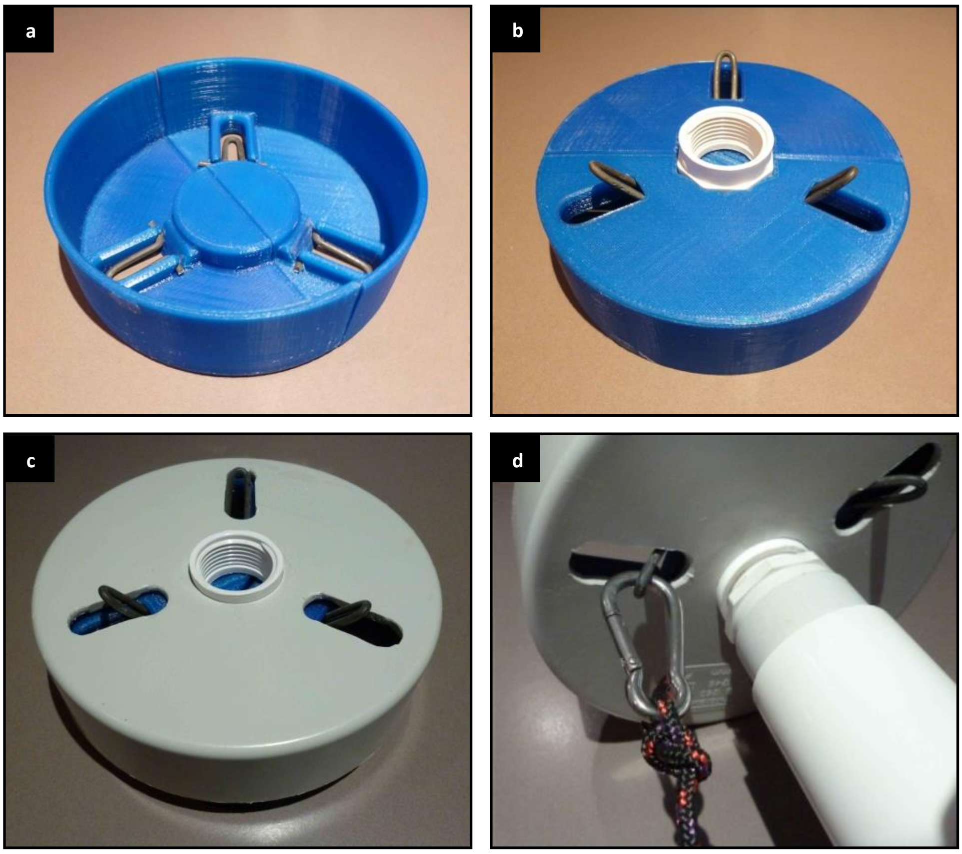


Figure 6.6.a. S2 housing: Internal detail of insert, **b.** S2 housing: External detail of insert, **c.** S2 housing: External bottom detail of cap, **d.** S2 housing: Detail of guy attachment to the hinging-connector

Redesigning the guy attachment system both reduced the deployment time (by one minute), as well as the likelihood of the mast failing (due to stress concentration induced by drilling holes through the top of the mast for the guy-connector brackets). Modifying the AP componentry made it easier to fit the electronics inside the housing, as can be seen in Figure 6.7.a. The total weight of the electronics housing (includes Wi-Fi AP componentry) is 966g.

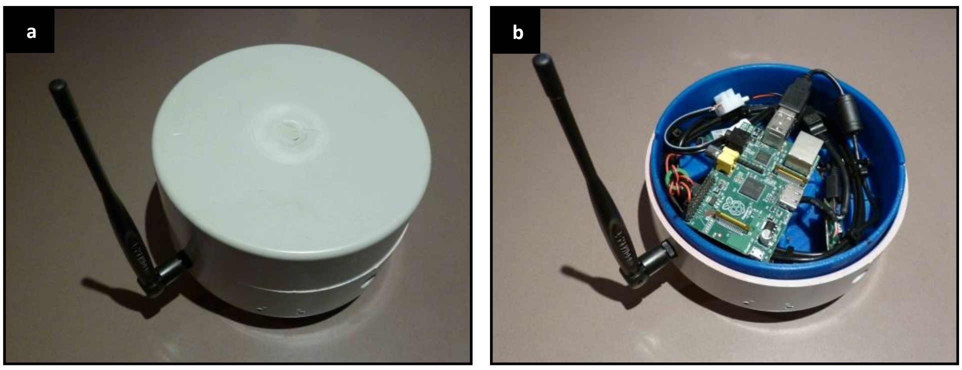


Figure 6.7.a. S2 housing: External top detail of housing, **b.** S2 housing: Internal detail of housing with AP components

6.1.6. Soft Carry-case

During S2 the soft carry-case was modified to an off-shelf standard 'arm chair' bag, purchasable from most outdoor leisure stores in Australia. This both lowered the production cost and helped achieve the project's part accessibility goal. Figures 6.8. illustrates how the tower is packaged.

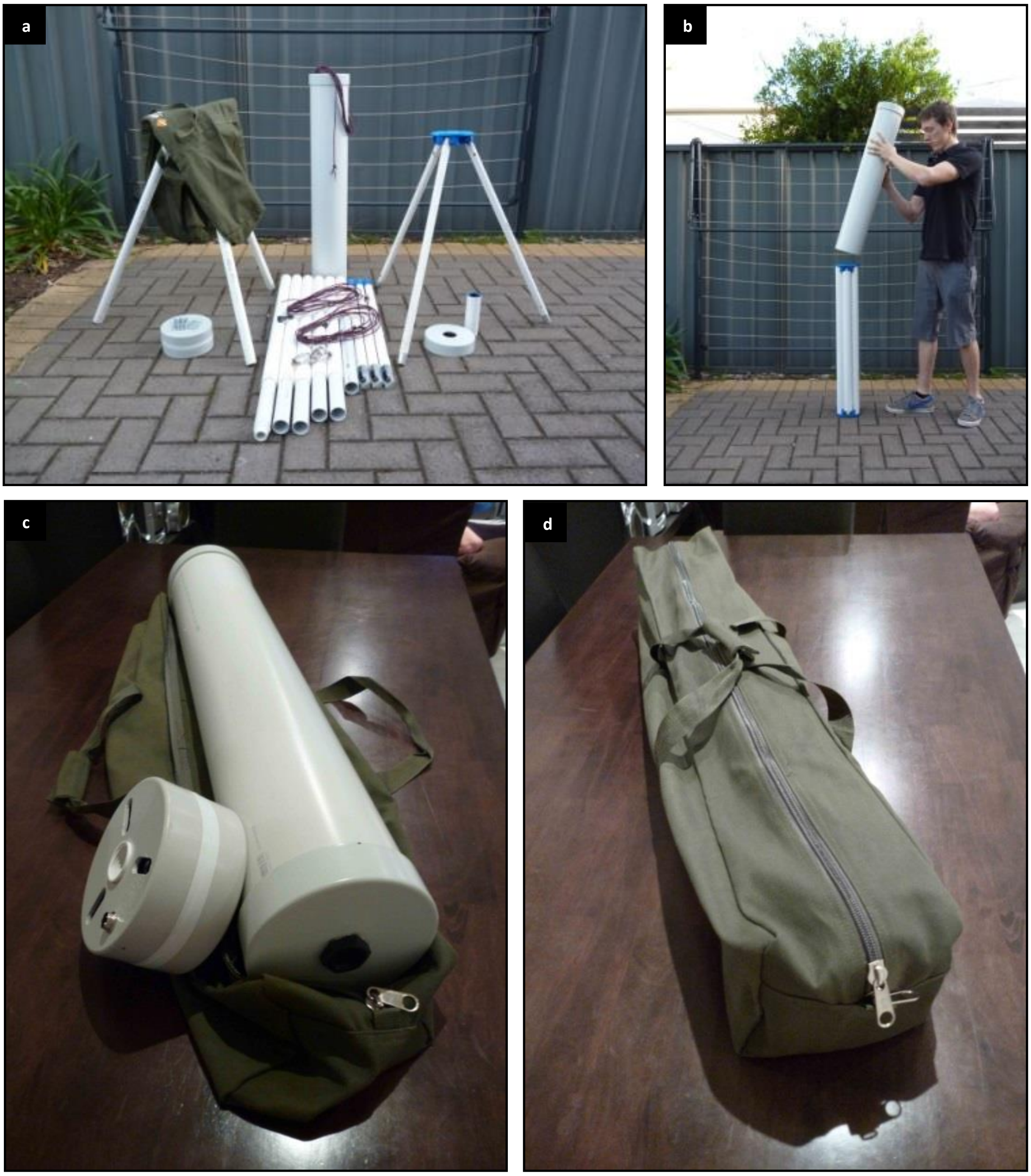


Figure 6.8.a. S2 tower unpacked, **b.** S2 tower packed into hard carry-case,
c. S2 hard and soft carry-cases, **d.** S2 tower packaged-state

6.2. S2 Experimental Analysis

Experimental analysis was undertaken on both the tower components and complete tower structure in order to determine the performance of the tower design. This involved initially testing the tripod bracket, mast and electronic housing to determine the strength of these components. After the tests were complete and the Flinders team were satisfied with the quality of the results, the tower structure as a whole was analysed. This involved determining the force required to topple the tower, determining the natural frequency of the tower within a varied spectrum of guy-rope tensions, and finally leaving the tower setup outside for an extended period to determine its dynamic wind load performance.

6.2.1. Tripod Bracket Strength Test

The strength of the tripod bracket was tested for two 3D printing infill variations. One bracket was printed with four shells at 50% infill and another was printed with four shells at 100% infill. The brackets were initially tested under compression, as shown in Figure 6.9.c. Both brackets were able to hold a mass of 83kg (75kg water vessel + 8kg steel weight) without any visible signs of deformation. The brackets were then located on a 40mm PVC-PN section (replicating the mast and load-supporting leg) with a hose clamp holding them in position, as shown in Figure 6.9.b. The brackets were dynamically loaded in tension by filling the water vessel connected to the bracket by a rope until it was full at 75L (approximately 75kg). In addition, an 8kg steel weight was added to the top of the water vessel in an effort to promote failure. However upon inspection of the brackets after removing the loads there were no visible signs of plastic deformation. This proved that both infill variations were capable of sustaining at least 814N of tensile force without yielding. Furthermore, the test also proved that that the stainless steel hose clamps are capable of generating frictional forces to remain securely clamped at this load.

Figure 6.9.a. Tripod bracket tension test setup, **b.** Visible bending in pipe at 83kg, **c.** Tripod bracket compression test setup, **d.** Left: Bracket printed with 4shells, 50% infill, Right: Bracket printed with 4shells, 100% infill

6.2.2. Mast & Electronics Housing Strength Test

The strength of the mast and electronics housing were tested under varying guy-rope tensions, ranging from 0-120N (the maximum force gauge reading). Through experimentation it was determined by the Flinders team that the optimal guy-rope tension is between 45-65N depending on the wind direction and speed. With this tension the mast is well-supported and free of buckling. To test the strength of the components all three guys were initially tensioned to 55N. One guy was then varied between 0-120N to determine if the mast or electronics housing would fail. While neither of the components failed, the mast was severely bowed when the guy was tensioned to 120N as can be seen in Figure 6.10.a. It was also realised that when the guy was at 120N, the natural frequency of the tower appeared to increase. Due to this observation it was decided by the Flinders team that the guy-rope tensions should be varied for future frequency analysis tests. It is important to note that when the guy tensions were varied during the natural frequency tests, as will be presented in Section 6.2.4., the mast and electronics housing were able to withstand at least 30 cycles of the guys being tensioned from the minimum to almost maximum possible tensions.

Figure 6.10.a. M&EH strength test: Maximum guy force reading: Setup, **b.** M&EH strength test: Mast at maximum guy force

6.2.3. Tower Toppling Test

The tower was analysed using two methods to determine its horizontally applied toppling force. The first method, as shown in Figure 6.11.a., involved attaching a force gauge to the centroid of the tower and gradually applying a force until the tower was on the verge of toppling. This method shows that the tower would topple with 47N of horizontal force applied at the centroid.

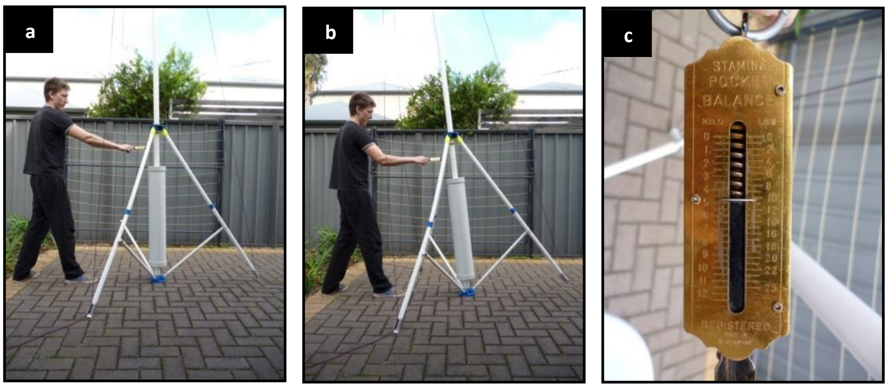


Figure 6.11.a. Toppling test 1: Setup, **b.** Toppling test 1: Toppling angle, **c.** Toppling test 1: Force reading

The second method, as shown in Figure 6.12.a, involved suspending an empty water vessel from a rope tied to the centroid of the tower and passed over a pulley attached to a tree. The vessel was filled with water until the tower tipped, by which time the hose was removed from the vessel. The water vessel was then weighed. This method showed that the tower would topple with 50N of horizontal force applied at the centroid. The Flinders team attributed the difference in force values to frictional forces and the fact that there was a small delay between when it was realised that the tower was toppling and the hose being removed.

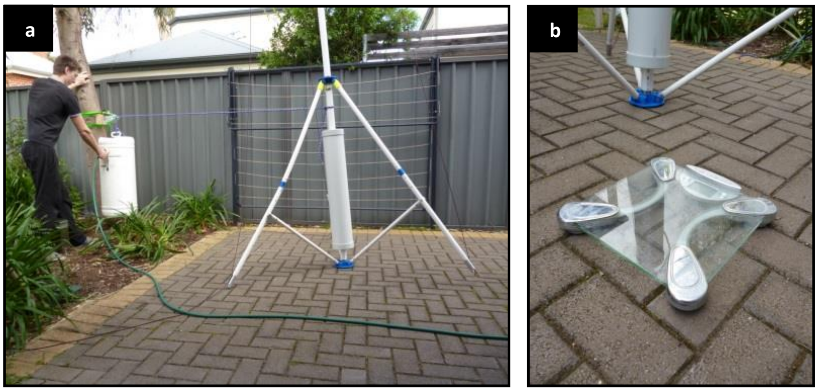


Figure 6.12.a. Toppling test 2: Setup, **b.** Toppling test 2: Weighing device

6.2.4. Tower Natural Frequency Test

The natural frequency of the tower was analysed using an iPhone4 and a vibration smartphone application. The application was developed by Diffraction Limited Design (2013) to utilise iPhone's accelerometer and gyroscope to measure and characterise the vibration experienced during a predetermined sample period. The application outputs both time domain and frequency domain .csv files so that the responses can be analysed with more sophisticated software. In addition, the application also provides instant feedback on the iPhone after the analysis has been completed, as can be seen in Figures 6.13.a.&.b.

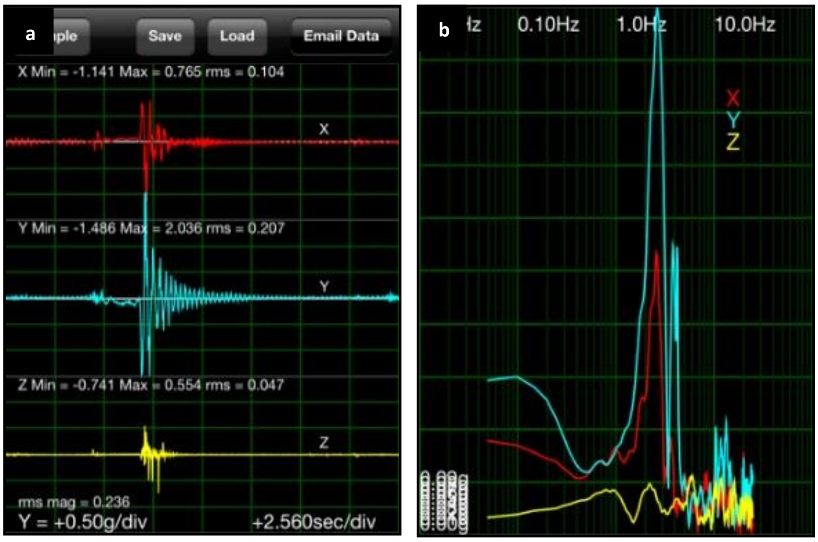


Figure 6.13.a. Frequency test: Application time domain screen, **b.** Frequency test: Application frequency domain screen

In order to utilise the application to test the natural frequency of the tower, the phone was secured in the electronics housing at the beginning of each test period, as shown in Figure 6.14.a. Once the tower was erected and filled with water, the guy-ropes were tensioned to 0N, 55N, or 100N. To excite the structure one of the guy-ropes was 'plucked' in a similar manner to plucking a guitar string. Once the tower had finished vibrating the phone was removed and the data was logged. This proved to be a lengthy process because the Flinders team decided to only accept test results which had a dominant-single-axis response and minimal 'noise' in the other axes. In addition, the process was completed for both 3.6m and 6m masts, so that the effect of the mast length could be examined.

