POLYSAND

SOLO PROJECT - FINAL REPORT

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Abstract

This report explores a novel sustainable material (sand bonded with waste plastic (PBS) a.k.a Polysand), from a Design Engineering perspective. The material holds relevance for low-income regions that lack waste infrastructure. Enabling environmental clean-up efforts in areas that need it most by creating value out of an abundant waste.

Fence posts were selected as an appropriate application for the material based on the recently characterised material properties, and an understanding of local needs. A design specification was selected and justified appropriately.

Optimisation of the fence post design using Finite Element Analysis (FEA) and numerical optimisation methods was undertaken. A mass reduction of 86% was achieved. The model was constrained to prioritize ease of manufacture, making it appropriate for super low-cost methods.

The optimised design was then critically evaluated against benchmark designs using LCIA tools and cost analysis. The optimised design had the lowest environmental impact score out of the benchmark designs. The design also achieved an approximate manufacturing cost of £7.75, allowing it to be retailed at a competitive price.

Through optimisation techniques, a clearer understanding of how it can be manufactured into more complex geometries, Polysand has the potential to be financially and environmentally sustainable building material.

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PART ONE

Contextual Investigation

Background

Despite being a 'basic human right' effective waste management is not available for over 2 billion people worldwide (1). Globally, Sub-Saharan countries collect the lowest proportion of solid waste (44% compared to 90% in Europe and Central Asia (2)). Within this, low income, rural regions have the absolute lowest waste collection rates (2).

Uncollected waste has been shown to adversely affect public health by being burnt and blocking drains, encouraging the spread of disease and contributing to flooding (1). The environmental implications are vast. Unsurpisingly, 70% of ocean plastic come from places with no waste management (3).

Recycling waste plastic can be done effectively, but often requires expensive machinery. This makes the technology far less scalable for regions where the problem of waste plastic is most prevalent. There is no lack of entrepreneurs aiming to make a profit out of cleaning up plastic waste, however the vast start-up cost and low profitability makes the business hard to scale (4).

Low cost recycling techniques exist. For instance, the Precious Plastic movement has created a range of open plan machinery that can be manufactured for around £250-£400 per machine (5). This assumes access to metal fabrication equipment, technical skill and most importantly electricity to power the machines. While in Sub-Saharan Africa, almost 50% of the population live in 'extreme poverty' (6) and 70% lack access to electricity (7). Even these 'low cost' solutions don't make sense for such environments.

PBS was first established in the Cameroon as an opportunity to recycle waste plastic using super low-cost technologies (8). The material is produced by mixing collected waste LDPE and sand in a cauldron over an open fire and shovelled into a metal mould (9). The addition of sand to plastic greatly improves the strength of the material, while reducing the high cost plastic content. Research undertaken at Imperial College London has established the optimum sand grain size, proportions and the mechanical properties of PBS (8).

The material has been adopted by the charity WasteAid who have set up over 27 community driven recycling workshops in The Gambia and Pakistan (9). The charity teaches communities about waste awareness and trains teams to collect, process and manufacture waste into paving tiles. WasteAid now aims to expand its product range.

Objectives

Expand the product range made from PBS using low cost production methods for use by WasteAid in Gunjur, The Gambia.

Fiigure 1 - Beach Pollution in Gunjur, The Gambia

Problem Definition

The problem of unsustainable construction and specifically fencing was selected to explore. A large part of my project has been finding appropriate applications for this material. The tools that I used to aid in this process are demonstrated in the parts 1, 2 and 3 of this report. I investigated the properties of the material, developed a network of contacts and stakeholders, creatively explored the problem space, and researched local demand and global issues.

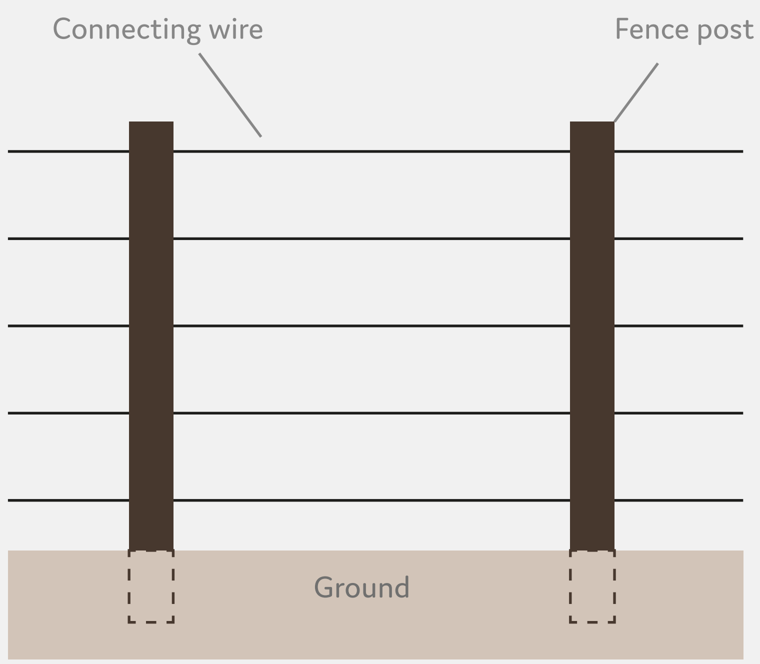


Figure 2 - Initial fencing system design

Local Demand & Global Issues

The building sector is one of the biggest contributors to energy and resource depletion according to Horvath (2004), with the consumption of two-fifths of the world's material and energy flows attributed to the housing sector (10).

Fences and walls are ubiquitous throughout the world but hold a particular relevance for Sub-Saharan African countries. Figure 2 shows a typical wire and post fence design. Here compound housing is incredibly popular especially in rural and low-income areas (11). For instance, in Ghana compound houses are experiencing an annual growth rate of 5.5% (11). I have engaged with Eekosgambia, a sustainable construction company in The Gambia, who have established interest in purchasing 10,000 fencepost units through WasteAid.

A compound house is a cluster of buildings contained within a wall or fence enclosure. These are normally made from either timber or concrete (12). Both these materials come with their own environmental implications. For instance, much of the timber supply in the Gambia comes from the Casamance forest which is under pressure from deforestation (13) (14). Cement production accounts for 4% of global green house gas emmissions (10).

The first design of a PBS solution by WasteAid (see Figure 3) weighs over 80 kg and uses around 3000 plastic bags to produce one fence post (15). The issue with this solution is that it is far too material inefficient, costing too much to produce for it to be commercially viable.

This is an opportunity for innovation.

Figure 3 - Initial fence post design

Material Properties

Polysand is a strong, tough composite material made from LDPE binder and sand aggregate (8). The addition of sand greatly improves the strength of LDPE (see Figure 4).
To find an appropriate application for the material, its characterised properties were compared to other materials. A comparison of compressive strength, Young's modulus and density are shown in Figure 4. Polysand was found to have similar compressive strength to both Pine wood and concrete, making it appropriate for applications that these materials are conventionally used for such as construction.

However, LDPE is a thermoplastic. This means that it can be reformed with the application of heat. This is advantageous for recycling the material but also it limits the type of application that the material can be used for. For instance, the material should not be used as a structural element in a building as in the case of fire, the consequences would be catastrophic. Fence posts have a low risk of being exposed to extreme heat and low consequences in the case of failure.

Figure 6 shows the microscopic grain structure of the material. The optimum proportions of sand and LDPE are 75% and 25% by weight. Optimum grain size was found to be <500μm (8). The properties under these conditions are found in Table 1.

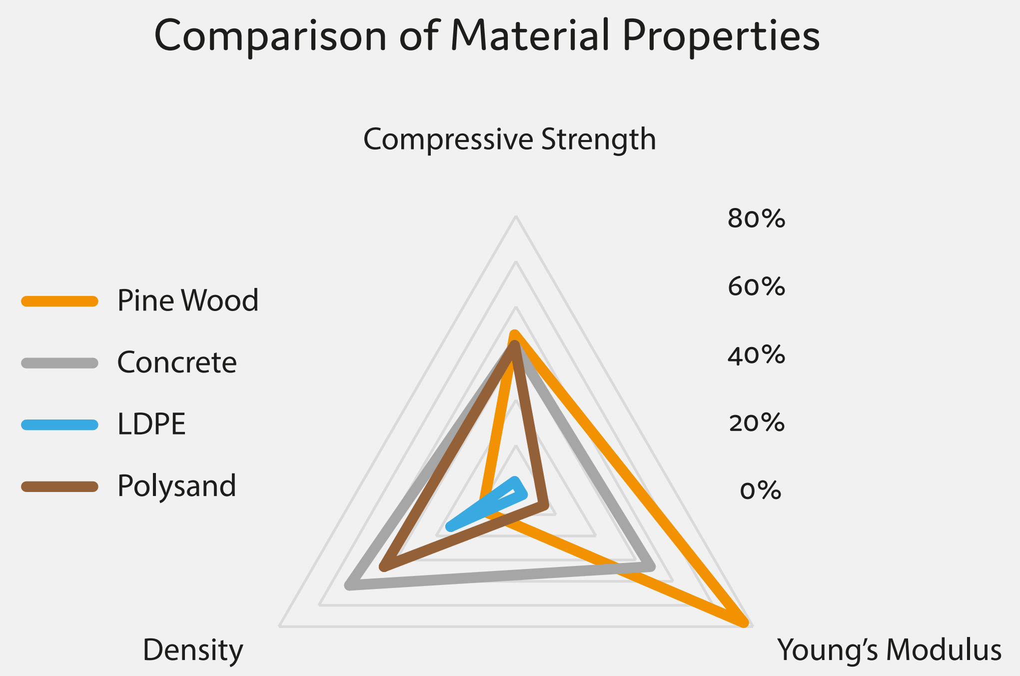


Figure 4 - Comparison on normalised material properties

Compressive Strength	28.2 MPa
Tensile Strength	34.1 MPa
Flexural Strength	14.9 Mpa
Density	1.92 g/cm³

Table 1 - material properties. Taken from Kumi-Larbi A (2018).

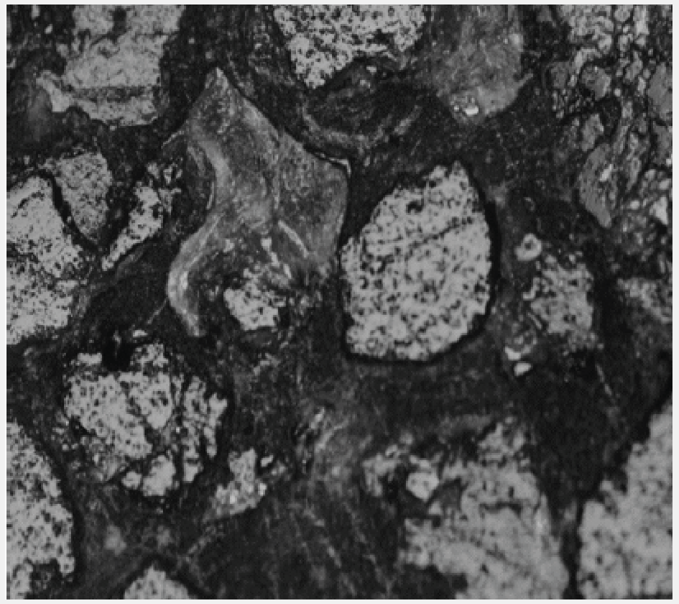


Figure 5 - Microscopic grain structure of PBS. Taken from Kumi-Larbi A (2018).

PART TWO

Stakeholder Engagement

Stakeholder Engagement

Throughout the project I have collaborated with a multitude of different stakeholders on many different levels. My primary stakeholder and theoretical client is WasteAid UK, with whom I have worked closely in defining the problem as well obtaining key insights concerning the real operations occurring in The Gambia. The project has been based at Imperial College London, and I have worked closely with my Primary and Secondary tutors on the project. I have worked across departments, with individuals from the Department of Civil Engineering who have and continue to work on characterising the properties of the material. A broader snapshot of the landscape of stakeholders I have connected with can be seen on the following page.

Stakeholders

In order to tackle this project, one initially very complex and far removed from my previous experiences, I have interacted with many stakeholders. A selection of these interactions are outlined in the stakeholder map (Figure 6) below.

Kevin Ison - EekosGambia

Representative from Eekos Gambia, a sustainable construction company based in the Gambia and potential customer. Kevin helped understand the local demand and picing of buidling materials.

Zoë Lenkiewicz - Head of Programmes and Engagement at WasteAid

I contacted Zoë Lenkiewicz, head of operations and outreach Aid to gain insight to life in the Gambia and the current progress on the manufacturing up to this point.

We have met once in person and share regular email correspondance.

A group of students at the RCA

Who designed a modular building brick made from recycled PET bottles. We met to learn from their experiences and discuss collaboration to produce simple moulds for their design.

Marco Aurisicchio & Elena Dieckmann

I met with my tutor team regularly to discuss the progress of the project.

Chris Cheeseman & Alexander Kumi-Larbi Jnr

Alex and his supervisor Chris are from the Civil & Environmental Engineering Department at Imperial College London and are investigating the mechanical properties of the material. We meet regularly and share resources and findings.

Gordon Addy

Gordon's wealth of knowledge from his years working in a foundry was incredibly useful in the prototyping phase.