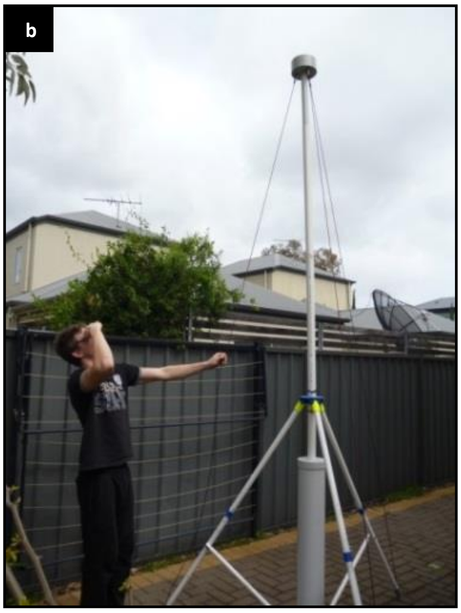


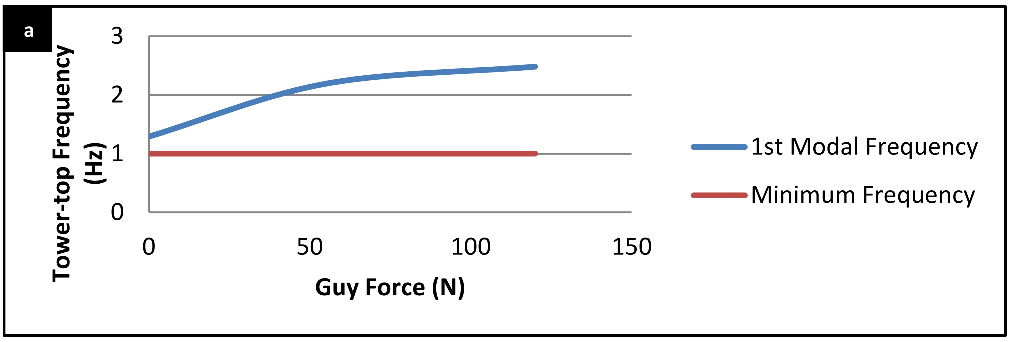
Figure 6.14.a. Frequency test: Phone location, **b.** Frequency test: Setup, **a.** Frequency test: Phone location

After the Flinders team had achieved 'relatively noise free' results for the six testing scenarios, the results were compiled and analysed. It was realised that a 3.6m mast, for all tensions, would satisfy the natural frequency requirement of being less than 1Hz, as outlined in Chapter 3. However the 6m mast results showed that the guy-ropes should be tensioned to approximately 30N in order to achieve a natural frequency greater than 1 Hz. The exact results of the frequency tests can be seen in Table 6.1. Upon inspection of Figure 6.15.a.&.b. it can be seen that the relationship between guy-rope tension and natural frequency of the tower is non-linear. For a more detailed understanding of this relationship it is advised that further research is undertaken in this area.

Table 6.1. Summary of frequency test results

Experiment	Guy Force (N)	3.6m (Hz)	6m (Hz)
1	0	1.29	0.83
2	55	2.19	1.17
3	120	2.48	1.35

*table notes: Mast bowed at 120N



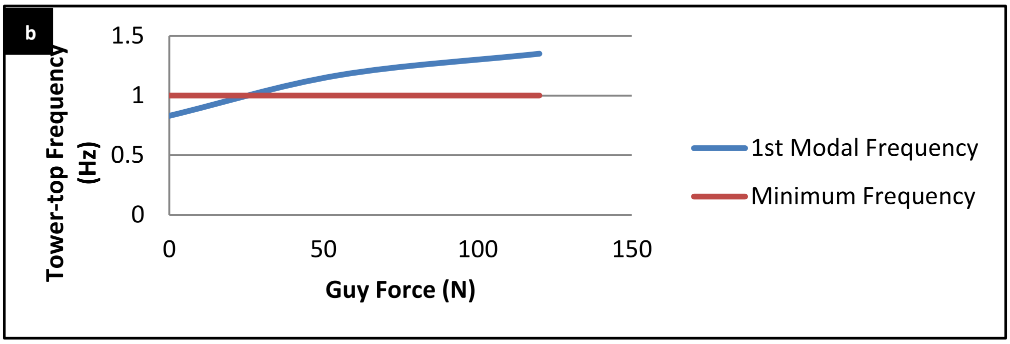


Figure 6.15.a. Frequency test: 3.6m mast performance curve, **b.** Frequency test: 6m mast performance curve

6.2.5. Tower Durability Test

The tower was setup outside a Parkside, SA 5063 backyard, as shown in Figures 6.16.a.&.b., in order to analyse how the tower performed under dynamic wind loads. In order to determine if the tower was capable of withstanding dynamic loads in both freestanding (guy-ropes attached to feet without being pegged) and pegged states, the tower was left to stand for two weeks with pegs (located at 4m from the central vertical axis) and two weeks without pegs. The website Willyweather.com was used to determine the maximum and average wind speeds for each day, as well as the main wind direction. These results are outlined in Table 6.2. During this four week period the tower did not topple over, nor did any of the components fail. The pegged tower state proved to withstand a maximum wind speed of 22.6m/s blowing from WSW on 26 September, and the freestanding tower state proved to withstand a maximum wind speed of 22.1m/s blowing from NW on 30 September.

Figure 6.16.a. Durability test 1: Pegged setup, **b.** Durability test 2: Freestanding setup

Table 6.2. Durability test wind details

Test Condition	*Date*		*Wind Direction*	*Strongest Wind Speed (km/h)*	*m/s*	*Average Wind Speed (km/h)*	*m/s*
Pegged guys 4m from central axis	Monday	16-Sep	WSW	50	13.9	20.2	5.6
	Tuesday	17-Sep	N	68.4	19.0	16.6	4.6
	Wednesday	18-Sep	WNW	55.4	15.4	24.5	6.8
	Thursday	19-Sep	WSW	53.6	14.9	13.3	3.7
	Friday	20-Sep	WNW	33.5	9.3	11.9	3.3
	Saturday	21-Sep	WSW	50	13.9	9	2.5
	Sunday	22-Sep	N	29.5	8.2	8.3	2.3
	Monday	23-Sep	NW	51.8	14.4	15.1	4.2
	Tuesday	24-Sep	NW	46.4	12.9	13.7	3.8
	Wednesday	25-Sep	WNW	55.4	15.4	11.5	3.2
	Thursday	26-Sep	WSW	81.4	22.6	22.3	6.2
	Friday	27-Sep	N	55.4	15.4	15.1	4.2
	Saturday	28-Sep	WSW	42.5	11.8	13.7	3.8
	Sunday	29-Sep	N	42.5	11.8	11.5	3.2
Unpegged leg guys	Monday	30-Sep	NW	79.6	22.1	17.6	4.9
	Tuesday	1-Oct	W	57.2	15.9	19.4	5.4
	Wednesday	2-Oct	W	66.6	18.5	22.3	6.2
	Thursday	3-Oct	SSW	35.3	9.8	14.8	4.1
	Friday	4-Oct	WNW	40.7	11.3	11.2	3.1
	Saturday	5-Oct	NNW	50	13.9	13.7	3.8
	Sunday	6-Oct	W	35.3	9.8	9.7	2.7

	Monday	7-Oct	W	33.5	9.3	10.1	2.8
	Tuesday	8-Oct	N	31.3	8.7	17.6	4.9
	Wednesday	9-Oct	N	50	13.9	16.6	4.6
	Thursday	10-Oct	WSW	51.8	14.4	13	3.6
	Friday	11-Oct	WNW	31.3	8.7	9	2.5
	Saturday	12-Oct	NNW	42.5	11.8	14	3.9
	Sunday	13-Oct	WSW	63	17.5	16.6	4.6

6.3. S2 Theoretical Analysis

In order to both verify the results from the experimental analysis, as well as gain a more detailed understanding of the performance of the tower and its components, several theoretical analyses were undertaken using two finite element analysis (FEA) simulation software packages. It is widely accepted that ANSYS Classic is the industry standard for solving a wide array of structural analysis problems. For this reason ANSYS Classic was initially used to perform FEA simulation on the general tower structure and the results from these initial simulations were then used by the author to develop various loading scenarios for more specific simulation of the custom-made and off-shelf parts and components. To analyse the performance of the individual components the Autodesk Inventor FEA simulation package was used. Since this package is built by ANSYS, based on their ANSYS Workbench package, it was deemed by the Flinders team to be adequate for the purposes of the project. It should be noted that theoretical 'hand calculations' were also undertaken as a means of cross-referencing the FEA simulation results.

6.3.1. Material Properties

There were four key materials used to develop the tower design and S2 prototype; polyvinyl chloride (PVC), polylactic acid (PLA), aluminium and stainless steel. The mechanical properties that were used to develop the FEA models are outlined in Table 6.3. The properties of PLA were outlined in Chapter 5 (apart from the Poisson's ratio) and the properties of the other materials were referenced from a combination of manufacturers' product detail sheets (for PVC) and the Autodesk Inventor material library database. The mechanical material properties of the two main Australian PVC pipe manufacturers (Vinidex and Holman) can be seen in Appendix L. It should be noted that the 'worst case' mechanical properties were used for PLA from Chapter 5, and that adhesives (PVC cement and liquid nails) were neglected from the FEA simulations.

Table 6.3. Summary of mechanical material properties

Material	*Grade*	*Young's Modulus (GPa)*	Poisson's ratio	*Yield Strength (MPa)*
Polylactic Acid	3D printable filament	2.4	0.4	32
Polyvinyl Chloride	Un-plasticised	3	0.38	52
Aluminium	6061-T6	69	0.33	95
Stainless Steel	316	193	0.3	250

6.3.2. Tower Simulations

ANSYS Classic was used to perform FEA simulations of the tower structure under self-weight and wind loads. As shown in Figure 6.17. the tower structure was generated from nodes and elements which represent the 'general geometry' of the tower design. Considering that simple bar element models are widely known to predict higher displacements and thus stress values than beam element models, a bar element model was used to introduce an indirect increase in the tower's factor of safety. In addition, to simulate the incompressible guy-ropes, 'Link180 elements' were used. These elements facilitate the prescription of pre-stress, in which case 4.38MPa was applied to simulate the 4mm guy-ropes under 55N of tension force. As shown in Figure 6.17., and depicted by the red arrows, loads were applied at the middle-central node of the tower (representing the centroid). The horizontal load of 24N was determined as per the method prescribed in Chapter 3 from calculating wind loads. The exact calculations can be seen in Appendix I The vertical load of 360N was determined from weighing the S2 prototype with its live 'water' load. Also as shown in Figure 6.17., and depicted by the blue arrows, the boundary conditions of the tower consisted of disallowing the bottom node to translate downwards (i.e. representing the ground) and translate to the left by fixing the bottom right node, which was needed to allow the simulation to compute. Lastly, it is important to note that each of the cross-sections of the beams were set to reflect the S2 tower design, and the quadrilateral element mesh density was set to a maximum of 2mm in length.

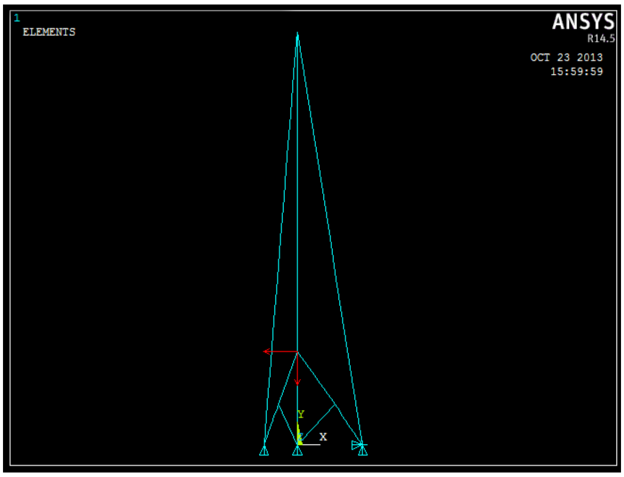


Figure 6.17. Tower simulation boundary and loading conditions

The ANSYS Classic FEA simulations of the complete tower firstly showed that the beams experience negligible bending stress from the applied loads (i.e. less than 1kPa). However the axial stress predictions proved to be somewhat larger through the structure. As shown in Figure 6.18.a., the mast and ballast experienced approximately 2.4MPa in compressions, the legs 0.8MPa in compressions and the guy-ropes 8.9kPa in tension. Given that the stress in the guys was significantly less than their pre-stress value of 4.38Mpa, it was realised that this drop was associated with a minuscule downward (Y-axis) deflection experienced by the mast and legs. The simulations also showed that the structure experienced the most displacement in the X-axis, with the greatest being -1.71mm in the two legs left of the centre, as highlighted by 'MN' in Figure 6.18.b.

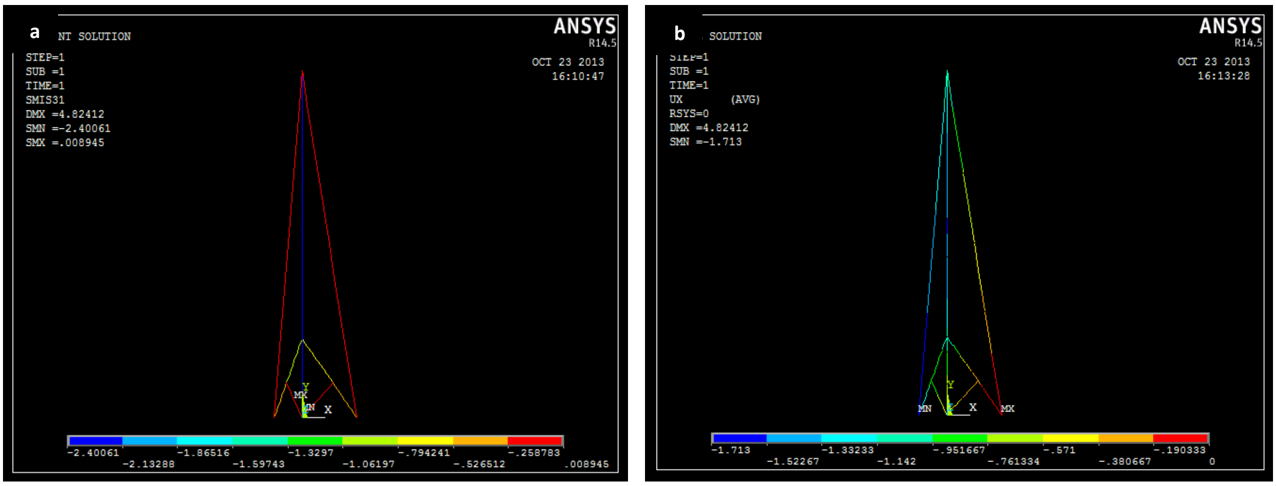


Figure 6.18.a. Tower simulation: Axial stress distribution, **b.** Tower simulation: X-axis displacement

Unfortunately the Flinders team had difficulty using ANSYS Classic to analyse the modal vibrations of the tower due to the use of the Link180 elements (used for the guy-ropes). However, since the S2 tower had been designed using Autodesk Inventor, the team reverted to using Inventor's FEA simulation package to perform a frequency analysis of the tower. The boundary and loading conditions, as well as the material properties were kept the same as when using the ANSYS Classic model and the first mode vibration of the structure was found to be 6.32Hz. Considering that this frequency was significantly larger than the experimental frequencies determined in Section 6.2.4. the Flinders team decided to use Equation 5 from Section 3.2.2.3. to verify this result.

$$n = \frac{1500 \times \left(\frac{(1 \times 0.16) + (5 \times 0.04)}{6} \right)}{6^2} = 2.81Hz$$

Using Equation 5, based on the geometry of the S2 tower design, it was determined that the natural frequency of the tower was 2.81Hz. Although this value was also significantly larger than the experimentally found frequency (1.17Hz) for a 6m mast with optimised guy-rope tension (55N), it is still more than half the frequency predicted by the Inventor model. The Flinders team believe that this high prediction was largely due to the guy-ropes being modelled as incompressible elements.

6.3.3. Mast & Ballast Simulations

The Autodesk inventor FEA simulation package was used to analyse the performance of the mast and ballast together, under the predetermined maximum wind load. The material properties were assigned as per Section 6.3.1., and the geometries obviously reflected the S2 design. The boundary conditions involved fixing the bottom surface of the load-supporting leg, as well as the top cap of the ballast (to simulate the mast being held stable by the tripod bracket and composite legs). The wind load magnitude was set the same as described in Section 6.3.2. (24N), and the live water load (360N) was modelled to completely fill the ballast using the Inventor 'water profile'. Two loading scenarios were simulated in order to determine the 'worst case' performance of the mast. Furthermore, only Von-Mises stress was examined to simplify the analysis. The first simulation used a 24N point load applied to the location representing the tower's centroid, as illustrated in Figures 6.19.a.&.b. This simulation predicted the maximum Von-Mises stress to be 0.84MPa at a location just above the top ballast cap, and the maximum displacement to be 1.28mm at the top of the mast. The second used a 24N distributed load applied over the entire mast (i.e. 4N per mast section), as illustrated in Figures 6.19.c.&.d. This simulation predicted the maximum Von-Mises stress to be 1.09MPa at the second mast joint above the ballast, and the maximum displacement to be 5.49mm at the top of the mast. These results are discussed in more detail in Section 6.4.1.

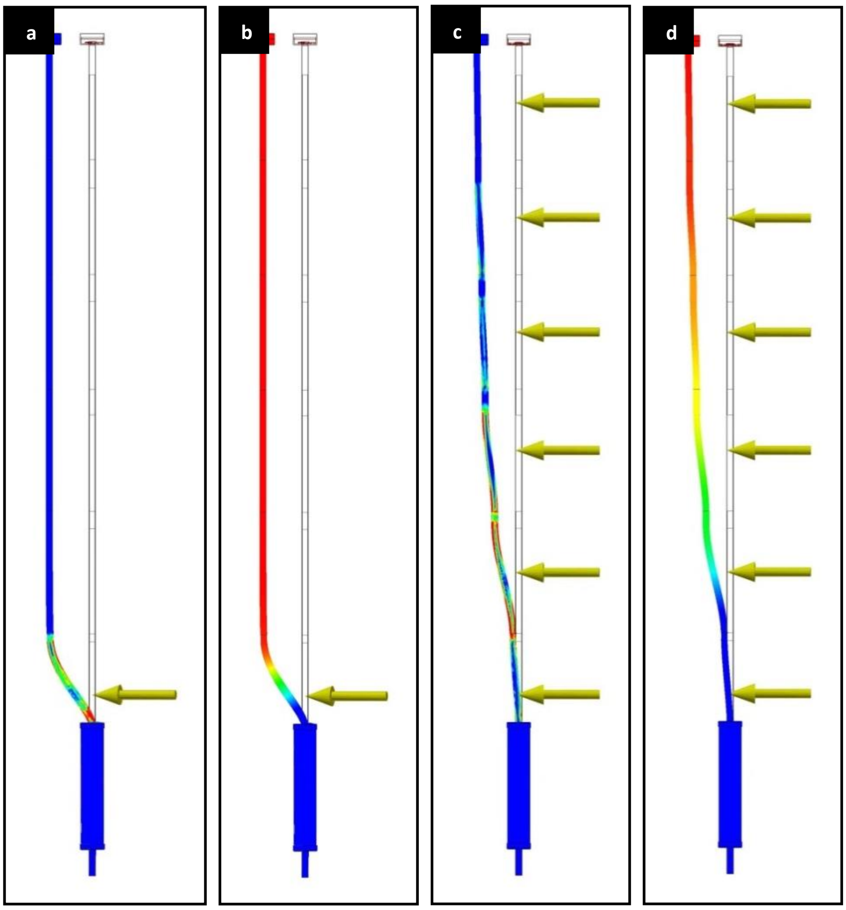


Figure 6.19.a. Mast & ballast simulation 1: Von-Mises stress distribution, **b.** Mast & ballast simulation 1: X-axis displacement, **c.** Mast & ballast simulation 2: Von-Mises stress distribution, **d.** Mast & ballast simulation 2: X-axis displacement

6.3.4. Tripod Bracket Simulations

The Inventor FEA simulation package was also used to analyse the performance of the tripod bracket based on the magnitude of the maximum compressive load experienced by the tripod legs. The material properties were assigned as per Section 6.3.1. and the geometries reflected the S2 design. The boundary conditions involved fixing the internal collar surface, and once again a maximum quadrilateral element length of 1mm was used to set the mesh density. The composite legs experienced 0.8MPa in compression, as determined in Section 6.3.2., and the maximum cross-sectional area of the two composite leg variations is 491mm^2 (25mm diameter), a compressive force of 193N was applied at 45° (leg angle) to each side of the pin-joint hole for two of the three holes, and a 193N tensile force was applied to the remaining pin-joint holes. These loading conditions were also reversed to simulate the wind blowing from the opposite direction. Of the two simulation configurations, the simulation with two tensile forces predicted the maximum Von-Mises stress of 1.63MPa located on the outside of the pin-joints, and the maximum displacement to be 0.018mm. The results are discussed in more detail in Section 6.4.1.