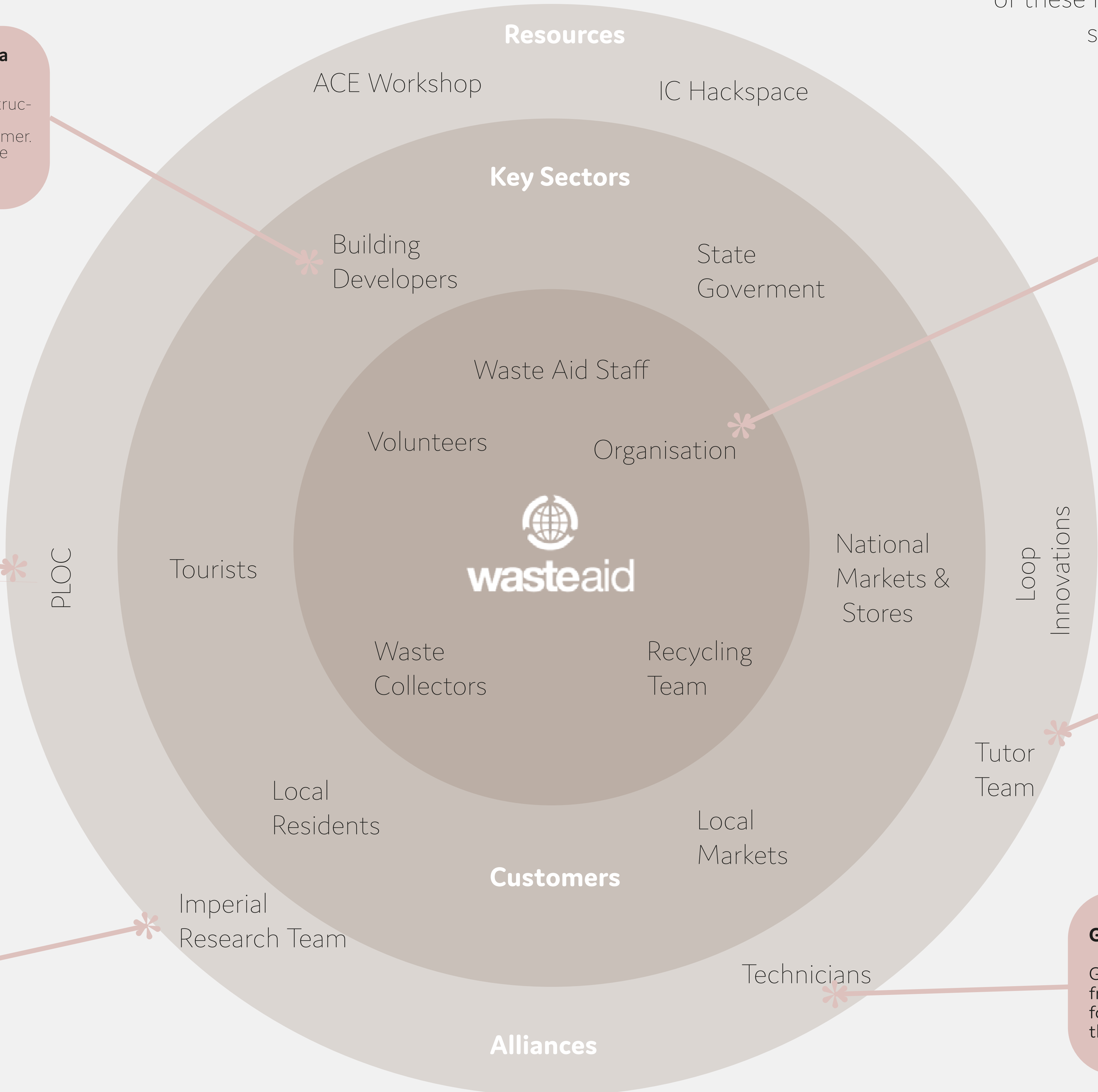


Figure 6 - Stakeholder Map

PART THREE Problem Development

Problem Development

One of the hardest problems faced in this project was selecting the right problem to solve. I considered many different problems and potential solutions by using creative tools such as user journey mapping and brain-storming with key stakeholders. I decided to focus on fence post design as this problem could be well defined, met an established demand, and was a problem that I felt I could tackle effectively. Following the selection of the idea, a set of design requirements and targets were established (see Figure 7).

User Journey Mapping

User journey mapping (Figure 7) was used as an ideation tool for identifying problems through the eyes of the primary client, WasteAid. I focused on solutions that would help improve the organisation, and its workforce. The idea that was settled on to move forward was developing the product range available by making a useful product with local demand that also expands the manufacturing capabilities of the organisation by making more complex two-part mould. Making fenceposts was selected because it had a realistic prototyping feasibility for the timescale of the project.

	Set-up		Processing			Distribution	End of life
Event Stage	**Setting up workshop**	**On-boarding / training**	**Collecting waste**	**Sorting / cleaning**	**Manufacturing**	**Storing/ selling products**	**Recycling**
Pain Points	- Very few tools available	- Langauge barrier/ poor literacy	- Inefficent - Hand picking bad for workers backs	- Contaminants slip through	- Only very simple product shapes - Open fire is smokey health issue	- Products lack demand - Products lack value	- Degradation of material unknown
Ideas	- Produce tools to aid the manufacturing process	- Teach workforce key info in a way they will understand	- Waste collection infrastructure	- Low cost plastic identification tool	- Complex moulds - Find out how dangerous it is - Make it safer	- Make product with local demand	- Quantify mechanical properties after recycling life cycles and UV light exposure
Solutions	- Hammers, benches	- Educational tools to communicate instructions	- Hand held litter picking tool - Bins for waste collection	- Identification methodology - PLASTELL by Mahota an Imperial startup exists, I have put them in contact with WasteAid	- 2 part mould design - Measure off-gassing components - Cheap extractor - Solar oven	- Construction materials - Fences - Modular brick - Furniture	- Research Project into material properties

Figure 7 - User Journey Mapping. The selected idea is bounded by a red box.

Design Specifications

A set of design requirements for the fence post was developed alongside means of testing each metric. These are displayed in Table 2. Not all design requirements were tested in the validation section. The tests that were undertaken are highlighted in bold.

Metric	Value	Explanation	Testing
Loading	>1400 N	Fence must withstand the weight of an adult human (safety factor of 2)	**FEA**
Loading	> 375 Pa *	Fence must withstand lateral forces from wind	**FEA**
Manufacturability	n/a	Must be manufacturable using current low cost equipment	**Approximation of techniques**
Mass	<< 80 kg	Fence post must be significantly lighter than the original design mass of 80 kg	**Volume and mass calculation**
Height	>2 m	Fence must be at least 2 m tall.	**Measurement**
Cost of manufacture	<£15	Cost of manufaturing must be competitive and scalable for the targeted communities.	**Costing**
Time of Installation	<2 hrs	The solution must be easy to deploy.	User testing
Aesthetics	n/a	The end users and customers must enjoy the look and feelof the product	User testing
Lifespan	10 years	The product should last many years without breaking or degrading from UV or ambient heat.	Lab test
Sustainability	n/a	The product should have lower embodied energy, CO_2 and other appropriate LCA metrics than current solutions.	**LCA**

* approximation based on wind speed of 25 m/s

Table 2 - Design specifications

PART FOUR Design Optimisation

Design Optimisation

The current fence post design is simply too bulky, material inefficient and expensive to produce for it to be commercially viable. The design also far exceeds the mechanical requirements of a fence post. Therefore, the design can be optimised to satisfy the requirements while minimising the volume of the post and the use of materials.

The characterization of the material's mechanical properties has allowed the use of certain Design Engineering tools. Finite Element Analysis (FEA) and numerical optimisation have been used to produce an optimal solution. For the optimisation process I have simplified the loading requirements to a worst case beam bending scenario.

Initially, the cross section style of the fence post was selected by comparing the success of various designs in particular design categories. These include the maximum bending stress, the mass, and the manufacturability of the design. Secondly, numerical optimisation reduces the mass of the fence post while satisfying the constraints by altering selected dimension variables. The optimised solution reduced the mass of the fence post by 86%.

Cross Section Optimisation

1. Cross-section selection

The initial stage in the process was establishing which cross-sectional shape would be the most effective at achieving the objectives (low mass, adequate strength and easy manufacturability with low cost methods). The loading of the material has been simplified to a beam bending scenario of an average adult male (70 kg) standing at the end of the fixed beam. A safety factor of 2 was incorporated. Although this loading scenario is unlikely, it will include large enough forces for it to encompass other more complex but smaller loading scenarios.

Because of the limited manufacturing capabilities available, it was of upmost importance that the design be made as simply as possible. Therefore, a scoring system was implemented (Equation 1) to categorise the designs on how easily they could be manufactured. Requiring a simple one-part mould scored a 3, a two part mould with one complex shape scored a 2, a two part mould with two complex shapes scored a 1, anything that could not be made using equipment available scored a 0.

Figure 8 shows the distribution of forces in bending. The design should therefore maximise material around the extremities and minimise material in the central region. Using the same baseline dimensions, 7 different cross sections were tested using Solidworks FEA static studies. The loading scenario is described in Figure 9. and the results are shown in Table 3.

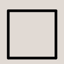
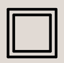
Design	Mass (kg)	Max Stress 1 (MPa)	Max Stress 2 (MPa)	Manufacturability	Score ($\times 10^{-2}$)
	86.4	1.6	1.6	3	2.17
	67.8	2.8	2.8	1	0.52
	13.6	27.0	25.0	2	0.16
	20.8	2.8	6.2	1	1.72
	10.4	21.3	13.4	2	0.90
	15.4	5.3	9.5	2	2.45
	39.8	2.3	2.3	0	0

Table 3 - FEA results and scoring for each cross section. Max Stress 1 and 2 are in the vertical and horizontal plane respectively

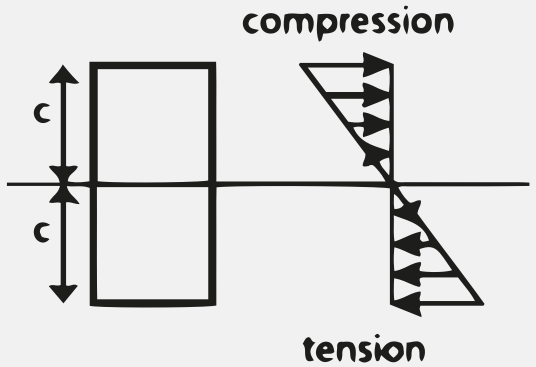


Figure 8 - Force distribution in bending

$$score = \frac{manufacturability}{mass \times \sigma_{max}}$$

Equation 1 - calculating score value

The I beam and hollow square cross section perfomed best in terms of the maximum bending stress in the vertical plane when considered with mass. The square tube perfomed best in both planes. However, due to the low manufacturability of these designs they did not score the highest.

The U cross section had the highest total score, partly due to its relatively high strength to mass ratio and high manufacturability score.

The inspiration for the U cross section was derived from the same principles of the I beam design. By having the body of material at the extremities of the beam to account for the areas of highest stress. While manufacturing capabilites remain limited and experimental, the U cross section will be selected to take forward. However, as techniques improve, or the type of manufacturing changes, a more complex cross sectiion such as the square tube should be used.

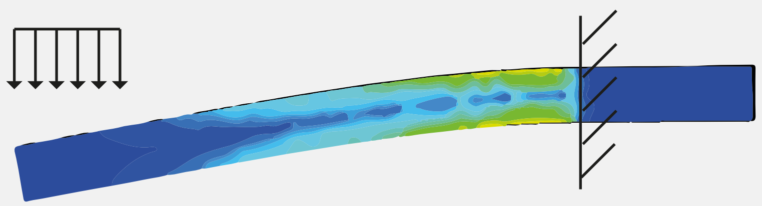


Figure 9 - Beam bending scenario and stress distribution in square beam

Cross Section Optimisation

2. Dimension Optimisation

To achieve a beam with a minimum mass that was able to satisfy the design requirements, an optimisation problem was set up. Effective topological optimisation of a beam cross section has been achieved by Liu, An et al. (2008) (16). However, because of the requirement for simplicity of design and manufacturability topological optimisation was avoided as it created complex shapes. Instead a simple numerical optimisation problem was developed (Equation 2) based on beam bending theory. The dimensional variables of the cross section are indicated in Figure 10..

$$\text{minimise } w.r.t\ b,d \quad Volume(b,d) = 2(b_1 d_1 - b_2 d_2)$$

$$\text{subject to} \quad g_1(x):\ \sigma_{max} - 2.82 \times 10^6 \leq 0$$

$$\text{where} \quad \sigma_{max} = \frac{M_{max} y}{I}$$

$$\text{where} \quad I = \frac{b_1 d_1^3}{12} \frac{b_2 d_2^3}{12}$$

$$M_{max} = 1400 \times 1.5$$

$$g_2(x):\ b_2 - b_1 + 0.02 \leq 0$$

$$g_3(x):\ d_2 - d_1 + 0.02 \leq 0$$

Equation 2 - Optimisation Formulation

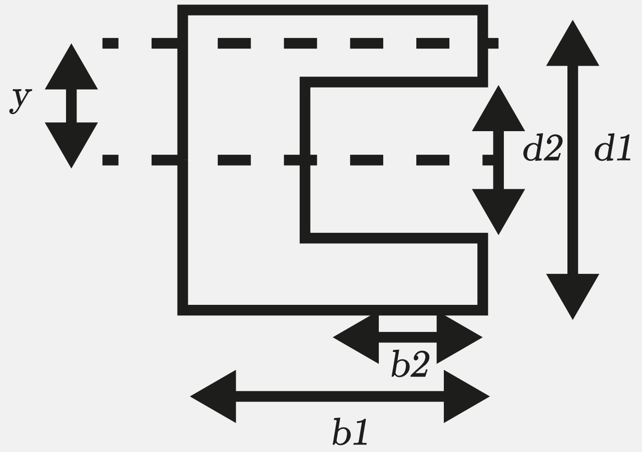


Figure 10 - Diagram of dimensional variables

The objective function is the minimisation of the volume of the beam. Constraint g(1) ensures that the max bending stress of the beam is less than the compressive strength of the material. Constraints g(2) and g(3) ensure the minimum thickness is greater than 2 cm. This is because, when produced too thin the material breaks easily. A multi-variable non-linear solver 'fmincon' was used in MATLAB (17).