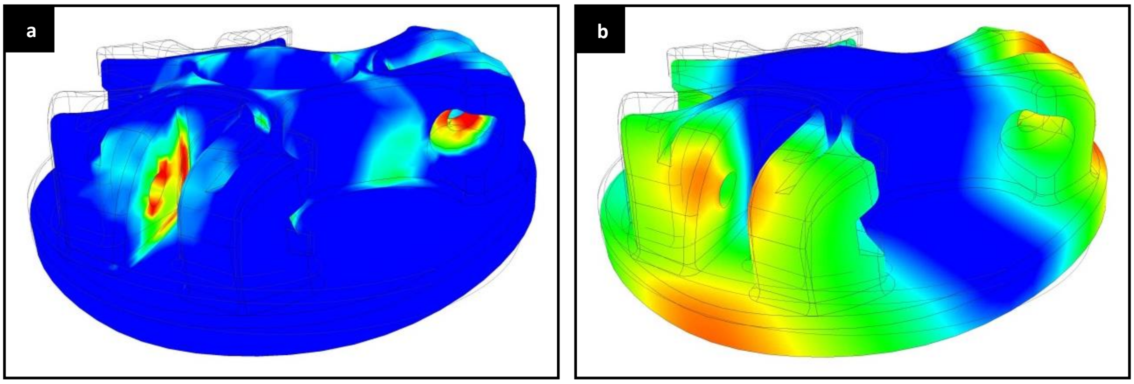


Figure 6.20.a. Tripod bracket simulation: Von-Mises stress distribution, **b.** Tripod bracket simulation: Y-axis displacement

6.3.5. Electronics Housing Simulations

The Inventor FEA simulation package was used to analyse the performance of the tripod bracket based on the maximum 'achievable without severe mast bowing' guy-rope tensile force (120N). The material properties were assigned as per Section 6.3.1., and the geometries reflected the S2 design. The boundary conditions involved fixing the threaded PVC adapter which attached the housing to the mast. Once again the maximum quadrilateral element of 1mm was used to set the mesh density. The loading conditions involved applying three tensile forces to the stainless steel hinging-connectors each with a magnitude of 120N. This simulation predicted the maximum Von-Mises stress in the PLA part of the housing to be 2.1MPa, and the maximum displacement was negligible (0.036mm). The simulation also predicted the maximum Von-Mises stress in the stainless steel connectors to be 27.5MPa, and the maximum displacement was also negligible. Finally, it was predicted that the maximum Von-Mises stress in the PVC adapter to be 1.5MPa with negligible displacement. The results are discussed in more detail in Section 6.4.1.

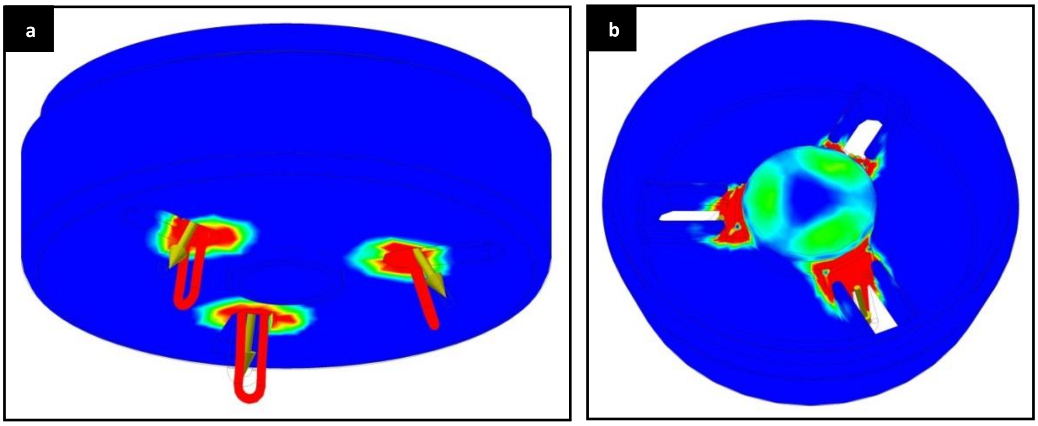


Figure 6.21.a. Electronics housing simulation: Von-Mises stress distribution bottom view,
b. Electronics housing simulation: Von-Mises stress distribution top view

6.4. S2 Performance Review

A performance review was undertaken to help analyse the 'relative performance' of the tower design compared to existing competitor products, as well as determining whether the project goals had been achieved. This involved initially compiling and analysing data obtained from the theoretical and experimental tests, before summarising the project costs and comparing the tower's performance with competitor products.

6.4.1. Theoretical Analysis Summary

Through examination of the theoretical results it can be seen that the stress, displacement and natural frequency of the tower values all fall within an acceptable range. As summarised in Table 6.4., the tower's minimum factor of safety (FOS) is nine, which is six above the project target. For the purpose of the project, all part and components displacements were proven to be negligible in accordance with Dr Paul Gardener-Stephen's recommendation for maximum tower-tip deflection and for the tower structure to remain stable. The first mode of vibration frequency was found to be 6.32Hz. However this was believed to be rather inaccurate due to the method used to model the guy-ropes. However using Equation 5 from Chapter 3. showed that the Australian Standards' theoretical natural frequency of the 2.81Hz is still substantially above 1Hz, and therefore a dynamic analysis of the structure was not required. Lastly, it is important for the reader to note that the author accepts that some of the boundary conditions used to simulate the actual boundary conditions would have contributed to inaccuracies in the FEA results.

Table 6.4. Summary of custom-made and 'modified purpose' off-shelf components stress analysis

Part	*Material*	*Yield Strength (MPa)*	*Theoretical Stress (MPa)*	*Factor of Safety*
Tripod Bracket	Polylactic Acid	32	1.6	19
Housing Inner	Polylactic Acid	32	2.1	15
Housing Outer	Polyvinyl Chloride	52	1.5	34
Housing Hinging-Connector	Stainless Steel 316	250	27.5	9
Mast	Polyvinyl Chloride	52	1.1	47

6.4.2. Experimental Analysis Summary

Through examination of experimental analysis results it was seen that all the components custom-designed for the tower meet their performance objectives. The tripod bracket was proven to be strong enough to support a load far in excess (814N) of its required load (193N), for both the four shelled 50% and 10% infill 3D print variations. The mast and electronics housing proved to be strong enough to sustain a maximum 'achievable without severe mast bowing' tensile force of 120N, and durable enough to remain free of failure during more than 30 guy-load-unload cycles. The tower proved to be able to freestand without toppling when a load of up to 46N was applied to the centroid, and has a natural frequency of 1.17Hz with a 6m mast and guy-ropes tensioned to an optimal load of 55N. Lastly, the tower proved to be durable under dynamic wind loads, since the pegged tower-state was able to withstand a maximum wind speed of 22.6m/s and the freestanding tower-state 22.1m/s without component failure.

6.4.3. Prototype Costs

As introduced in Chapter 4, the 'MakerBot Replicator 2X 3D printing cost calculator' (Equation 6) was used to generate the costs for the custom-made parts. It is important to note that the 1% machine amortisation rate (29AUD per cycle) is a 'flat rate' which takes into consideration the labour cost associated with programming and unloading the part. Although this calculator could take additional factors into consideration, such as the time taken to print a part (i.e. to account for electricity usage), it was deemed by the Flinders team to be outside the scope of the project. As shown in Table 6.5., the total cost of the custom-made part for the S2 tower is 169AUD.

Table 6.5. Summary of MakerBot Replicator 2X part cost calculations

Part	Cost ($/kg)	Mass (kg)	Plastic Cost (AUD)	No. Printable per Cycle	Plastic Cost + Amortisation Rate (AUD)
Tripod Bracket	48	0.314	15.07	1	44.07
Inline Joiner	48	0.088	4.22	3	41.67
End Joiner	48	0.06	2.88	6	46.28
Electronics Housing Insert	48	0.182	8.74	1	37.74
				Total	***169.76***

*table notes: Replicator 2X part cost = (plastic weight × per weight cost) + 1% machine amortisation per cycle ($29)

In order to determine the difference in cost between using a domestic (hobbyist accessible) manufacturing process and a commercial manufacturing process, several commercial manufacturers were approached to determine how much it would cost to manufacture the part with either their 'additive manufacturing' or 'CNC machining' process. The Adelaide-based additive manufacturing manufacturers (3D Systems, Shapeways, 3D Prototypes & Models) were asked to provide quotes for both the tripod bracket and electronics housing insert made from ABS (since most did not fabricate parts using PLA). The CNC machining manufacturers (Arkidelo, Diemould, Levett, Nordon) were also asked to quote these parts made from aluminium 6061 (standard industrial grade). Table 6.6. summarises the average cost of these components as quoted by the manufacturers. It can be seen that for a minimum quantity of two, the parts are substantially dearer than the calculated Replicator 2X costs. However when a quantity of 60 is required, the costs becomes more comparable. Nonetheless, even at 60 units, the cost of the tripod bracket is 161AUD on average dearer than the Replicator 2X produced part, and the electronics insert is 93AUD on average dearer.

Table 6.6. Average cost of tripod bracket and electronics housing insert as quoted by manufacturers

Part	Process	Cost each – 2 (AUD)	Cost each – 60 (AUD)
Tripod Bracket	Additive Manufacturing	466	246
	CNC Machining	621	205
Electronics Housing	Additive Manufacturing	274	131
	CNC Machining	587	150

*table notes: Although they are not included as an appendix (to save on space), all quotes can be provided to the reader upon request.

To generate total cost for the project, the custom-made parts were costed as per the MakerBot Replicator 2X cost calculator. While it was permitted by the project client to disregard the original project cost goal of 250AUD in order to achieve the majority of the project goals, this meant that the original goal was not achieved. Instead the total cost of the structural components was 633AUD (383AUD over budget). Although it was realised at the completion of S1 that the project's cost goal was not being achieved, given that the overall design required an increase in strength and freestanding-stability, composite legs were introduced. The introduction of these legs both added weight and contributed to the substantial cost increase between S1 and S2. In contrast, replacing the UHF radio modem with a secondary Wi-Fi network adapter reduced the cost of the electronics by 51.70AUD. Table 6.7. summarises the complete project costs.

Table 6.7. Summary of project costs

Type	Classification	S1 Project Costs (AUD)	S2 Project Costs (AUD)
Structural	Custom-made parts	78.90	169.76
	Off-shelf parts	231.72	463.27
Electronics	Wi-Fi accesspoint parts	353.05	301.35
	Total	***663.67***	***934.38***

6.4.4. Project Goals

Once again the most important project goals, as determined from the Quality Functional deployment method, were reviewed to determine the quality of the project outcomes. As shown in Table 6.8., during S2 the total linear dimensions of the carry-case were reduced to meet the geometric specification of 140cm. However the low-cost target of 250AUD was still exceeded. Considering that all the key project goals were achieved except for one, the Flinders team considered that overall the project was successful in achieving its aim and goals.

Table 6.8. Summary of S2 project goal performances

Requirement	*Specification*	*S1 Performance*	*S2 Performance*	*Final Result*
Lightweight	Weight of tower suitcase < 32kg	15kg	19kg	Spec. achieved
Compact	Total linear dimensions < 140cm	150cm	140cm	Spec. achieved
Rapidly-deployable	Time to assemble tower < 15mins	8mins	7mins	Spec. achieved
Low-cost	Tower cost < 250AUD	310AUD	633AUD	Spec. not achieved
Maximise Wi-Fi coverage	Extend to height > 6m	6.5m	6.1m	Spec. achieved
Maximise factor of safety	Minimum FOS > 2	?	2	Spec. achieved
Maximise replacement part accessibility	No. off-shelf comp. > No. custom comp.	True	True	Spec. achieved
Minimise tower-tip deflection	Horizontal displacement < 1m	0.7m	0.4m	Spec. achieved
Minimise footing area	Footing area < 2.2m equilateral triangle	2.1m	2.1m	Spec. achieved
Minimise parts	No. unique parts < 15	8	11	Spec. achieved
Minimise joints	No. unique joints < 10	6	9	Spec. achieved

6.4.5. Competitor Product Comparison

The performance of the S2 tower was compared to structures which the literature reviewed revealed to be the benchmark. As can be seen in Table 6.9., the S2 tower proved to be only slightly heavier than the 'lightweight' GST05, substantially cheaper and lighter than the 'freestanding' VMCT13, quicker to setup than the 'rapidly-deployable' HDCA15, slightly heavier yet quicker to setup than the 'portable' PTM15, but unfortunately significantly more expensive than the 'low-cost' LC67. Although the S2 tower did not perform better in all categories than its competitors, the Flinders team believe that this tower design has positioned itself well in the telecommunication mast and tower product industry.

Table 6.9. S2 tower performance comparison with competitor products

Performance Characteristic	*Flinders Team (S2Tower)*	*GeoStrut (GST05)*	*NXL (VMCT13)*	*AP Landing (HDCA15)*	*Go Vertical (PTM15)*	*USAF (LC67)*
						
Best perform.	-	Lightweight	Freestanding	Rapid.-deploy.	Portable	Low-cost
Height (m)	6.1	5	13	15	8	6.7
Mass (kg)	19	18	120kg	unspecified	15	unspecified
Set-up (mins)	7	10	unspecified	30	20	30
Cost (AUD)	633	unspecified	1600	7800	230	163

*table notes: set-up times are based on different 'constructor abilities'

7. Chapter 7: Conclusion

The aim of the project was to research, design, construct, and analyse an open source, rapidly-deployable and portable Wi-Fi tower. It was to be designed from nationally accessible components and MakerBot Replicator 2X 3D printed parts, to fit inside a suitcase and comply with the major Australian airlines' checked-baggage regulations, and to be proven to be 'structurally sound' in accordance with relevant Australian Standards for the design and manufacture of telecommunication mast and tower structures. In addition, the design needed to comply with the OH&S legislations for temporary demountable structures (TDSs) at large outdoor music festivals (OMFs).

A tower design was conceptualised through the use of the Quality Function Deployment (QFD) methodology, and was evaluated using Pugh's decision-matrix (PDM) methodology. A Stage 1 (S1) design was modelled in Autodesk Inventor based on the preferred concept and constructed from a combination of standard off-shelf components accessible from major Australian hardware stores and 3D printed parts from the MakerBot Replicator 2X. The S1 design was analysed using experimental methods to determine the tower's deployment time, its structural stability and strength, and various geometric parameters. The mechanical material properties of the Replicator 2X's polylactic acid (PLA) printed parts were then examined through the use of an Instron tensile testing apparatus.

A Stage 2 (S2) tower design was then modelled to rectify problems identified at the completion of S1 and constructed to facilitate further experimental analysis. The S2 design was analysed experimentally to determine the strength of the components, the horizontal force required to topple the tower, the natural frequency of the tower with varying mast heights, and the durability of the tower under dynamic wind loads. Theoretical analysis of the S2 design was performed using two commercial finite element solvers; ANSYS Classic was used to analyse the tower's beams and Autodesk Inventor's FEA simulation package for the custom-made parts. The simulations were computed using design loads (primarily wind loads) stipulated by Australian Standards for mast and tower structures. Stress analyses were carried out by examining the Von-Mises, bending, and axial stresses present in the complete structure and individual parts. The displacement and first mode of vibration frequencies were also analysed using these software packages.

7.1. Tower Design Summary

The tower was designed to provide a rapidly-deployable, accessible solution for elevated mesh networks. Although the tower has been designed to elevate Wi-Fi accesspoint componentry to a height of 6.1m, the tower can also be reconfigured to operate at six heights less than this by removing the required number of 'stackable' mast sections (each approximately 900mm). The design is considered to be rapidly-deployable by a number of mechanical engineering academics since it can be setup in 7 minutes and completely packaged into a carry-case in less than 10 minutes. The open source nature of the design allows individuals wishing to construct a replica to do so with relative ease, since all the custom-made parts will be made accessible from the web (as 3D printable parts) and all the off-shelf parts are purchasable from the five major Australian hardware stores (Bunnings, Home, Masters, Mitre10, and Stratco). The tower has also been designed to be portable; its dead weight is only 19kg (live 'water' weight is 36kg) and its packaged-state is less than 140cm in total linear dimensions, making it suitable to be checked-in with an economy class checked-baggage allowance (23kg limit) with all the major Australian airlines. In order to be usable in the public domain the tower has been designed to comply with all the relevant Australian Standards (AS1170.1, AS1170.2, AS3995, AS4268, and AS4676). Furthermore, its design facilitates use at large outdoor music festivals (OMFs), whereby its footing plan can fit within three connected standard temporary fence panels (TFPs) and has the necessary design documentation to meet approval by OMF structural engineers as well as the regulators of OH&S legislations. Unfortunately, although permitted by the client in order to achieve 'strength and stability' goals; the final cost of the tower structure is 633AUD and therefore did not meet the project cost goal of being under 250AUD.