A local minimum solution was found and is shown below in Table 4. The solution satisfies all constraints and achieves a mass reduction of 86% which is illustrated in Figure 11.

	Original	Optimised	Change
b1 (m)	0.15	0.06	
d1 (m)	0.15	0.06	
b2 (m)	0	0.03	
d2 (m)	0	0.02	
σmax (Mpa)	1.6	19.6	
Volume (m3)	0.023	0.003	86.67%

Table 4 - Optimisation Results

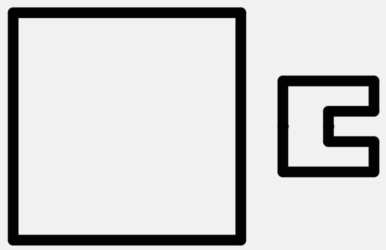


Figure 11 - Visualisation of optimisation results.
Original (left) and Optimised (right)

The limitations of this optimisation study are the simplifications used. The fence post loading is simplified to a beam bending scenario. This is unlikely to be the case in a real-life scenario, however it does cover a worst case scenario, with stress conditions worse than that experienced from someone falling on the fence or trying to climb it. This optimisation looks at beam bending in one plane. Because of the geometry selected, bending in the other plane requires asymmetrical bending equations. This was explored, however it was found that incorporating both planes made the optimisation prone to failure. So the simplification was retained. The data used for the simulations was acquired from lab samples. The differences in material properties made in the field may differ significantly.

PART FIVE

Physical Prototyping

Physical Prototyping

Polysand is an innovative new material. Hence, it has not been experimented with fully and the best manufacturing process was unknown at the beginning of the project. In the field, the material is made in bulk over an open fire. This was of course not possible while following the strict health and safety regulations at Imperial College London. The prototyping process consisted of a series of increasingly refined experiments. Each experiment tested a variation of either the material, means of processing the material, and the way in which it is moulded.

The outcome of the prototyping phase is a proof that the part geometry can be made from the material, with key insights into how this can be scaled to low tech and industrial manufacturing.

Prototype + Process

1

Making the material for the first time

The heating process with a hot plate and fume cupboard (Figure 11) took hours and the LDPE granules didn't melt properly, forming clusters (Figure 10).


Figure 10 - Mixed PBS


Figure 11 - Initial set up

4

Two part wooden mould

I used a rudimentary two part mdf laser cut mould. I found that the mould was not nearly strong enough and had to be held together with a g-clamp. I managed to press into the material although the low volume and slight delay in pressing meant that the material cooled and hardened. This meant that the shape was not fully formed. I also realised that I would need to locate the inside mould so that it created a symmetrical piece.


Figure 16 - Laser cut mould and output

2

DIY Hot Press

Pre mixed material (from 1) heated and compressed within oven (Figure 12).
Outcomes: Formed solid tile (Figure 13) in 30 minutes.

Limitations: heating area too small for large designs, and machine not accessible as off campus.


Figure 12 - DIY hot press


Figure 13 - Metal mould and output tile

5

Metal box mould

A metal box mould was used create a longer piece, here I used L shaped locators to fix the inside mould into the center of the piece. I also experimented with pre-melting the material in a glass baking tray, mixing it periodically before moulding it (Figure 17).

I was unable to remove the material from the mould (Figure 18), despite its 5 degree draft angle.


Figure 17 - Equipment


Figure 18 - Filled mould

3

Testing Furnace

A much larger furnace in the ACE workshop on campus was tested (Figure 14). Mixed LDPE powder and sand were heated in a mould and compressed post heating in ceramic mould (Figure 14). This worked well to form complex 3D shape (Figure 15), however not all the plastic melted completely.


Figure 14- ACE oven


Figure 13 - Ceramic mould


Figure 15 - Output tile

6

Pin fixed plywood mould

A sturdy plywood mould (Figure 19) held together with dowel pins. These pins allow the mould to be taken apart and the piece removed easily. The inside of the mould was treated with chelaque and wax to aid in the release of the material.
The outside mould seperated easily, whereas the inside mould was harder to remove because it was surrounded by material on all sides (Figure 19). The part needed some post-processing and due to the highly abrasive nature of the material this had to be achieved with a tile cutter.

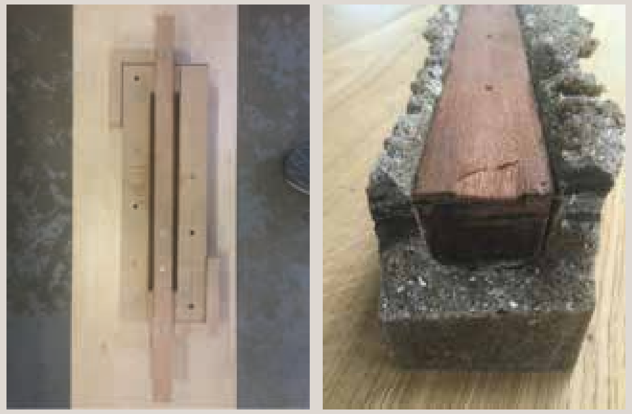


Figure 19 - Plywood mould and output product prior to cleaning.

Final Prototype

Figure 20 shows the final prototype, a section of fence post made from Polysand. The geometry of the part is similar to the optimised solution and stands as a proof of concept for the manufacturability of the design.

Figure 20 - Final Prototype

Observations & Conclusions

Observations

The prototpying process gleaned key insights about how the product should be manufactured.

Before the material is melted, it is absorbant and removes release agent, making it stick to the mould. Therefore the material should be melted in another container, seperate to the mould. This means that the material can be mixed during heating making sure it is completely and consistently melted.

The material is very adhesive. Even with the use of a 5 degree draft angle, chalaque, wax and silicon mould release, the internal wooden mould was incredibly difficult to remove. Therefore, a collapsible moulds is necessary.

The material doesn't seem to shrink much upon cooling. The coefficient of expansion woud be interesting to measure, so that an effective mould material can be selected that allows easy release.