This thesis has however showed that the Flinders team have travelled somewhat beyond the scope of the project to ensure their tower design is robust. Through completing a review of the mechanical material properties of polylactic acid (PLA) as well as polyvinyl chloride (PVC), the Flinders team was able to be sure that the tower's materials are structurally stable and durable, radio frequency transparent, relatively stable in ultraviolet (UV) light, and capable of resisting corrosion for a substantial period of time. Lastly, the tower has been experimentally analysed using full-scale models with the required design loads to ensure that the design has a high degree of stability, strength and durability, and has been theoretically analysed to ensure that stress concentrations, displacements, and the first mode of vibration frequency will not be detrimental to achieving a 'sound structure'.

7.2. 3D Printed Part Performances

This project has successfully shown the mechanical limits of the MakerBot Replicator 2X's 3D printed parts. Whilst a review of acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) highlighted the characteristics of the materials, and experimental tests confirmed the properties of PLA, it was through the design and development of many 3D printed parts that the capabilities of the process were realised. A major outcome of the project was the realisation that 3D printed parts with four shells and 50% infill are sufficiently strong and durable enough for the tower's design loads. This was concluded after the tower was able to withstand 30 days of dynamic wind loads. In contrast, two composite leg end-joiners failed whilst being transported (in the boot of a small car) in a non-packaged-state. It is believed that the leg end-joiners failed during transit because they were 'free to move' and subjected to a 'large shear force' generated from turning a corner quickly (whereby the tripod probably hit the wall of the boot at an 'awkward' angle). Nonetheless, since the tower was designed to be transported inside a 'hard' carry-case, for the purposes of the project, the Flinders team concluded that this 3D printing process is capable of meeting the project goals.

7.3. Lessons Learnt

There were two major lessons learnt by the Flinders team throughout the project. The first lesson came about through trying to develop a finite element model to simulate incompressible structures. It was realised that when using the Link180 element in ANSYS Classic, that this element cannot be used to develop models for predicting the modal frequencies of structures. In the situation where a modal analysis is required for incompressible structures, it was found that theoretical 'hand calculation' methods are much quicker and easier to solve than using commercial finite element solvers. The second major lesson learnt was realising the significant number of assumptions that need to be made when setting the loading and boundary conditions of parts connected to several other parts. It was realised that while the boundary and loading conditions for complete structures can be set to represent the actual conditions with a reasonable degree of accuracy, considering that parts such as the tripod bracket are both loaded and bounded by a number of other interconnected components (i.e. the composite legs), the set conditions are only accurate if the interconnected components achieve their assumed functions (i.e. composite legs stabilise the tripod bracket by achieving minimal displacement). For this reason, the importance of FOS's as well as accurately assumed loading and boundary conditions as recognised by the author.

7.4. Future Work

Several areas of future work are necessary in order to make this open source Wi-Fi tower safe to be fabricated by and setup in the public domain by 'amateur constructors'. A more detailed review of the anisotropic mechanical printing properties with various infill percentages of both PLA and ABS printed parts is required to develop printing guidelines for the 3D custom-made parts. To improve the performance of the design; implementing weight reduction methods (such as the strategic positioning and drilling of holes) throughout the mast will increase the natural frequency of the structure and by providing a footing plan extension mechanism (for applicable situations) this will increase the freestanding toppling force of the structure. If the design is to be utilised outside of mainland Australia, wind loads will need to be recalculated and ice loads will need to be taken into account according to the new location. In order to understand the 'complete' strength and durability of the tower, longer and higher magnitude load cycles are required for a broader range of experimental test procedures. Also, to verify the accuracy of the theoretical stress predictions, a detailed convergence study is required. Finally, in order to ensure that the tower meets all OMF OH&S legislations, the tower design needs to be certified by a professional structural engineer.

7.5. Summary

This project shows that it is possible to design an open source Wi-Fi tower as a solution for elevated mesh networks, complying with a broad array of engineering specifications. The two prototypes and multiple FEA models have proved that the design meets the requirements of the relevant Australian standards, and that a design has been achieved which fulfils the majority of the client's requirements.

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10. Appendices

10.1. Appendix A – Review of Wireless Mesh Networks

The purpose of this section is to provide a rudimentary overview of wireless mesh networks, to gain an appreciation for the type of network that WiFindUs are developing, and to provide a recommendation for suitable AP components.

10.1.1. Overview of WMNs

Wireless mesh networks (WMNs) have emerged as a key technology for next-generation wireless networking. Since WMNs have many advantages over other wireless networks, which will be discussed in Section 10.1.1.1. WMNs are undergoing rapid progress and inspiring numerous applications (Akyildiz et al. 2005).

If we consider that network topology is the arrangement of the various elements (i.e. links, nodes) of a computer, then the network topology of a mesh network is a type of networking where each node is required to capture and disseminate its own data, as well as serve as a relay for other nodes. By nature mesh networks are dynamically self-organised and self-configured so that the nodes can collaborate to propagate data throughout the network (Groth et al. 2005).

A WMN consists of mesh nodes (MNs) that form the backbone of the network, as shown in Figure 10.1. The MNs are able to configure automatically and re-configure dynamically to maintain the mesh connectivity, which gives the mesh its ‘self-forming’ and ‘self-healing’ characteristics (Johnson et al. 2007). Through an intelligent routing system, MNs are able to route data packets to another MN that is outside the direct wireless range. In essence, WMNs can efficiently route data from a source to a destination over multiple hops, which has the advantage in terms of network reliability over traditional single hop networks (Johnson et al. 2007).

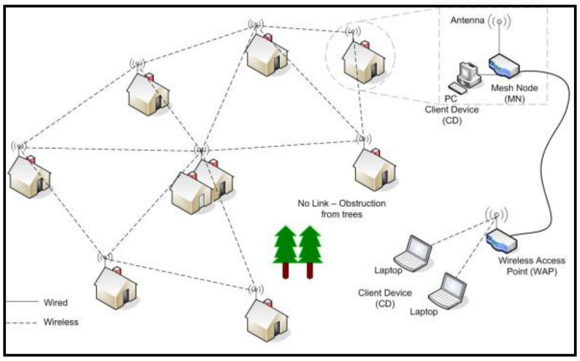


Figure 10.1. A Community deployed wireless mesh network (Johnson et al. 2007)

At this stage it is important to realise that WMNs are comprised of two types of MNs: mesh routers (MRs) and mesh clients (MCs), where all MNs consist of a wireless router and an antenna. While MNs usually use omnidirectional antennas to communicate only with other MNs, it is not difficult to change the antenna type to a directional antenna (Johnson et al. 2007).

A wireless access point (AP) is a type of MN that creates a hotspot (i.e. within antenna range) where any Wi-Fi enabled device can connect to the AP. Wi-Fi technologies will be discussed in more depth in Section 10.1.1.2.

The architecture of WMNs can be classified into three types: Infrastructure/Backbone WMNs, Client WMNs, and Hybrid WMNs (Akyildiz et al. 2005). In infrastructure meshing, APs provide internet access to MCs by forwarding data to mesh routers MRs (known as relaying), in a ‘multi-hop’ fashion until a mesh gateway (MG) is reached. Traditionally MGs act as bridges between the wireless infrastructure and the Internet (Benyamina et al. 2012). Figure 10.2.a. provides a schematic of how WMNs relay data as previously described. It should be noted that for the purpose of this project WiFindUs do not require an internet connection, and thus do not require MGs.

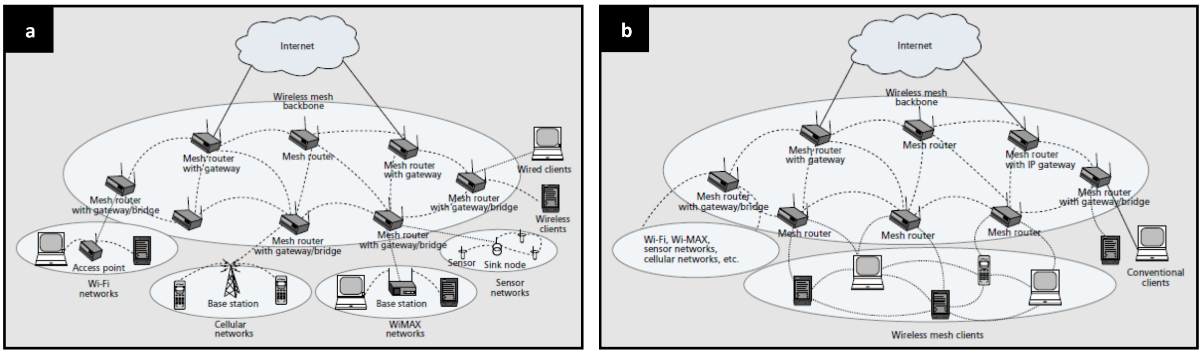


Figure 10.2.a. Infrastructure/Backbone WMN schematic, **b.** Hybrid WMN schematic (Akyildiz et al. 2005)

Client meshing provides peer-to-peer networks among MC devices. In this type of architecture, MCs construct the actual network, and are required to perform routing and configuration functionalities. For this reason MRs are not required for these types of networks, thus a Client WMN is actually the same as a conventional ad-hoc network. An ad-hoc network is network that does not rely on infrastructure (i.e. MRs), but instead each node participates in routing dynamically determined by network connectivity. Furthermore, in ad-hoc networks, typically all devices have equal status and are 'free to associate' with other in-range devices (Toh et al. 2002). It is important to note that an ad-hoc network often refers to a mode of operation of IEEE802.11. networks, which will be discussed in Section 10.1.1.2. (Gupta 2000).

The last common WMN architecture is known as Hybrid WMN meshing. This architecture is a combination of infrastructure and client meshing, as shown in Figure 10.2.b. In this type of network MCs can access MGs, through MRs, or other MCs (Akyildiz et al. 2005).

10.1.1.1. Advantages of WMNs

There are several advantages that WMNs offer over other wireless networks, which Johnson et al. (2007) discusses. Once the MNs have been configured and activated, WMNs form automatically, which has been characterised a 'self-forming' network trait. WMNs are 'fault tolerant', such that if redundant routes exist in the network, data flow is not interrupted in the rest of the network if a MN fails. Instead the network will dynamically reroute the data via the next available route. WMNs have the ability to 'self-heal', where if a MN drops out of the network, once the connection is restored, the MN can re-join the network seamlessly. WMNs also have low infrastructure and expansion costs. MNs can be built from low cost, common off-the shelf components. Furthermore, with the addition of one extra MN, the coverage of the network can be increased substantially relative to the original coverage. Lastly, due to their low power consumption and self-forming attributes, WMNs are very easy to deploy; with little training 'network constructors' can deploy a WMN in a multitude of different environments (Johnson et al. 2007).

10.1.1.2. Making WMNs Wireless

Wi-Fi is the name of a popular wireless networking technology that permits electronic devices to use radio waves to provide wireless high-speed Internet and network connections over short distances. The Wi-Fi Alliance, a non-for-profit organisation formed in 1999, owns the Wi-Fi trademark and defines Wi-Fi as any 'wireless local area network' (WLAN) product that has been developed to comply with the Institute of Electrical and Electronics Engineers (IEEE) 802.11 standards (Webopedia 2013). However, since most WLANs products are based on these standards, the term 'Wi-Fi' is used synonymous to 'WLAN'. Only products that meet the Wi-Fi Alliance's interoperability certification testing criteria successfully may use the 'Wi-Fi Certified' trademark.

Subsequent IEEE standards for Wi-Fi have been introduced to allow for greater bandwidth. The original 802.11 standard allowed a maximum data transmission rate of only 2Mbps, and then when 802.11n was introduced in 2007, is could perform at a maximum rate of 600 Mbps (Encyclopaedia Britannia 2013).

The United States of America set the precursor for Wi-Fi products. In 1985, the US Federal Communications Commission (FCC) released the bands of the radio spectrum at 900MHz, 2.4GHz, and 5.8 GHz for unlicensed use by anyone. This sparked technology firms to begin building wireless networks and devices to take advantage of the newly available radio spectrum (Encyclopaedia Britannia 2013). In 1991, NCR Corporation with AT&T Corporation invented the precursor to 802.11 intended for use in cashier systems (Charny 2002).

Australian inventions have dominated the Wi-Fi product market since, and have been the subject of many patent infringements. In 1992 and 1996, Australian organisation CSIRO obtained patents in Australian and America respectively, for a method used to 'unsmear' Wi-Fi signals (Sygall 2009). In April 2009, 14 technology based companies agreed to pay CSIRO $250 million for infringements on CSIRO patents (Moses 2010). This led to Wi-Fi being attributed as an Australian invention, though this has been the subject of some controversy (Australian Geographic 2010). CSIRO won a further $220 million settlement for Wi-Fi patent infringements in 2012 with global firms in the United States required to pay the CSIRO licensing rights estimated to be worth an additional $1 billion in royalties (ABC 2012).

10.1.1.3. Improving WMNs Performance

In 1999, Nasipuri et al. proved that performance WMNs can be greatly improved by using multiple channels. In such networks, a simultaneous transmission is possible as long as multiple channels are used, which in turn decreases the probability of packet collision because of traffic mitigation in each channel. Garces (2000) and So et al. (2004) proposed a number of MAC protocols for multi-channel transmission systems in ad-hoc networks (Benyamina et al. 2012). The IEEE 802.11 Wireless LAN standards allow multiple non-overlapping frequency channels to be used simultaneously to increase the aggregate bandwidth available to end-users (Raniwala et al. 2005).

In WMNs, two neighbouring nodes can communicate with each other only if they are assigned a common channel. Therefore the channel assignment may restrict possible routes between any pair of nodes in the network topology. Thus, the effectiveness of multi-channel routing algorithms is closely related to the channel assignment scheme being utilised (Benyamina et al. 2012).

In the last decade, numerous worldwide research efforts have addressed the problems of routing and channel assignment in multi-channel WMNs (Benyamina et al. 2012). Multi-channel multi-hop wireless ad-hoc network architectures have been built using standard 802.11 hardware to increase the traffic load (Raniwala et al. 2005). One method of multi-hop wireless networking (MWN) is to develop a set of centralised channel assignments, bandwidth allocations, and routing algorithms for multi-channel WMNs.

In 2005, Raniwala et al. proposed a dynamic channel assignment and routing techniques for multi-channel WMNs. By developing intelligent channels with bandwidth assignment, and equipping every WMN node with 2 multiple network interface cards (NICs) operating on different channels, the WMN proved to increase the performance by a factor of up to 8 compared with the conventional single-channel ad-hoc network architecture (Raniwala et al. 2005).

Cheng (2013) describes the advantages and disadvantages of multi-hop technologies. MWNs are rapid to deployment and have lower backhaul costs. They are easy to provide coverage in 'hard to wire' areas, and under the right circumstances, may: extend coverage due to multi-hop forwarding, enhance throughput due to shorter hops, and extend battery life due to lower power transmission. The disadvantages include: high complexity of routing/path management protocols, and extra delay due to multi-hop relaying.

Another recognised way of improving the performance of WMNs is to use directional antennas instead of the 'easy to set-up' omnidirectional antennas. Benyamina et al. (2012) discuss how this 'alternative performance' improvement scheme focuses on the optimisation of the location of MNs. In 2007, Chen et al. developed a plan for the deployment of WMNs by fixing the MGs positions and equipping routers with directional antennas. However, although there is much literature to support the benefits of using directional antennas, research was 'in general' suspended in this field by many research institutes. The main reason is that directional antennas require line of sight (LoS) environments, while relevant applications that can provide high LoS components can be hardly found (Alaweih et al. 2009).

10.1.1.4. WMN Design Challenges

With the advances in wireless technologies and the explosive growth of the Internet, wireless networks, especially WMNs, are going through an important evolution. Designing efficient WMNs has become a major task for networks operators (Benyamina et al. 2012).

Over the last few years, a plethora of studies has been carried out to improve the efficiency of wireless networks. Akyildiz et al. (2005) discuss the key challenges that network developers/operators face when trying to improve the performance of WMNs. While there are still many performance problems with WMNs, the most important and urgent ones are 'scalability' and 'security'.

Akyildiz et al. (2005) describe how existing MAC, routing and transport protocols are not scalable with either the number of nodes or the number of hops in the network. As discussed in Section 10.1.1.3. while this problem can be alleviated by increasing the network capacity through using multiple channels per node or developing wireless radios with higher transmission speed, these approaches do not truly enhance the scalability of WMNs, because resource utilisation is not actually improved. In order to achieve 'true scalability', it is essential to develop new MAC, routing and transport protocols for WMNs (Akyildiz et al. 2005).

WMNs are vulnerable to security attacks in various protocol layers. While security approaches may be effective for specific protocol layers, there needs to be a comprehensive mechanism to prevent or counter attacks in all protocol layers. The security problem is a result of the desire to have WMNs self-organise and self-configure, while at the same time secure. However due to distributive and collaborative protocols, current WMNs can only partially realise this objective (Akyildiz et al. 2005).

One of the fundamental requirements of WMNs, essential to the success of WiFindUs' solution is to provide a sufficient coverage area. Vural et al. (2013) discusses the key challenges associated with sustained coverage over large areas. As a user moves, a disconnection occurs if the user's mobility path crosses through holes in network coverage. Such holes are caused by either insufficient number of MNs deployed in localities or due to misconfiguration of transceivers causing sub-optimal use of transmission power (Vural et al. 2013).

10.1.1.5. WMN Design Considerations

WMNs need to be carefully designed to ensure that maintenance costs do not exceed the network's 'worth'. Johnson et al. (2007) discuss the trade-off between the cost of planning a network well at the start of the project and the cost of maintaining a badly designed network, and provide a recommendation on key areas of consideration. The first involves becoming familiar with the specific Wi-Fi equipment regulations of the telecommunications regulatory body. Most countries have specific maximum power output for wireless equipment operating on the 2.4GHz and 5.8GHz bands.

When it comes to Wi-Fi network operations, it is important to realise that although there are 13 channels available in Australia on the 802.11b/g standards, there are only three non-overlapping (non-interfering) bands. As shown in Figure 10.3. these are channels 1, 6, and 11.

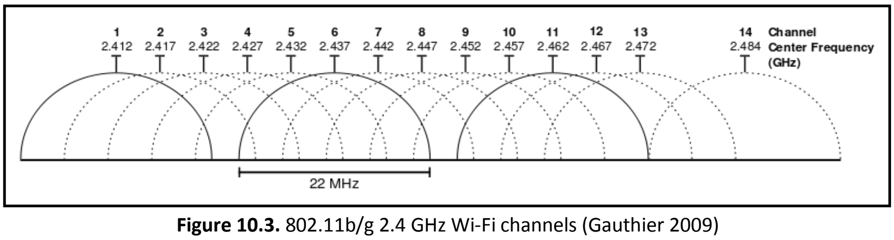


Figure 10.3. 802.11b/g 2.4 GHz Wi-Fi channels (Gauthier 2009)

On the topic of interference, it is also important to realise that Wi-Fi is a LoS technology. Various obstructions that have proven to interfere with the signals include: trees and plants, where water on leaves has a negative impact on signal strength. Metal construction materials like roofs or reinforcing in concrete walls are also proven to affect the signal strength (Johnson et al. 2007). Additional sources of Wi-Fi interference include: microwave ovens, air-conditioners and other radio equipment.