The material never truly reaches a liquid state. The consistency of the material is like that of putty when heated. This is most likely because of the high sand content. The viscosity of the material would be interesting to measure and would be helpful to enable mass manufacturing.

The material is soft when molten, but pressure is required to form it. However, the hardness and viscosity of the material when molten needs to be measured to enable the selection of forces used in mass manufacturing.

Although the melt point of LDPE is 180 degrees Celcius, temperatures up to 300 degrees Celcius were used in the oven, to speed up the process. The material began smoking at 450 degrees Celcius.

The material is very soft and malleable above 200 degrees Celcius, however it becomes incredibly hard once it cools. The moldability of the material is greatly affected by the rate of cooling, and is something that should be taken into account for mass manufacturing.

Once the material has cooled it becomes very hard and the high sand content makes it very abrasive, making post-processing of the material with conventional workshop tools nearly impossible. The material blunted a hacksaw blade with ease. The piece had to processed on a tile cutter used for concrete. Therefore, it is important to use a mould that produces a product that requires very little post processing. For instance, by making the internal mould run the entire length of the outside mould means that the ends do not have to be removed. More material was used than required, this meant that there is a large amount of flash on the top of the product tha had to be removed (Figure 19). By using the correct amount of material in conjuncture with having the internal mould at the bottom rather than pushed into the top will reduce the amount of post processing required.

Low Tech Manufacturing

Based on the insights gathered from the prototyping process, a conceptual design for the two part mould was created (Figure 21). The mould is fabricated from sheet steel and is entirely disassemblable to allow the part to be removed easily. The internal part of the mould is bolted in to the end face of the outside mould. This removes the gap of material from the ends, allows easy location of the internal mould relative to the outside part. The internal part is positioned at the bottom of the mould, rather than at the top. This eliminates the flash produced (Figure 19) and allows a clean surface on all edges.

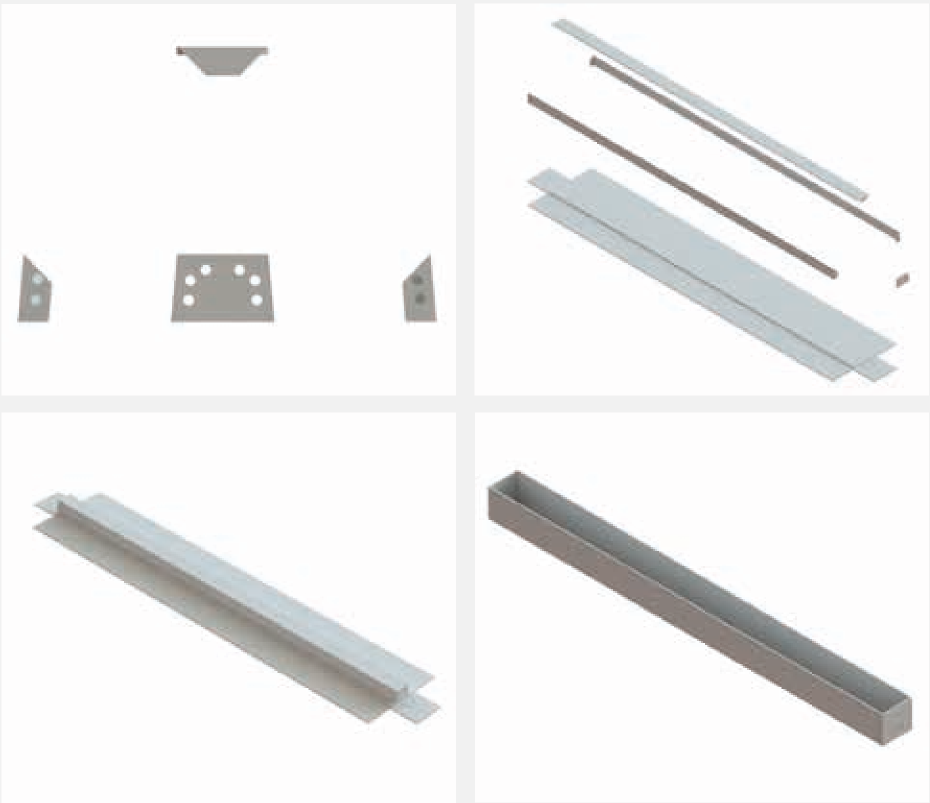


Figure 21 - Low cost collapsible mould design. From top left clockwise - a) Exploded internal mould b) Exploded entire mould c) Entire mould open d) Entire mould closed

Industrial Manufacturing

If fence posts made from Polysand were to be industrially manufactured then that changes the design criteria and hence more comlex shapes such as the I and hollow square cross section could be produced. Extrusion of the Polysand mix through a die would be an effective way of producing the complex cross sections. For this to be effective, granules of pre-mixed material should be produced prior to manufacturing in a specialised factory. This is a potential business model that could be more cost effective than completely decentralised manufacturing.

PART SIX

Validation

Validation Methods

Environmental, economic, and social impact make up the three pillars of sustainability. These three factors formed the basis of validation for the optimised design. A life cycle analysis was used to evaluate the environmental impact of the whole product system. The optimised design was compared to the original, a wooden post, and a concrete post. Similarly, a cost analysis of the manufacturing process was performed and used as an evaluation tool. Although cleaning up the local environment and providing employment have clear social benefit, it is harder to measure the direct impact from this. Therefore, a discussion of the social impact of the design is laid out.

LCA

LCA

A life cycle assessment (LCA) provides a holistic approach of understanding the environmental impact of "the whole industrial system involved in the production, use and waste management of a product or service" (18). There are many assessment methodologies available that are either pressure orientated, environmental damage orientated or filter the impact through a single parameter such as carbon footprint or energy (19).

The methodologies used in this project are both a break down of embodied energy (EE) and embodied (CO_2) by phase as well as an environmental damage orientated life cycle impact assessment (LCIA) using a ReCiPe (17) framework. OpenLCA free software was used for the analysis.

ReCiPe was selected for a couple of reasons. Firstly, A comparison of LCIA methods for construction materials (20) showed a high similarity between varying indicator methods (including the ReCiPe framework). In addition, the ReCiPe framework has been used effectively for analysing commercial building materials in Hong Kong (21).

Assumptions

Key assumptions were made about the system. The system model was based around the WasteAid workshop in Gunjur, The Gambia. Materials were sourced from common sources. For instance, cement is imported from China, wood is forested at the Casamance forest in Senegal, Sand and the collected LDPE are sourced locally. The database used was the Exiobase 2.2 (22) which provided detailed global information on the environmental impact of industrial inputs and outputs. This was used in conjuncture with the ReCiPe (17) framework. The models of each system are detailed in Appendix 4A. The LCA was performed per unit. The emissions involved in the manufacturing process of Polysand have been omitted as it is produced on an open wood fire, which can be considered carbon neutral. The manufacturing of both concrete tand wood are included in the material production.

Results

Figure 22 shows a comparison of energy consumption at the different life stages for each of the four designs. Polysand (original) had the highest energy consumption (116 MJ), followed by Concrete (111 MJ), Wood (83 MJ) and Polysand (Optimised) (57 MJ). The most significant contributor to the energy consumption of Polysand (original) is the manufacturing phase. The largest contributor to Concrete is the transport, having the cement component imported from China.

Figure 23 shows a comparison of Carbon Dioxide emissions at the different life stages for each of the four designs. Concrete had the highest total emissions (10 kg) followed by Wood (4.5 kg), Polysand (original)(1.68 kg) and Polysand (Optimised) (0.7).

It must be noted that the Polysand (optimised) post design scored lowest in both EE and CO2 out of all designs. The optimisation process has reduced the energy consumption by 60% when compared to Polysand (original).

Figure 24 shows a relative comparison of results of the LCIA between the designs. A relative percentage value was used because different impact categories have different units and orders of magnitude so cannot be directly compared visually. The full list of results and impact categories can be found in Appendix 4C.

Concrete scored the highest in all but two categories. These were agricultural land occupation and terrestrial ecotoxicity. A single score for each design was calculated by applying a normalisation and weighting factor to each impact category (21) . These scores were aggregated to find the overall score for each design. Concrete had the highest impact score (2.22E+16), then Polysand (Original) (8.88E+14), Wood (5.61E+14) and finally Polysand (Optimised) scored the lowest (1.79E+14).