On the topic of safety, Wi-Fi electronics are susceptible to lightning damage and thus lightning protection should be considered. Johnson et al. (2007) advise the use of plastics structures, were possible, to minimise the risk of lightning damage.

Lastly, Johnson et al. (2007) recommend developing schematic mesh plots of the sites (i.e. AP locations) and selecting a network topology during the planning phase of a WMN. The schematic plot needs to confirm the position of the APs relative to each other, as shown in Figures 10.4.a.&.b. The aim of these plots is to ensure that the site has sufficient coverage. When selecting the network topology type the purpose and performance demands need to be considered. WiFindUs have selected a mesh network, as shown in Figure 10.4.a., which is widely regarded as the simplest topology to configure. There are many other network topologies, with extensions such as in Figure 10.4.b., however it is outside the scope of this thesis to further review these topologies.

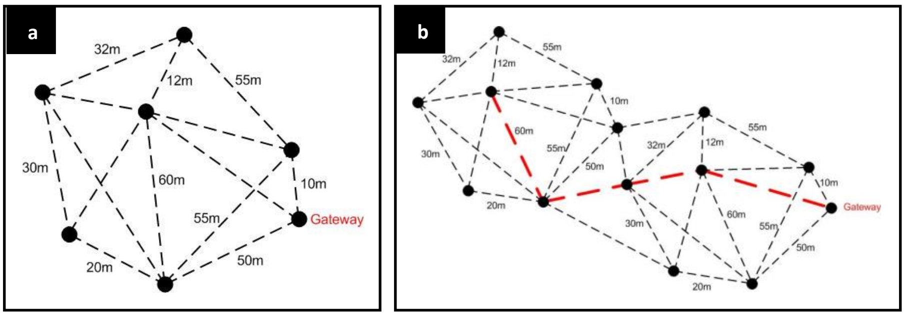


Figure 10.4.a. Simple mesh network plot, **b.** Network plot of mesh with backbone (Johnson et al. 2007)

10.1.2. Rapidly-deployable WMNs

To date the majority of rapidly-deployable networks have been motivated by the needs of first responders and military personnel arriving to incident emergency areas, such as a chemical spill, hurricane, or other natural or man-made disaster (Souryal et al. 2009).

In 2001, Midekiff et al. developed a rapidly deployable ‘last mile’ wireless high-speed communications system to support emergency management workers for applications such as Geographic Information Systems (GISs) and to access video conferencing. Although some aspects of their literature were useful, such as the overview of their rapidly-deployable equipment, the study largely focussed on devising methods to access remote databases and GIS engines.

More recently, rapidly-deployable network research has been directed towards improving coverage in ‘traditional’ low-coverage areas, such as hi-rise buildings, subterranean buildings, caves, and underground mines. In 2009, Souryal et al. developed an automated deployment algorithm that indicates when a mesh node needs to be deployed as the coverage area grows.

It became evident that this area of research that there has not been much cited research on rapidly-deployable WMNs that do not require connection with external communication channels (i.e. the Internet). Furthermore, Souryal et al. (2009) highlights the gap in research for rapidly-deployable WMNs.

10.1.3. Outdoor WMNs

Due to the massive emergence and deployment of outdoor WMNs, outdoor Wi-Fi based communication is becoming increasingly popular. Several studies have been conducted to measure the performance of outdoor WMNs, and to provide a recommendation for performance targets of these WMNs (Bianchi et al. 2006).

Novarum (2010) recommend deploying a 'dense network'; more than 60 APs per square mile, which roughly equates to a spacing of 200m between APs. However, applying this mesh density to the pilot study area (Bonython Park) would mean that WiFindUs would only require four APs, which is almost an order of magnitude less than the WiFindUs network engineer's estimation.

Bianchi et al. (2006) recommend using an 802.11b network over an 802.11g, since their study proved the 802.11b technology to be more robust. However, Novarum (2010) advise against permitting 802.11b clients to connect to any new WMN, and support this argument by suggesting that this technology will 'degrade the entire network'. They also advise against 802.11g networks because they deliver 'unacceptable coverage' (80% for laptops and below 50% for smartphones). Instead Novarum recommend using an 802.11n network, since these networks deliver 'excellent coverage' (95% for laptops and below 90% for smartphones). Furthermore, Novarum recommend using 2.4GHz APs with a 5GHz backhaul, since the use of 2x2 multiple-input and multiple-output (MIMO), or better, dramatically improves the low level rate of packet errors and materially increases network performance, capacity and useful coverage.

10.1.4. Serval WMN Projects

Serval is a not-for-profit telecommunication systems, project-based Flinders University research team, aiming to improve worldwide communications through the use of WMNs.

10.1.4.1. Serval Projects

Serval are currently working on two projects. The first of which is focused on developing a temporary self-organising, self-powered mobile network for disaster areas formed with small deployable phone towers. Their second project is to develop a permanent system for remote areas that requires no infrastructure and creates a mesh-based phone network between Wi-Fi enabled mobile phones (Serval 2013).

In order to fulfil the requirements of their two projects, Serval have designed a 'Serval Mesh Extender' (SME) in the essence of increasing the range of their WMNs and facilitating unskilled deployment of which. The SME acts as a Wi-Fi AP, and also allows the use of a variety of other radios to provide longer-range and more energy efficient mesh networking, that "under ideal conditions should be able to support links over tens of kilometres" (Gardner-Stephen 2013). Figures 10.5.a.&.b. shows the hardware which makes up the SME.

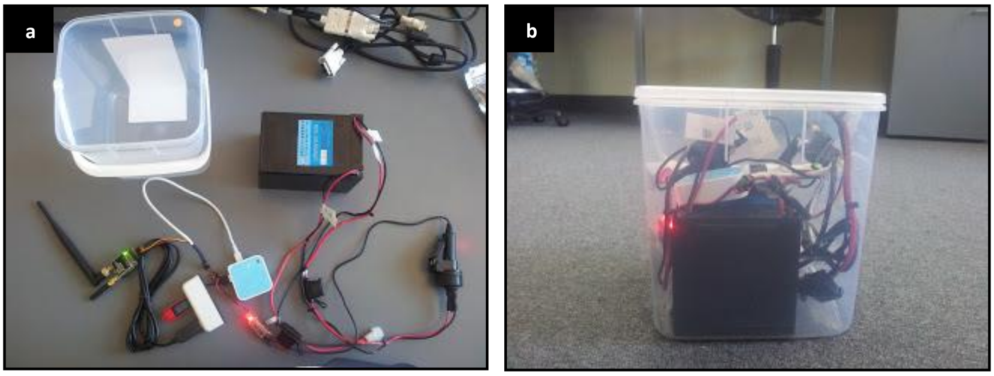


Figure 10.5.a. SME components, **b.** SME housed (Gardner-Stephen 2013)

The SME has an embedded router running the mesh software (Serval Rhizome) with 802.11n Wi-Fi running in ad-hoc mode so that the SME's can mesh with each other. A core functionality of the SME is that they will simultaneously run in AP mode so that phones can connect to them as Wi-Fi clients, and hence not need to be routed or otherwise able to run in ad-hoc mode. The other capability in the SME is a long-range UHF radio operating in an appropriate ISM band, so that the SME can communicate over long distances (Serval 2013).

A USB memory stick is included for extra storage; since the embedded router's flash (4MB) is far too small for a Serval Rhizome node that "might want to cache gigabytes of data". This involved adding a passive USB hub so that both the radio and memory stick could share the single USB port on the router. The SME is powered by a 120Wh LiFePO4 battery, which is expected to be capable of powering these units for close to a week (Gardner-Stephen 2013). Table 10.1. outlines the exact components that make-up the SME, as well as the associated costs.

Table 10.1. Serval: cost of SME (TP-Link 2013; RFDesign 2013)

	Component Description	*Make*	*Model*	*Price*	*%*
1	**Embedded Router**	TP-Link	WR703Ns	25.00	7%
2	**UHF Radio Modem**	RFDesign	RFD900	89.50	25%
3	**Antenna 900MHz 2dBi monopole**	RFDesign		5.95	2%
4	**Antenna 900MHz 3dBi monopole**	RFDesign		6.95	2%
5	**Universal Battery Elimination Circuit**	RFDesign	5V 3A	5.75	2%
6	**USB to TTL Cable**	FTDI		17.95	5%
7	**USB Memory**	-	16 GB	22.00	6%
8	**Passive USB Hub**	-	-	4.00	1%
9	**Battery**	Powerizer	12V 10Ah, 120Wh	135.00	38%
10	**Car Accessory connector**	-		13.00	4%
11	**Voltage Adaptor**	Jaycar	Low Voltage	7.95	2%
12	**Misc Cabling**			20.00	6%
			Total	**353.05**	**100%**

Gardner-Stephen (2013) measured the fundamental components of the SME to draw less than 1W sustained. He also believes that the SME's power consumption can be optimised to approximately 0.3W on average.

10.1.4.2. Serval Requirements

In order to help to elevate the SME and improve the range of their WMNs, Serval requires a rapidly-deployable, portable network tower. Currently, Serval are using an aluminium antenna pole to elevate their UHF radio. However this structure is unable to stand freely, and is not cost-effective to transport.

10.1.4.3. WiFindUs-Serval Collaboration

In March 2013, the WiFindUs and Serval project teams decided to collaborate to help each other in areas were external expertise are required. WiFindUs have allowed Serval to use their tower design upon completion of this project, and Serval have agreed to help WiFindUs with the design of their WMN, as well as provide help with the construction of WiFindUs' APs. As a result of the collaboration, WiFindUs and the project team have decided to use the SME components as a foundation for their APs, and are looking to undertake various tests to optimise the capabilities of the components for WiFindUs' purposes.

10.1.5. Recommendation for WiFindUs' WMN

Through researching WMNs several recommendations can be made to WiFindUs to help with the design and construction of their AP for the pilot study. Dr Paul Gardener-Stephen supports the WiFindUs network engineer's estimation for required number of APs, and personally estimated that 25 APs would be required to service the Bonython Park area. Furthermore, both Dr Paul Gardener-Stephen and Novarum support the use of an 802.11n WMN operating on the 2.4GHz band.

Considering that the main purpose of designing an AP tower is to optimise the coverage of the WMN, it is essential to understand the coverage performance of the recommended radio devices. As shown in Figure 10.6.a. the embedded router recommended for the WiFindUs AP has been manufactured by TP-Link, and the UHF radio modem has been manufactured by RFDesign. The performance of these two components was determined to ensure that they could fulfil WiFindUs' AP requirements.

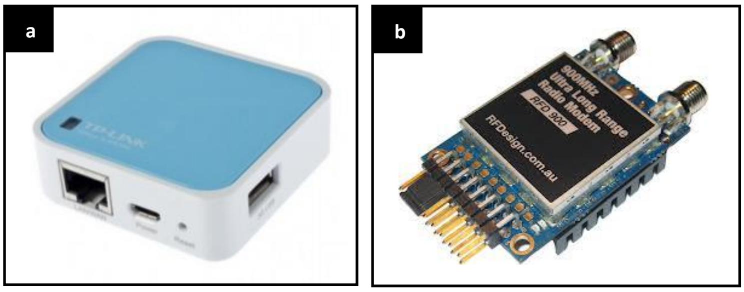


Figure 10.6.a. TP-Link: WR703Ns embedded router (TP-Link 2011),
b. RF Design RFD900 UHF radio modem (RFDesign 2012)

The radiation pattern of the embedded router's antenna was found to be omni-directional. In the field of antenna design, the term radiation pattern refers to the directional dependence of the strength of the radio waves from the antenna (Cheng 1998). In other words, the radiation pattern tells you which direction the electromagnetic waves propagate, and what strength they are in each direction.

The polarisation of the antenna is a slightly different concept to radiation patterns. Polarisation is the orientation of the wireless signal; it can be vertical, horizontal, circular or combinations of these. The key difference is that radiation patterns tell you where the antenna sends a signal, whereas the polarisation tells you how the signal gets there. The E-Plane and H-Plane are reference planes for linearly polarised antennas. Figure 10.7.a. shows the relationship between the two planes for a horizontally polarised Yagi antenna, and Figure 10.7.b. shows the relationship between the two planes for a vertically polarised omni-directional dipole antenna. It should be noted that the second polarisation type mentioned is common for short range WMNs (Liveport 2007), and depicts the polarisation of the recommended embedded router's omni-directional antenna.

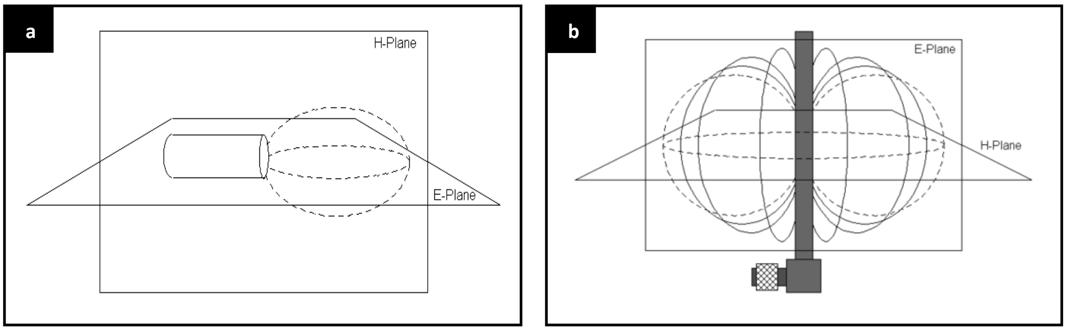


Figure 10.7.a. E- & H-Planes for a horizontally polarised yagi antenna (Liftarn 2007a),
b. E- & H-Planes for a vertically polarised omni-directional antenna (Liftarn 2007b)

In April 2013, the results from Dr Paul Gardener-Stephen's outdoor coverage analysis of the recommended embedded router were discussed. Gardner-Stephen (2013) analysed the coverage through a series of tests in an unobstructed, low-density environment. The 'coverage border' was defined as the point where substantial packet-loss started occurring. It was found that the H-Plane coverage of the vertically polarised omni-directional antenna was approximately 120m. The tests also found that locating the router at a height between 6-8m 'optimised' E-Plane coverage. Gardener-Stephen confirmed that 'optimal E-Plane coverage' was deemed as "just being able to connect to the base of the tower, while still achieving a near maximal H-Plane coverage".

Through reviewing RFDesign (2012) technical data sheets, it was quickly realised that the coverage of their UHF radio modem would easily meet WiFindUs' AP performance requirements. RFDesign (2012) state that this radio modem, which will be used to facilitate communication between the towers, can transmit and receive in excess of 40km depending on antennas and geographic coordinate system (GCS) setup.

10.2. Appendix B – LABC Temporary Demountable Structures Checklist

The LABC (2012) advise OMF engineers to check the following areas of each large temporary demountable structure (TDS):

1. Ground conditions are in accordance with the design
2. Baseplates, spreaders and soil anchorages are correctly installed and tested
3. Coefficients of friction are as per the design
4. The structure is set out as designed
5. Connections are correctly made
6. Members and couplers are not damaged
7. Bracing systems are laid out and connected correctly
8. Compression members are appropriately restrained
9. Tensile members are correctly sized and appropriately connected
10. Crowd barriers are appropriately braced/connected to resist the design loads

10.3. Appendix C – HSE Essential TDS Documents

Design concept and statement:
All proper designs will have calculations to determine the balance of loading and scale of forces acting on the structure. Therefore, the designer should be able to provide:

- A statement as to what the structure is designed to do (the concept);
- A list of items or connections that require particular checking each time the structure is erected;
- Particularly for outdoor structures, details of the methods of transferring all horizontal forces, eg wind, back to the ground (without which the structure will not be stable).

The physical checking of temporary structures becomes much more effective and simple if the designer's statement is available to the local authority.

Construction drawings:
Construction drawings will normally be required for all but the simplest temporary structures. These should be accompanied by full calculations, design loads and any relevant test results. These documents should normally be sent to the local authority at least 14 days before the event. It should be recognised that supplementary details, eg loads from lighting and sound suppliers, may not be available until nearer to the event.

Risk assessment:
A risk assessment should be carried out by the contractor to cover the erection and design of the temporary demountable structure. Remember that the effort and resources applied to health and safety issues should be proportional to risks associated with the project and the difficulty of managing those risks. It may be necessary to carry out another risk assessment to consider the hazards that the temporary demountable structure may create by being in the venue.

Safety method statement:
A safety method statement should be drawn up for the erection and dismantling of any structure. This should be submitted with the initial plans and calculations to the local authority. The method statement should be specific to the structure.

Completion certificate
If self-certification is used, it is unlikely that the local authority will carry out any inspections of the temporary demountable structure. It is therefore critical to ensure that each contractor certifies their structure/s as complete and that this documentation is passed to the local authority.

10.4. Appendix D – Review of Australian Standards

Table 10.2. Summary of reviewed Australian Standards

Standard	*Scope*	*Classification*
AS1170.1 (1989) Minimum design loads on structures - Part 1: Dead and live loads and load combinations	This Standard sets out requirements for establishing the minimum dead, live, wind, and snow loads, as well as load combinations to be used in the limit state design of structures and members.	**Relevant** (Specifies dead load requirements for tower structures)
AS1170.2 (1989) Minimum design loads on structures - Part 2: Wind loads	This Standard sets out the procedures for determining design wind speeds and wind loads to be used in structural design of all buildings and components of buildings, bridges, and other structures subjected to wind.	**Relevant** (Specifies wind load requirements for tower structures)
AS1417.1 (1987) Receiving Antennas for Radio and Television in the Frequency Range 30 MHz to 1 GHz construction	This Standard applies to the safety and security of fixed antennas with their supporting structures for use with radio and television broadcast receiving equipment operating within the frequency range 30MHz to 1GHz.	**Irrelevant** (Wi-Fi operates at either 2.4Ghz or 5GHz)
AS1798 (1992) Lighting poles and bracket arms - Preferred dimensions	This Standard specifies preferred dimensions for poles which are designed to support luminaires and ancillary equipment for the lighting of roads and other outdoor public spaces. The dimensions specified also apply to joint-use lighting	**Irrelevant** (Focusses on permanent structures)
AS2550.20 (2005) Cranes Hoists and Winches - Safe Use Self-Erecting Tower Cranes	This Standard specifies the requirements for the safe use of self-erecting tower cranes.	**Irrelevant** (Focusses on large / heavy industrial equipment)
AS3995 (1994) Design of steel lattice towers and masts	This Standard sets out the procedures for determination of design wind speeds and wind loads, and other appropriate standards to be used in the structural design of steel lattice towers and masts, with or without ancillaries such as antennas, for communication purposes. It also applies to other lattice towers and masts where the predominant load is wind load on the structure. It further sets out the basis for the strength assessment of members and connections of lattice towers and masts.	**Relevant** (Specifies wind load requirements for tower structures)
AS4268 (2008) Radio equipment and systems - short range devices - limits and methods of measurement	This standard specifies the minimum performance and methods of measurement for short range devices (SRDs) supplied for use under the Australian Radiocommunications (low Interference Potential Devices) Class Licence 2000 and the Radiocommunications (Radio-controlled Models) Class 2002.	**Relevant** (Specifies performance requirements for AP)
AS4676 (2000) Structural design requirements for utility services poles	This Standard sets out general requirements for structural design and minimum design loads applicable to pole structures supporting - a) street or floodlighting; b) road or railway signalling equipment; c) aerial conductors carrying electric power, or communication signals; d) equipment for communication through the atmosphere; or e) any combination of these.	**Relevant** (Specifies the design requirements for tower structure)

10.5. Appendix E – QFD Wind Load Calculations

Table 10.3. C1 Wind load calculations

Part	*Quantity*	*Pipe Area (mm^2)*	*1/2 Area (mm^2)*	*1/2 Area (m^2)*	*Component Area*
RHS - Leg	3	N/A	101474	0.101474	0.304422
Pipe - Leg (50mm)	3	184317	92158	0.092158	0.276475
Pipe - Ballast (300mm)	1	1041061	520530	0.520530	0.520530
Pipe - Mast (80mm)	3	249125	124563	0.124563	0.373688
Pipe - Mast (65mm)	2	209701	104851	0.104851	0.209701
Cap - Electronics (300mm)	2	50306	25153	0.025153	0.050306
				Total Structure Area (m^2)	**1.735123**
Fd =	Cd.Az.qz	Where,	Cd =	1.8	
			Az =	1.735123	
Fd =	**13.539**		qz =	4.335	
*Parts neglected	Tripod Bracket				
	Tripod Bracket Bolts				
	Mast Couplers				
	Ballast Caps				

Table 10.4. C2 Wind load calculations

Part	Quantity	Pipe Area (mm^2)	1/2 Area (mm^2)	1/2 Area (m^2)	Component Area
Pipe - Foot (40mm)	1	38013	19007	0.019007	0.019007
Pipe - Leg (15mm)	3	67544	33772	0.033772	0.101316
Pipe - Leg (25mm)	3	105872	52936	0.052936	0.158808
Pipe - Leg (32mm)	3	133204	66602	0.066602	0.199805
Pipe - Ballast (300mm)	1	502655	251327	0.251327	0.251327
Pipe - Mast (40mm)	1	608212	304106	0.304106	0.304106
Cap - Electronics (150mm)	2	21682	10841	0.010841	0.021682
				Total Structure Area (m^2)	**1.056051**
Fd =	Cd.Az.qz	Where,	Cd =	1.8	
			Az =	1.056051	
Fd =	**8.240**		qz =	4.335	
*Parts neglected	Tripod Brackets				
	Tripod Bracket Couplers				
	Mast Couplers				
	Ballast Caps				

Table 10.5. C3 Wind load calculations

Part	*Quantity*	*Pipe Area (mm^2)*	*1/2 Area (mm^2)*	*1/2 Area (m^2)*	*Component Area*
Pipe - Top (15mm)	3	70194	35097	0.035097	0.105291
Pipe - Top (20mm)	3	85294	42647	0.042647	0.127941
Pipe - Top Brace (20mm)	3	31762	15881	0.015881	0.047642
Pipe - Mid (32mm)	6	95504	47752	0.047752	0.286513
Pipe - Mid Brace (32mm)	3	31762	15881	0.015881	0.047642
Pipe - Mid (40mm)	6	131696	65848	0.065848	0.395087
Pipe - Brace (40mm)	9	120637	60319	0.060319	0.542867
Pipe - Bottom (40mm)	3	169159	84580	0.084580	0.253739
Pipe - Bottom Brace (40mm)	3	67331	33665	0.033665	0.100996
Cap - Electronics (150mm)	2	21682	10841	0.010841	0.021682
				Total Structure Area (m^2)	**1.929401**
Fd =	Cd.Az.qz	Where,	Cd =	1.8	
			Az =	1.929401	
Fd =	**15.055**		qz =	4.335	
*Parts neglected	Elbows				
	Couplers				

Table 10.6. C4 Wind load calculations

Part	Quantity	Pipe Area (mm^2)	1/2 Area (mm^2)	1/2 Area (m^2)	Component Area
Pipe - Top (15mm)	3	57703	28851	0.028851	0.086554
Pipe - Top Brace (15mm)	3	10000	5000	0.005000	0.015000
Pipe - Top (20mm)	3	70686	35343	0.035343	0.106029
Pipe - Top Brace (20mm)	3	42261	21130	0.021130	0.063391
Pipe - Top (25mm)	3	90478	45239	0.045239	0.135717
Pipe - Top Brace (25mm)	3	91986	45993	0.045993	0.137979
Pipe - Mid (32mm)	3	110270	55135	0.055135	0.165405
Pipe - Mid Brace (32mm)	3	139462	69731	0.069731	0.209192
Pipe - Mid (40mm)	3	115642	57821	0.057821	0.173463
Pipe - Mid Brace (40mm)	3	201731	100866	0.100866	0.302597
Pipe - Bottom (50mm)	3	152681	76341	0.076341	0.229022
Pipe - Bottom Brace (50mm)	3	303823	151912	0.151912	0.455735
Pipe - Leg (150mm)	1	495439	247720	0.247720	0.247720
Cap - Electronics (150mm)	2	21682	10841	0.010841	0.021682
				Total Structure Area (m^2)	**2.349485**
Fd =	Cd.Az.qz	Where,	Cd =	1.8	
			Az =	2.349485	
Fd =	**18.333**		qz =	4.335	
*Parts neglected	Elbows				
	Couplers				

Table 10.7. C5 Wind load calculations

Part	Quantity	Pipe Area (mm^2)	1/2 Area (mm^2)	1/2 Area (m^2)	Component Area
Pipe - Top (40mm)	1	535227	267613	0.267613	0.267613
Pipe - Mid (40mm)	3	127712	63856	0.063856	0.191568
Pipe - Mid Brace (40mm)	3	76027	38013	0.038013	0.114040
Pipe - Bottom (50mm)	3	190066	95033	0.095033	0.285100
Pipe - Leg (65mm)	3	237190	118595	0.118595	0.355785
Cap - Electronics (150mm)	2	21682	10841	0.010841	0.021682
				Total Structure Area (m^2)	**1.235788**
Fd =	Cd.Az.qz	Where,	Cd =	1.8	
			Az =	1.235788	
Fd =	**9.643**		qz =	4.335	
*Parts neglected	Elbows				
	Couplers				

Table 10.8. C6 Wind load calculations

Part	Quantity	Pipe Area (mm^2)	1/2 Area (mm^2)	1/2 Area (m^2)	Component Area
Pipe - Top (25mm)	3	195863	97931	0.097931	0.293794
Pipe - Top Brace (25mm)	6	52936	26468	0.026468	0.158808
Pipe - Mid (32mm)	3	246427	123213	0.123213	0.369640
Pipe - Mid Brace (32mm)	6	133204	66602	0.066602	0.399611
Pipe - Bottom (40mm)	9	304106	152053	0.152053	1.368478
Pipe - Bottom Brace (40mm)	12	208313	104156	0.104156	1.249876
Pipe - Leg (150mm)	3	149251	74625	0.074625	0.223876
Cap - Electronics (150mm)	2	21682	10841	0.010841	0.021682
				Total Structure Area (m^2)	**4.085764**
Fd =	Cd.Az.qz	Where,	Cd =	1.8	
			Az =	4.085764	
Fd =	**31.881**		qz =	4.335	
*Parts neglected	Elbows				
	Couplers				

10.6. Appendix F – Stage 1 Prototype Costs

Table 10.9. S1 tower prototype cost breakdown (Bunnings 2013)

Part	Description	Material	Brand	Supplier	Part Cost	Quantity	Total Cost
Ballast	Pipe - 150x1000mm	DWV PVC	Vinidex	Bunnings	21.00	1	**21**
Ballast Cap	Cap - 150mm Push-on	DWV PVC	Vinidex	Bunnings	16.56	1	**16.56**
Collar Bracket	Print - 150mm Tripod	ABS	Makerbot	Flinders	39.45	2	**78.90**
Electronics Housing	Cap - 150mm Push-on	DWV PVC	Vinidex	Bunnings	16.56	2	**33.12**
Electronics Housing Cap	Cap - 25mm BSP Thread	Polypropylene	Philmac	Bunnings	2.89	1	**2.89**
Electronics Housing Clip	Clip - Suitcase	Zinc Plated	Zenith	Bunnings	7.50	2	**15**
Electronics Housing Tape	Tape - Insulation	PVC	Nitto	Bunnings	2.10	1	**2.1**
Electronics Housing Thread	Valve Socket - 25mm	PN-18 PVC	Holman	Bunnings	2.50	1	**2.5**
Glue Cement	125mL Solvent Cement	Type N	Protex	Bunnings	4.90	1	**4.9**
Glue Primer	125mL Priming Fluid	Red	Protex	Bunnings	4.76	1	**4.76**
Glue Silicone	Silicon - 300g All Purpose	Silicone Polymer	Parfix	Bunnings	4.98	1	**4.98**
Leg Bottom	Pipe - 25x1000mm	PN-12 PVC	Holman	Bunnings	3.99	3	**11.97**
Leg Bottom Reducer	Reducer - 32-25mm	PN-18 PVC	Holman	Bunnings	2.40	3	**7.2**
Leg Centre	Pipe - 40x1000mm	PN-9 PVC	Holman	Bunnings	5.25	1	**5.25**
Leg Centre Cap	Cap - 25mm BSP Thread	Polypropylene	Philmac	Bunnings	2.89	1	**2.89**
Leg Centre Thread	Valve Socket - 25mm	PN-18 PVC	Holman	Bunnings	2.50	1	**2.5**
Leg Support	Pipe - 32x1000mm	PN-12 PVC	Holman	Bunnings	3.99	3	**11.97**
Leg Tee	Tee - 32mm	PN-18 PVC	Holman	Bunnings	2.40	3	**7.2**
Leg Top	Pipe - 32x1000mm	PN-12 PVC	Holman	Bunnings	3.99	2	**7.98**
Mast Bottom	Pipe - 40x1000mm	PN-9 PVC	Holman	Bunnings	5.25	3	**15.75**
Mast Bottom Coupler	Coupler - 40mm	PN-18 PVC	Holman	Bunnings	3.00	3	**9**
Mast Stabiliser Bolt	Eye Bolt - 8x75x20mm (2qty)	Galvanised	Zenith	Bunnings	3.30	2	**6.6**
Mast Stabiliser Hook	Hook - 6x60mm (5qty)	Zinc Plated	Zenith	Bunnings	5.10	1	**5.1**
Mast Stabiliser Rope	Rope - 4mmx50m	Polypropylene	Grunt	Bunnings	13.00	1	**13**
Mast Top	Pipe - 40x1000mm	DWV PVC	Vinidex	Bunnings	5.25	2	**10.5**
Mast Top Coupler	Coupler - 40mm	DWV PVC	Holman	Bunnings	3.00	2	**6**
						Total Cost of Stage 1 Tower Prototype	***309.62AUD***

*table notes: Custom parts cost estimate = (weight of plastic × cost per weight) + 1% machine amortisation

= (0.22 × 48) + 29 = $39.45

Table 10.10. S1 electronics prototype cost breakdown (Battery Space 2013; RFDesign 2012; TP-Link 2011; Vakoss 2013)

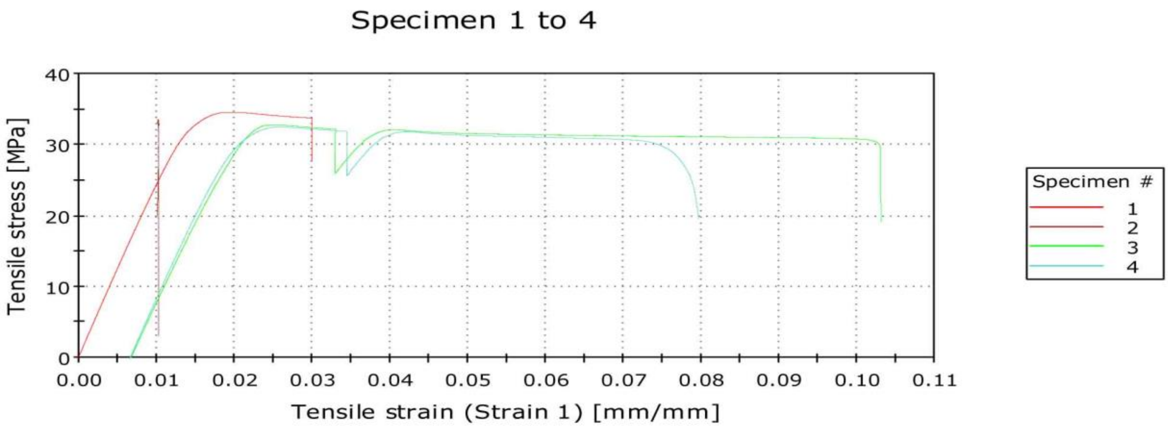
	Component Description	Make	Model	Price (AUD)
1	Embedded Router	TP-Link	WR703Ns	25
2	UHF Radio Modem	RFDesign	RFD900	89.5
3	Antenna 900MHz 2dBi monopole	RFDesign		5.95
4	Antenna 900MHz 3dBi monopole	RFDesign		6.95
5	Universal Battery Elimination Circuit	RFDesign	5V 3A	5.75
6	USB to TTL Cable	FTDI		17.95
7	USB Memory	-	16 GB	22
8	Passive USB Hub	-	-	4
9	Battery LiFePO4	Powerizer	12V 10Ah, 120Wh	135
10	Car Accessory connector	-		13
11	Voltage Adaptor	Jaycar	Low Voltage	7.95
12	Misc. Cabling			20
		Total Cost of Stage 1 Electronics Prototype		***353.05***

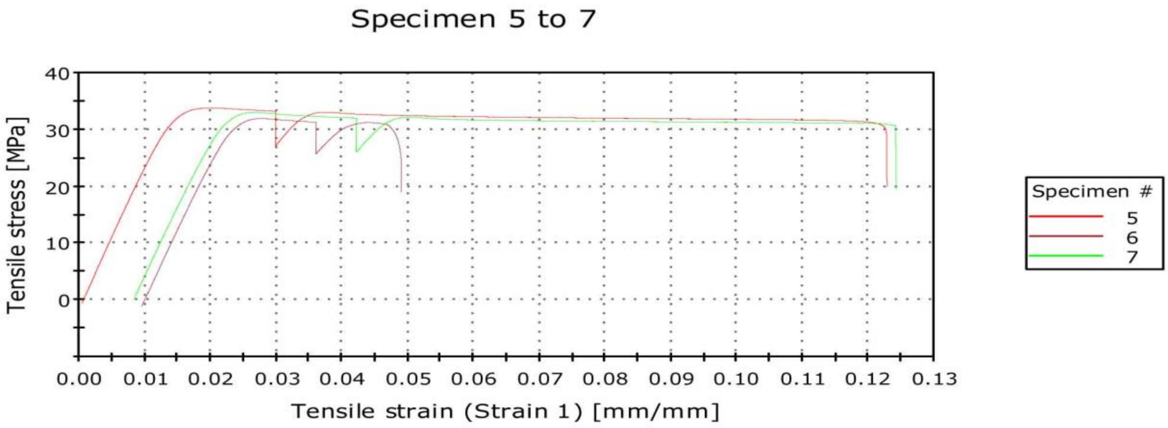
10.7. Appendix G – 3D Printed PLA Material Testing

10.7.1. Tensile Tests Results: Vertical Specimens

Dogbone

Criteria 1	
Criteria 2	
Export raw data	True





	Material	Geometry	Tensile stress at Yield (Zero slope) [MPa]	Modulus (Automatic) [MPa]
1	PLA	Rectangular	34.55994	2,509.22898
2	PLA	Rectangular	21.88539	289.90728
3	PLA	Rectangular	32.74262	2,356.54666

	Material	Geometry	Tensile stress at Yield (Zero slope) [MPa]	Modulus (Automatic) [MPa]
4	PLA	Rectangular	32.46602	2,457.03508
5	PLA	Rectangular	33.79255	2,592.36309
6	PLA	Rectangular	31.90523	2,501.42673
7	PLA	Rectangular	32.98196	2,504.81640

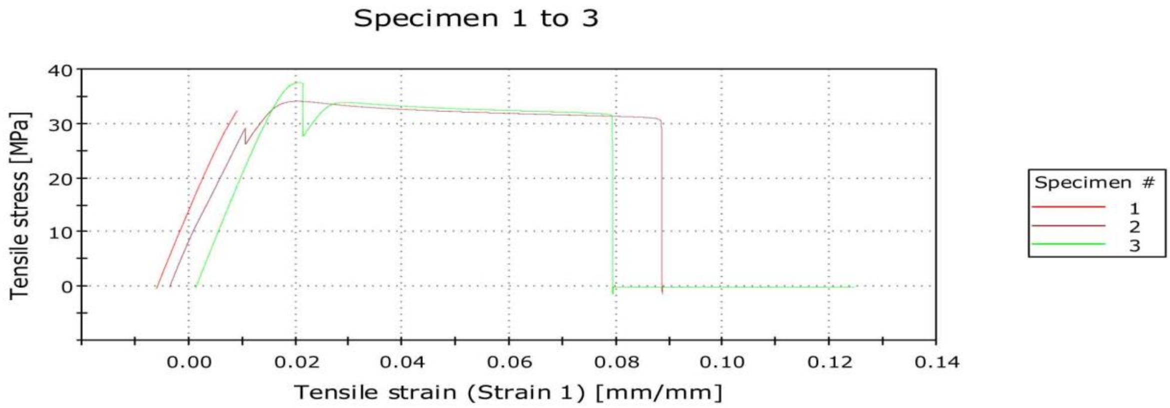
	Reduction of area at Area reduction [%]
1	5.19769
2	5.19769
3	6.47213
4	6.82212
5	6.79757
6	9.69318
7	6.16320

Figure 10.8. Tensile tests results: Vertical specimens (1-6) *note one additional test result

10.7.2. Tensile Tests Results: Horizontal Specimens

Dogbone

Data: Criteria 1
Data: Criteria 2



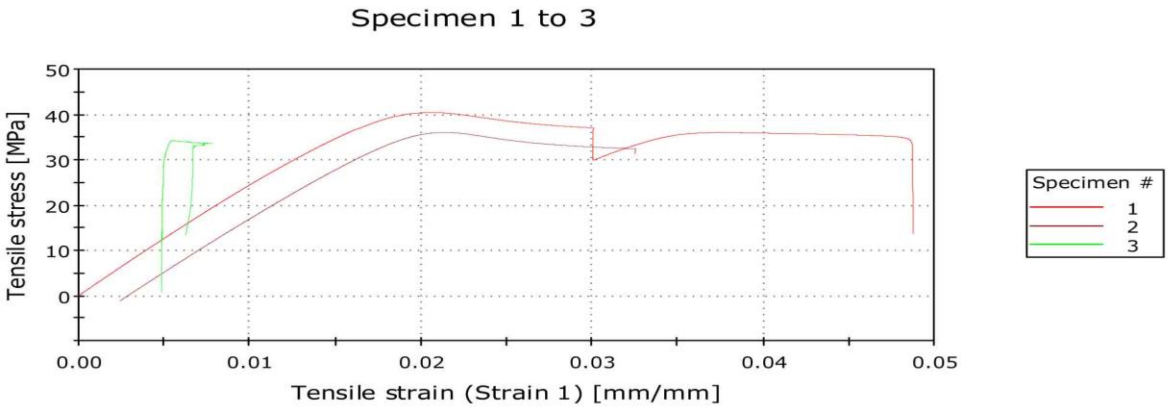
	Material	Geometry	Tensile stress at Yield (Zero slope) [MPa]	Modulus (Automatic) [MPa]
1	PLA	Rectangular	-----	2,421.32507
2	<None>	Rectangular	34.16172	2,317.65542
3	PLA	Rectangular	37.55092	2,441.20978

	Reduction of area at Area reduction [%]
1	0.43635
2	-0.72522
3	-0.77936

Figure 10.9. Tensile tests results: Horizontal specimens (1-3)

Dogbone

Criteria 1
Criteria 2



	Material	Geometry	Tensile stress at Yield (Zero slope) [MPa]	Modulus (Automatic) [MPa]
1	<None>	Rectangular	40.52941	2,539.90334
2	PLA	Rectangular	36.04834	2,424.08478
3	<None>	Rectangular	34.27050	205,667.92731

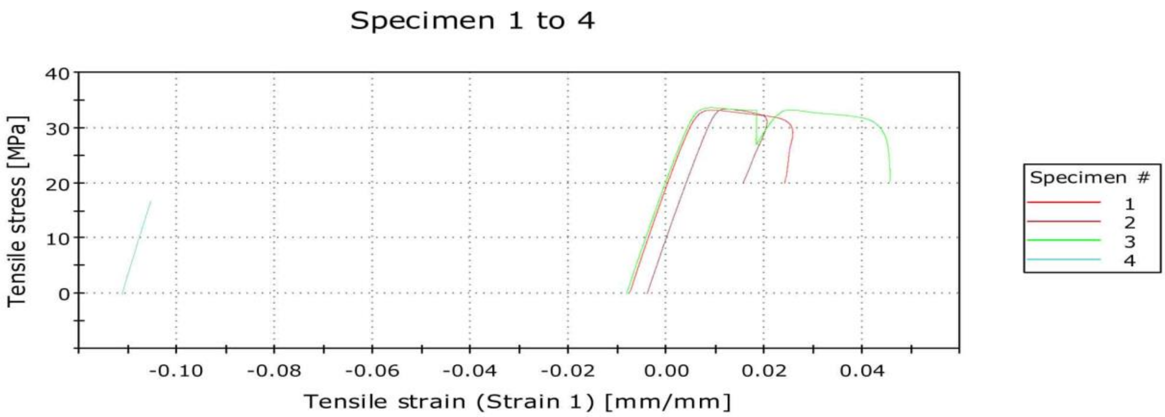
	Reduction of area at Area reduction [%]
1	-4.16667
2	2.83187
3	-4.16667

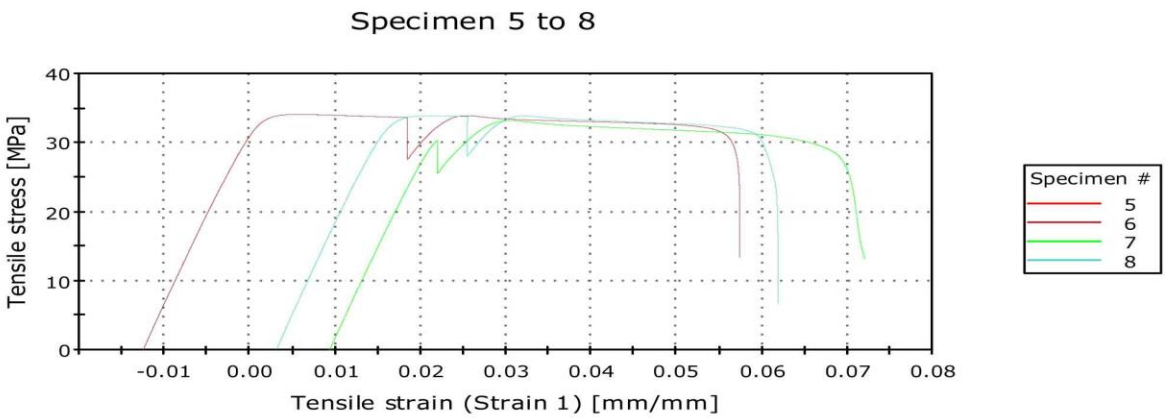
Figure 10.10. Tensile tests results: Horizontal specimens (4-5) *note one additional test result

10.7.3. Tensile Tests Results: Angular Thickness Specimens

Dogbone

Criteria 1	
Criteria 2	
Export raw data	True





	Material	Geometry	Tensile stress at Yield (Zero slope) [MPa]	Modulus (Automatic) [MPa]
1	PLA	Rectangular	33.18095	2,650.80112
2	PLA	Rectangular	33.46706	2,591.64377
3	PLA	Rectangular	33.64521	2,603.02656

	Material	Geometry	Tensile stress at Yield (Zero slope) [MPa]	Modulus (Automatic) [MPa]
4	<None>	Rectangular	-----	2,973.29415
5	PLA	Rectangular	-----	-----
6	PLA	Rectangular	34.08686	2,687.74869
7	PLA	Rectangular	33.18901	2,673.40663
8	PLA	Rectangular	33.89017	2,732.18561

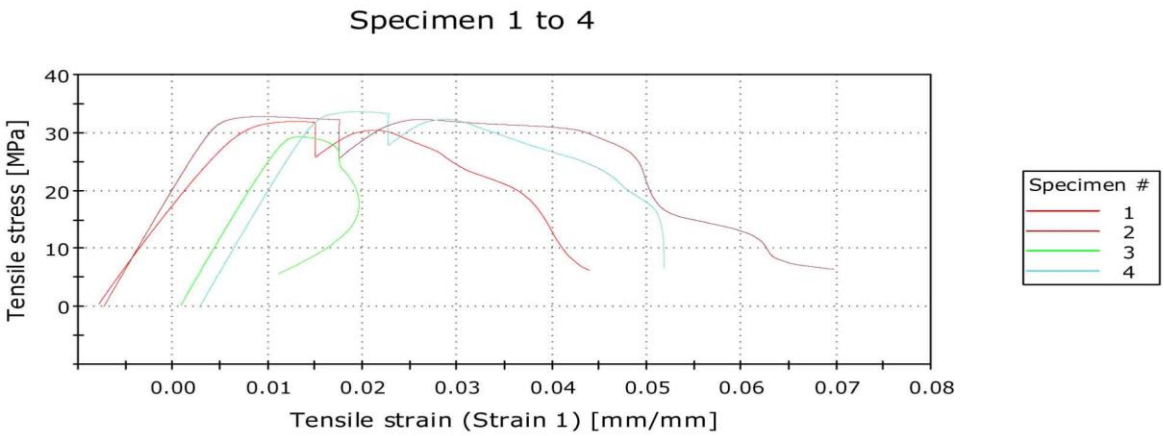
	Reduction of area at Area reduction [%]
1	-1.19750
2	-1.19409
3	2.41999
4	-0.77936
5	-----
6	-0.77936
7	2.41999
8	0.03998

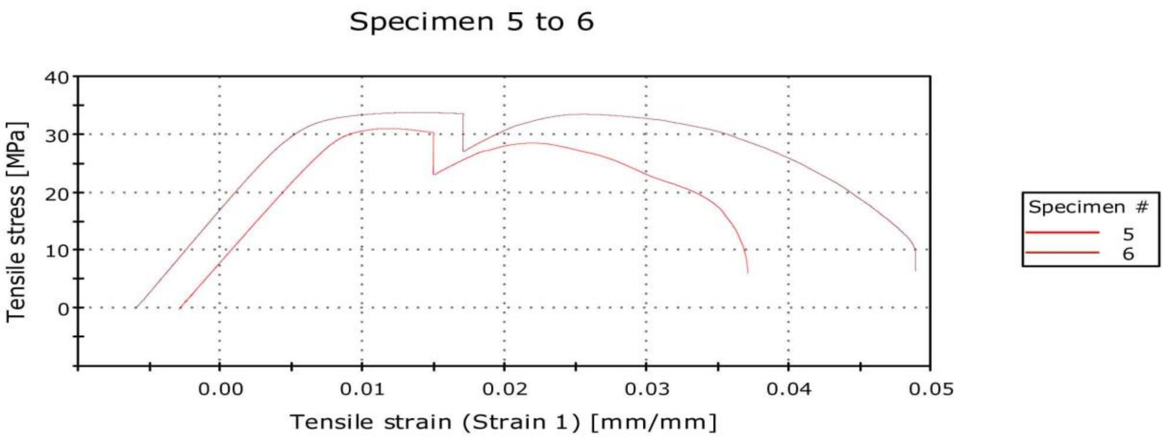
Figure 10.11. Tensile tests results: Angular thickness specimens (1-6) *note two additional test results

10.7.4. Tensile Tests Results: Angular Width Specimens

Dogbone

Criteria 1	
Criteria 2	
Export raw data	True





	Material	Geometry	Tensile stress at Yield (Zero slope) [MPa]	Modulus (Automatic) [MPa]
1	PLA	Rectangular	31.91993	2,264.15040
2	PLA	Rectangular	32.75043	2,819.38325
3	PLA	Rectangular	-----	2,803.11934

	Material	Geometry	Tensile stress at Yield (Zero slope) [MPa]	Modulus (Automatic) [MPa]
4	PLA	Rectangular	33.66463	2,803.27538
5	PLA	Rectangular	30.99955	2,784.37042
6	PLA	Rectangular	33.77726	2,879.86253

	Reduction of area at Area reduction [%]
1	1.63934
2	1.63934
3	2.81827
4	-0.36802
5	2.01842
6	-1.19409

Figure 10.12. Tensile tests results: Angular width specimens (1-6)

10.8. Appendix H – Stage 2 Natural Frequency Test Results

*please consult .csv files on attached CD for the exact record of the tests

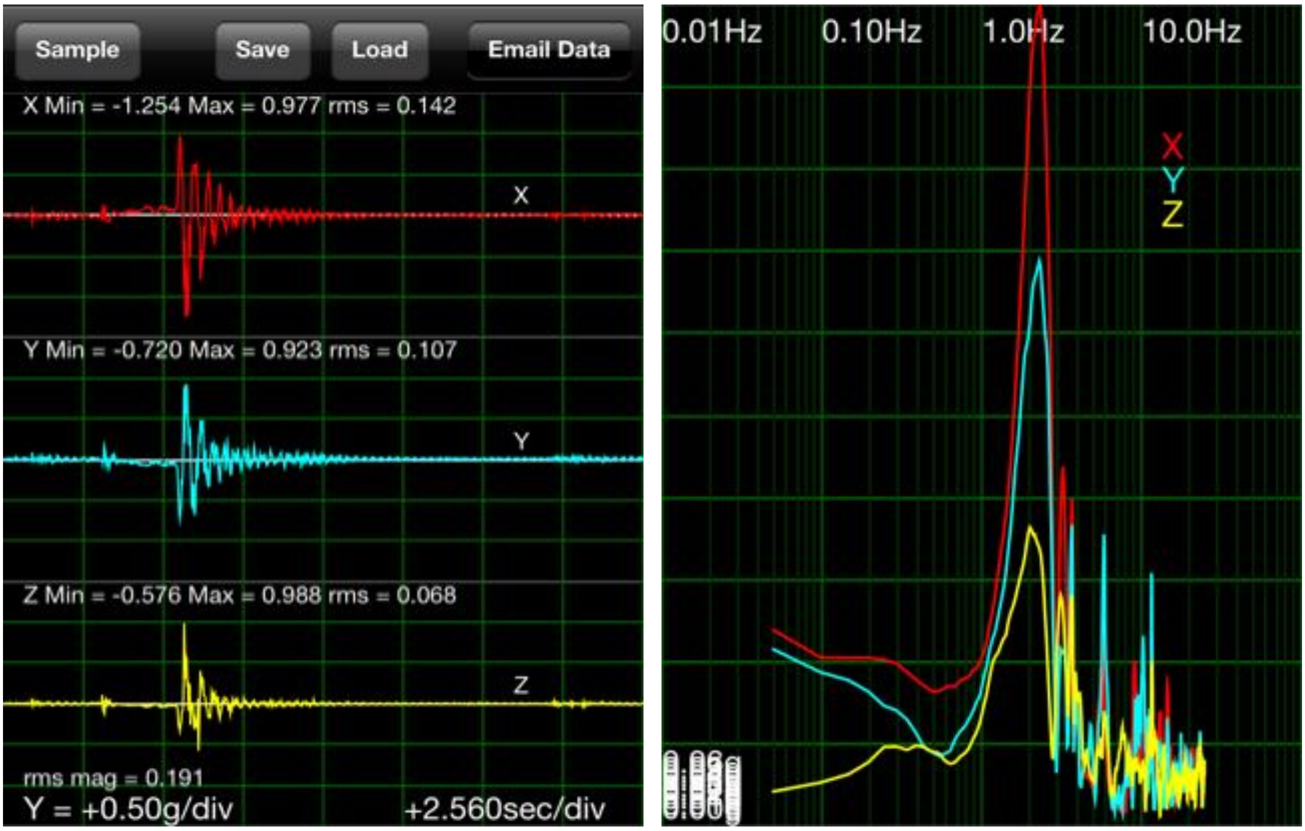


Figure 10.13. Frequency test 1: 3.6m mast results

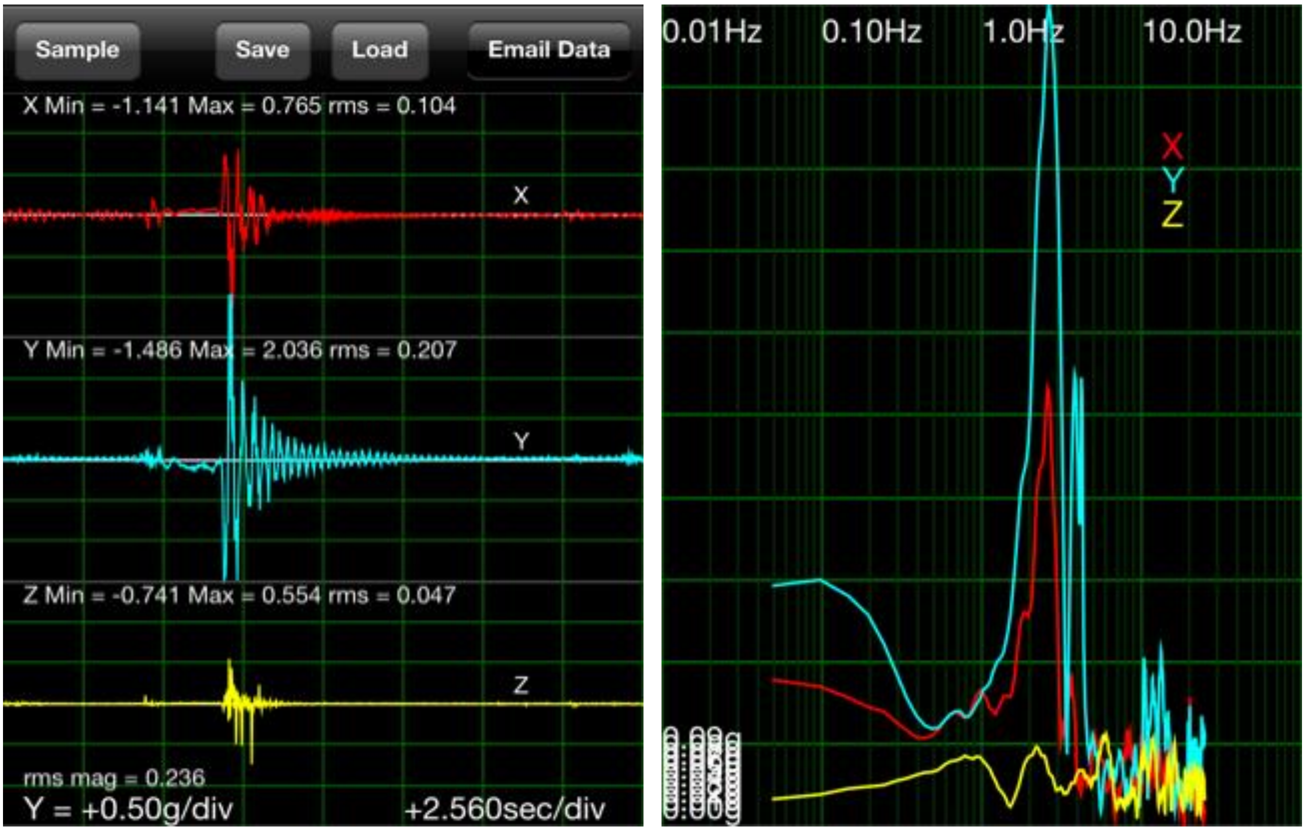


Figure 10.14. Frequency test 2: 3.6m mast results

Figure 10.15. Frequency test 3: 3.6m mast results

Figure 10.16. Frequency test 1: 6m mast results

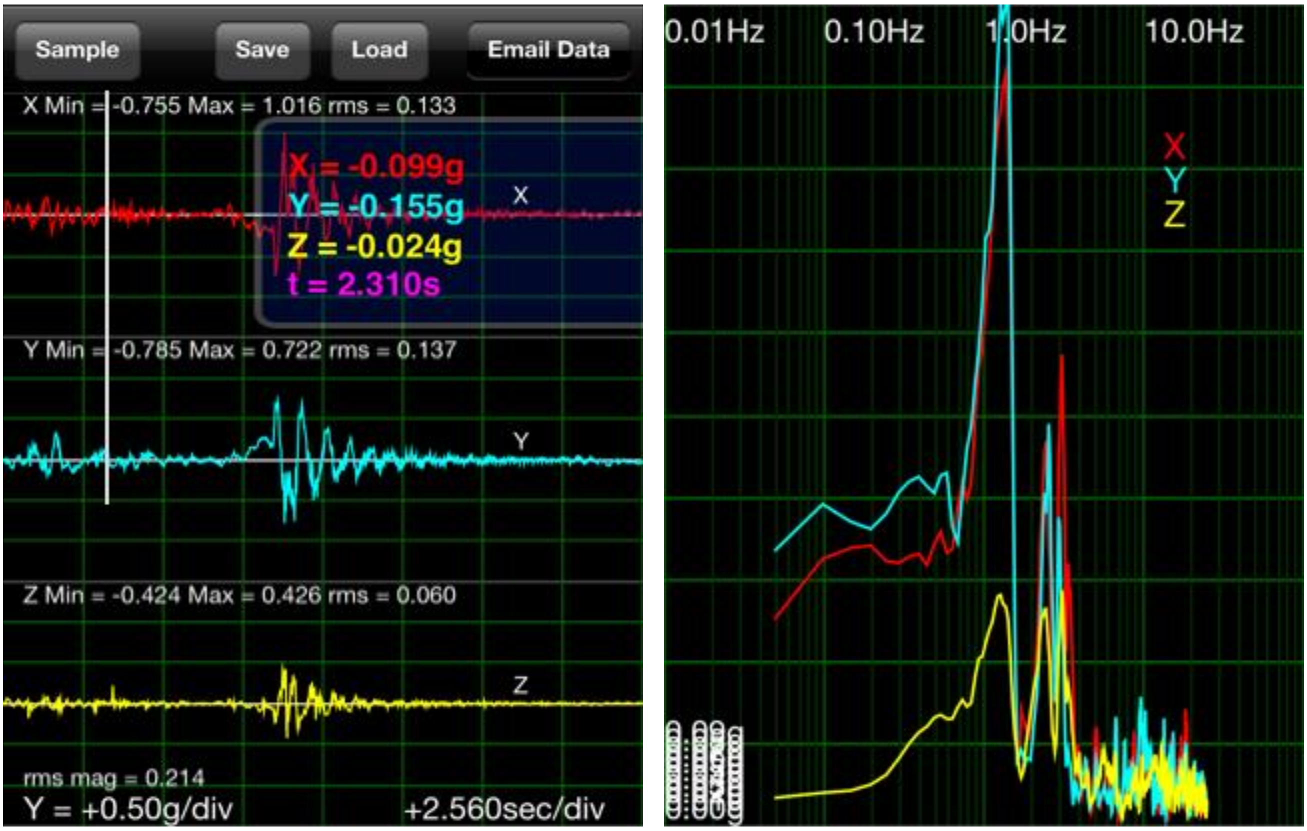


Figure 10.17. Frequency test 2: 6m mast results

Figure 10.18. Frequency test 3: 6m mast results

10.9. Appendix I – Stage 2 Wind Load Calculations

Table 10.11. S2 Wind load calculations

Part	*Quantity*	*Total Pipe Area (mm^2)*	*Area (m^2)*	*Total Component Area*
Pipe - Foot (40mm)	1	28453	0.028453	0.028453
Pipe Joiner Top Tripod	3	10697	0.010697	0.032092
Tripod Top Pipe 25mm	3	78957	0.078957	0.236871
Inline Joiner	3	3527	0.003527	0.010581
Outer leg 25C	3	73890	0.073890	0.221671
Pipe Joiner Bottom Tripod	6	14683	0.014683	0.088095
Pipe Bottom Tripod	3	73890	0.073890	0.221671
Footing	3	7435	0.007435	0.022305
Tripod Bracket	2	71909	0.071909	0.143818
Pipe Mast 40mm	4.82	132286	0.132286	0.637619
Cap - Electronics (150mm)	1	37919	0.037919	0.037919
Pipe - Ballast (150mm)	1	449876	0.449876	0.449876
			Total Area (m^2)	**2.131**

Defined Variables		
Wind Velocity (V)	85	
Drag Coefficient(Cd)	1.8	
Projected Area (Az)	2.131	
Height of Hill (H)	10	
Multiplier Terrain Height Centroid (Mz,cat)	0.61	<= 3m, AS3994 Table 2.3.3.2
Multiplier wind direction (Md)	1	worst case, AS3994 Table 2.2.5
Height of centroid (z)	1.35	
distance from crest (x)	0	
Equations		
qz =	0.6*(10^-3)*(Vz^2)	
Fd =	Cd.Az.qz	
Vz =	V.M(z,cat).Mt.Md	
Mt =	1+ H(1-|x|/4Lg)/3.5(z+Lg))	
Lg =	0.4H	
Results		
Length to determine Mt (Lg)	4	
Multiplier Topographic (Mt)	1.955357143	
Gust Wind Velocity (Vz)	101.3852679	
qz	6.167383523	
Fd =	**23.657**	
*Parts neglected	Tripod Brackets	
	Tripod Bracket Couplers	
	Mast Couplers	
	Ballast Caps	
	Couplers	

10.10. Appendix J – Stage 2 Prototype Costs

Table 10.12. S2 tower prototype cost breakdown (Bunnings 2013)

Component	Part	Description	Material	Brand	Supplier	Unit Cost	Quantity	Total Cost
Ballast	**Housing**	Pipe 150mm	DWV PVC	Vinidex	Mitre10	21.00	1	**21.00**
	Cap	Cap 150mm Push-on	DWV PVC	Vinidex	Bunnings	16.56	2	**33.12**
	Bush	Bush BSP 25mm	HDPE	Philmac	Bunnings	2.5	1	**2.50**
	Bush Cap	Cap BSP	HDPE	Philmac	Bunnings	1.82	1	**1.82**
Centre Support	**Bush**	Bush BSP 25mm	HDPE	Philmac	Bunnings	2.5	1	**2.50**
	Clamp	Hose Clamp 40-57mm	SS	Tridon	Bunnings	1.97	1	**1.97**
	Leg Inner	Pipe 40mm	DWV PVC	Vinidex	Bunnings	3.57	0.15	**0.54**
	Leg Outer	Pipe 40mm	PN-9 PVC	Holman	Bunnings	4.84	0.15	**0.73**
	Nipple	Nipple BSP 25mm	HDPE	Philmac	Bunnings	1.8	1	**1.80**
	Socket	Faucet Socket BSP 25mm	PN-18 PVC	Holman	Bunnings	2.99	1	**2.99**
Tripod Bracket	**Collar Bracket**	Print 150mm Bracket	ABS	Makerbot	Flinders	44.07	2	**88.14**
	Bolt	Hex M8 50mm	Zinc Plated	Zenith	Bunnings	0.54	6	**3.24**
Tripod Upper Leg	**Leg**	Pipe 25mm	PN-12 PVC	Holman	Bunnings	3.43	3	**10.29**
	Bolt	Hex M8 50mm	Zinc Plated	Zenith	Bunnings	0.54	3	**1.62**
	End Joiner	Print 25mm Joiner	ABS	Makerbot	Flinders	15.43	3	**46.28**
Tripod Lower Leg	**Leg Outer**	Pipe 20mm	PN-12 PVC	Holman	Bunnings	2.87	3	**8.61**
	Bolt	Hex M8 50mm	Zinc Plated	Zenith	Bunnings	0.54	3	**1.62**
	End Joiner	Aluminium Round 25.4mm	6060T5 Aluminium	Capral	Capral	15.43	6	**92.56**
	Leg Inner	Dowel 19mm	Tasmanian Oak	-	Bunnings	3.51	3	**10.53**
Outer Leg	**Adhesive**	Building Adhesive 320g	Liquid Nails	Selleys	Bunnings	0.73	3	**2.20**
	Bolt	Hex M4 50mm	Zinc Plated	Zenith	Bunnings	0.35	6	**2.10**
	Guy Tensioner	V-Cleat 3-6mm	PTFE	Ronstan	Whitworths	6.95	3	**20.85**
	Inline Joiner	Print 25mm Joiner	ABS	Makerbot	Flinders	13.89	3	**41.67**
	Leg Footing	Aluminium Round 36mm	2011T3 Aluminium	Capral	Capral	3.96	3	**11.88**
	Leg Inner Brace	Dowel 19mm	Tasmanian Oak	-	Bunnings	3.51	3	**10.53**
	Leg Inner Shell	Conduit Rigid 25mm	PVC	Deta	Bunnings	1.00	3	**3.00**
	Leg Outer Shell	Pipe 25mm	PN-12 PVC	Holman	Bunnings	3.43	3	**10.29**
	Leg Spacer	Conduit Coupling 25mm	PVC	Deta	Bunnings	0.40	6	**2.40**
Anchorage	**Carabiner**	Snap Hook 5mm	316-SS	Zenith	Bunnings	7.28	3	**21.84**
	Guy Rope	Braided 16 Plait 4mm	Polyester	Whittam	Whitworths	1.65	21	**34.65**
	Tent Peg	Peg 7x215mm	Mild Steel	Whites	Bunnings	0.79	3	**2.38**
Electronics Housing	**Housing**	Cap 150mm Push-on	DWV PVC	Vinidex	Bunnings	16.56	2	**33.12**
	Guy Clip	Wire 3mm	Galvanised	Whites	Bunnings	0.29	0.2	**0.06**
	Housing Ribs	Print 150mm Cap	ABS	Makerbot	Flinders	8.74	1	**8.74**
	Tape	Tape Insulation	PVC	Nitto	Bunnings	2.10	1	**2.10**
	Threaded Fitting	Adapter BSP 25mm	PN-18 PVC	Holman	Bunnings	3.7	1	**3.70**
Mast	**Mast Outer**	Pipe 40mm	PN-9 PVC	Holman	Bunnings	4.84	6	**29.04**
	Clamp	Hose Clamp 40-57mm	SS	Tridon	Bunnings	1.97	3	**5.91**
	Mast Inner	Pipe 40mm	DWV PVC	Vinidex	Bunnings	3.57	6	**21.40**
	Threaded Fitting	Valve Socket BSP 25mm	PN-18 PVC	Holman	Bunnings	2.50	1	**2.50**
Suitcase	**Bag**	Action Chair 200x200x1400mm	Canvas	Oztrail	Snowys	27.95	1	**27.95**
Miscellaneous	**Cement**	Solvent Cement 1L	Type N	Protex	Bunnings	9.90	0.1	**0.99**
	Primer	Priming Fluid 500mL	Red	Protex	Bunnings	13.80	0.1	**1.38**
	Silicone	All Purpose Adhesive 300g	Silicone Polymer	Parfix	Bunnings	4.98	0.1	**0.50**
						Total Cost of Stage 2 Tower Prototype		**633.03**

Table 10.13. S2 electronics prototype cost breakdown
(Battery Space 2013; Columbus 2013; Comfast 2013; Element14 2013; Turnigy 2013; Zipp 2013)

	Component Description	*Make*	*Model*	*Price (AUD)*
1	Wireless Wi-Fi Network Adapter (x2)	Comfast	WN730A	17.80
2	Single-board computer	Raspberry Pi	Model B	38.00
3	GPS data logger receiver	Columbus	V-800	38.95
4	Universal Battery Elimination Circuit	RF Design	5V 3A	5.75
5	USB Memory	-	16 GB	22.00
6	Passive USB Hub	Zipp	4 Ports USB 2.0 HUB	10.00
7	Battery	Powerizer	12V 10Ah, 120Wh	135.00
8	Voltage Adaptor	Jaycar	Low Voltage	7.95
9	Micro Phone Connector	Jaycar	MIC/P	2.95
10	Micro Phone Connector	Jaycar	MIC/P	2.95
11	Misc. Cabling	-	-	20.00
		Total Cost of Stage 2 Electronics Prototype		***301.35***

10.11. Appendix K – Stage 2 Tripod Bracket Engineering Drawing

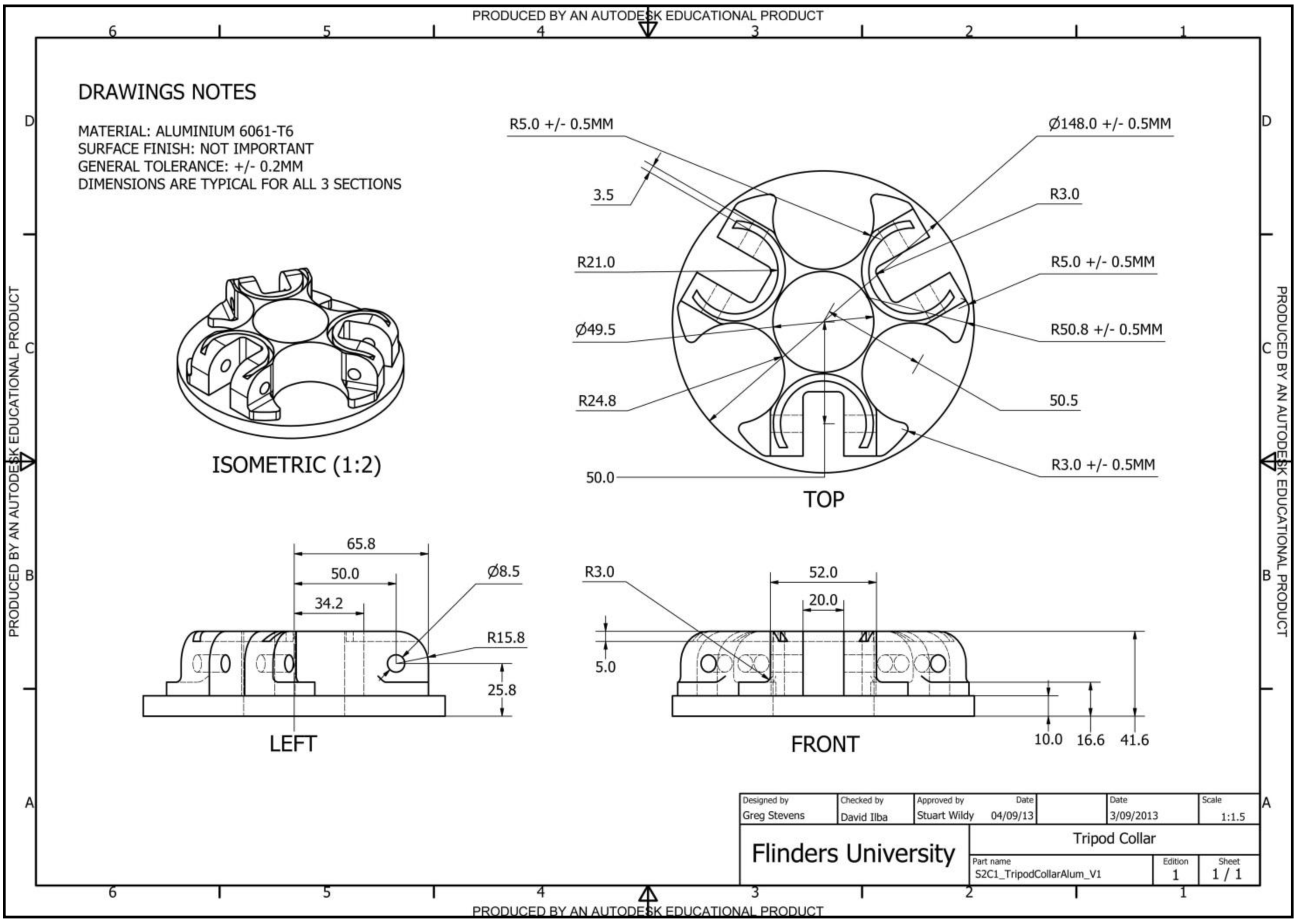


Figure 10.19. S2 aluminium tripod bracket engineering drawing used to obtain cost estimates

10.12. Appendix L – Mechanical Properties of PVC

Table 10.14. Mechanical properties of PVC (Vinidex 2011)

Property	*Value*	*Conditions and Remarks*
Ultimate tensile strength	52 MPa	AS 1175 Tensometer at constant strain rate cf: PE 30
Elongation at break	50 - 80%	AS 1175 Tensometer at constant strain rate cf: PE 600-900
Short term creep rupture	44 MPa	Constant load 1 hour value cf: PE 14, ABS 25
Long term creep rupture	28 MPa	Constant load extrapolated 50 year value cf: PE 8-12
Elastic tensile modulus	3.0 - 3.3 GPa	1% strain at 100 seconds cf: PE 0.9-1.2
Elastic flexural modulus	2.7 - 3.0 GPa	1% strain at 100 seconds cf: PE 0.7-0.9
Long term creep modulus	0.9 - 1.2 GPa	Constant load extrapolated 50 year secant value cf: PE 0.2 - 0.3
Shear modulus	1.0 GPa	1% strain at 100 seconds $G=E/2/(1+\mu)$ cf: PE 0.2
Bulk modulus	4.7 GPa	1% strain at 100 seconds $K=E/3/(1-2\mu)$ cf: PE 2.0
Poisson's ratio	0.4	Increases marginally with time under load. cf: PE 0.45

Table 10.15. Mechanical properties of PVC (Holman 2013)

Property	*Value*
Specific gravity	1.42
Vicat softening temperature - ISO 2507-2	>79°C
Effect on potable water - AS/NZS 4020	Complies
Hydrostatic design stress - AS/NZS 4765	17.5 MPa
Short term min. hoop stress at 1 hour and 20°C	38.0 MPa
Minimum required strength (MRS) at 20°C extrapolated to 50 years	24.5 MPa
Minimum notched hoop strength at 20°C extrapolated to 50 years	24.5 MPa
Elastic modulus - ISO 9969	3000 MPa
Flexural modulus - ISO 9969	3000 MPa
Poisson's Ratio	0.38 – 0.40