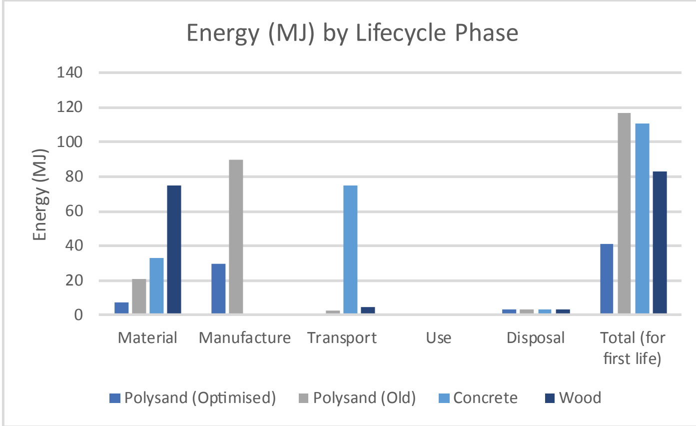


Figure 22 - Comparison of energy consumption by lifecycle phase

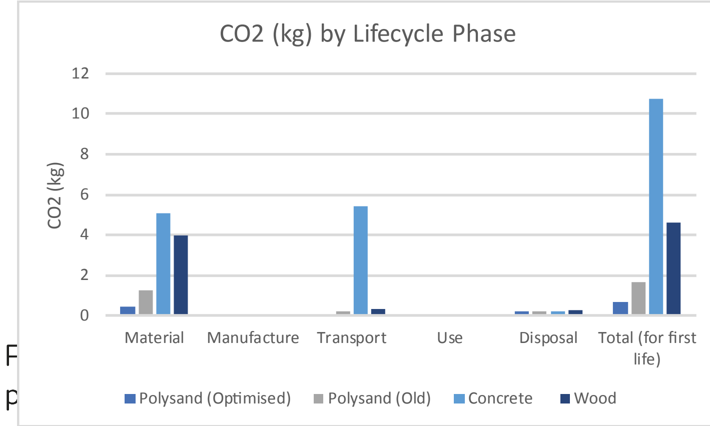


Figure 23 - Comparison of CO2 emmisions by lifecycle phase

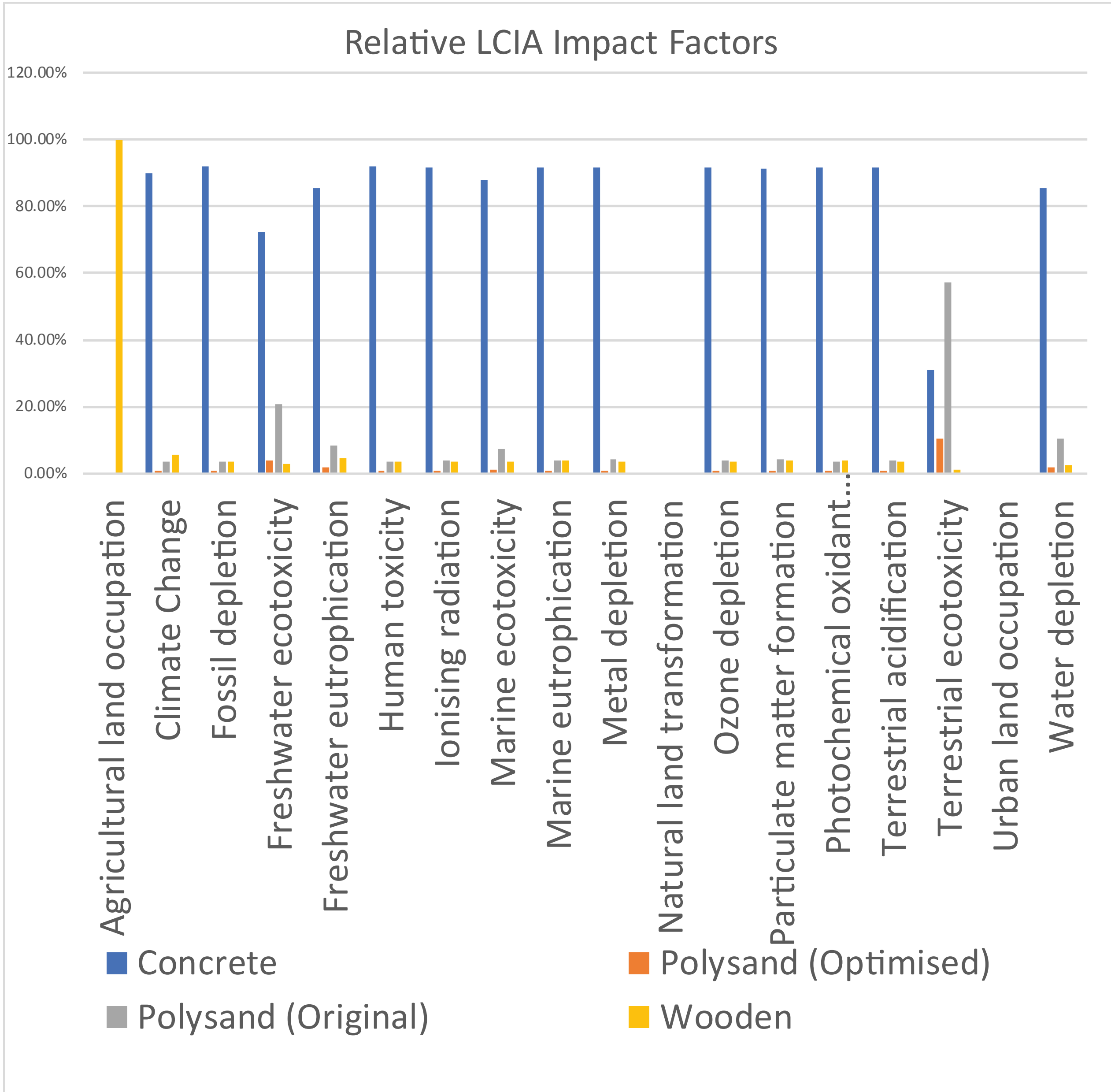


Figure 24 - Comparison of LCIA impact categories

Cost Analysis

The product needs to have a competitive price for the business to be sustainable. Table 5 shows the calculations of cost for the optimised Polysand fence post.

Assumptions about the rate of collection, sorting, cleaning, melting and moulding were approximated based on information provided by Zoe Lenkiewicz (15). The average hourly wage in The Gambia of 286 GMD (£4.86) (23) was used for wage calculations. The cost of sand was approximated using local information found online (24). The cost of manufacturing the mould is based on approximate manufacturing costs and a lifespan of 1000 uses was estimated.

Wages						
Process	Collection	Sorting	Cleaning	Melting	Moulding	**Total**
kg / person hour	2	18	18	75	75	
Hours per unit	1.25	0.138889	0.138889	0.033333	0.033333	**1.594**
Cost per unit	£5.54	£0.62	£0.62	£0.15	£0.15	**£7.06**
Sand						
Cost per kg	£0.04					
Cost per unit	£0.30					**£0.30**
Mould						
Cost of manufacture	£400					
Number of uses	1000					
Cost per unit	£0.40					**£0.40**
Total cost						**£7.76**

Table 5 - Calculations of manufacturing costs

Table 6 shows a comparison of costs between fenceposts. The optimised design costs £7.76 to produce. This is an 86% reduction in cost when compared to the original design. To understand the profitability of the product, more information about company overheads are required. However, if the product is sold for twice the cost of manufacture it will fall in a similar price bracket as its competitors. Wooden and concrete posts cost the equivalent of £10 and £15 respectively..

	PolySand	**Original**	**Wood**	**Concrete**
Cost per unit	£7.76	£57.17	£10.00	£15.00

Table 6 - Table of costs

An interesting observation from the cost analysis is that the single largest contributor to the cost per unit is the wages spent on collecting the waste plastic (Table 5). Additionally, this technology is for use in areas where there is no waste infrastructure. Therefore, it would be financially beneficial for a company using this manufacturing method to implement a form of waste collection. This would also help prevent waste from from reaching public and natural spaces.

Social Impact

The social impact of this project can be felt both directly and indirectly. In a direct way, each unit pays the wages of an individual for 1.6 hours work. The fabrication of the metal mould supports a local metal workshop. The purchasing of sand supports a local building merchant.

Each unit produced facilitates the collection of 2.5 kg of LDPE plastic waste as well as a considerable amount of other assorted waste that is present. This potentially has a whole array of indirect positive social affects. Removing litter from the environment can prevent waterways being blocked, preventing sewage contamination and the spread of water borne diseases (25). Humans are exposed to micro and nano-plastics through the consumption of marine food-stuff (25) which may adversely affect human health. Preventing plastics from reaching the ocean therefore improves the safety of seafood. Floating macro-plastic debris represents a hazard to boats which cause significant injury and death (25).

Coastline litter presents a significant potential loss of income for local communities. Industries affected by coastline litter include the fishing industry and tourism (25). The psychological impact of litter-induced degradation may affect local individuals negatively. Conversely, the transformation of cleaning the local natural environment may have a positive impact on the quality of life and wellbeing of local communities.

Discussion

When discussing the success of the project it is important to refer back to the initial design specifications (Table 2).

Metric 1 - Loading > 1400 N
This value was incorporated into the opimisation constraints and fed into the final design. Using FEA tests, the final design was found to withstand the force applied. However, these tests are simplified and based on lab derived values. They don't take into account manufacturing faults such as a non-homogenous material. Therefore, a physical loading test of a full size model would be an appropriate means of testing the real life performance of the design.

Metric 2 - Manufacturability
Design considerations for keeping the maufacturing process simple and low cost were implemented throughout the design process. Good progress was made in understanding the manufacturing process required to produce the product. However, this is not at a stage that it is ready to roll out. A design for a collapsible two part mould was laid out, but this should be prototyped fully in the future.

Metric 3 - Mass << 80 kg
The mass of the product was reduced by 86%. This is a significant reduction.

Metric 4 - Height = 2 m
The overall height of design was 2 m tall. However, the prototype produced was only 0.3 m long. This was because the prototype was a proof of concept. However, there is no reason why the length cannot be extended in the future to make a ful scale model.

Metric 5 - Cost <£15
The cost of manufacture was approximated to be £7.76. This price allows the product to be competitive, while making it cheap enough to produce using super-low cost methods. However, this value is based on estimates and should be updated with current values during deployment to remain relevant.

Metric 6 - Time of installation < 2 hrs
This is not considered, as the installation methods are not radically different compared to conventional designs. This would require a full scale model to test fully. However, the full fence design and installation is something that requires more work in developing.

Metric 7 - Aesthetics
The final prototype had an interesting aesthetic, however this was not considered in the valdiation process and would require further user testing.

Metric 8 - Lifespan > 10 year
This metric was not tested and would require more long term experiments of the durability of the materal when exposed to UV light and repetitive loading.

Metric 9 - Environmental Sustainability
The optimised design scored lowest for EE, CO_2 and overall LCIA out of the four designs analysed. This suggests that the Polysand material is more environmentally sustainable than the other options. It should be noted that the original Polysand design scored highest in some categories, which suggests that the material itself is not without issues. For instance, it scored highest in terrestrial ecotoxicity. However, the significant reduction in the volume of material used has led to the impact of the design falling beneath that of conventional methods. It must be noted that this approximation excludes the primary production of LDPE, which may explain the lower impact. The model, however, does not include the positive impact of the clean up process which would yeild significantly lower results if incorporated.

PART SEVEN

Conclusion & Reflection

Conclusion

Overall, the proposed design achieves seven out of the ten design requirements laid out initially. The new design has an 86% reduction in weight and cost while achieving desired strength characteristics. The LCIA & LCA showed that the new design had a lower overall impact score than the other benchmark designs. The cost analysis showed that the design put forward could be competitively priced, making it financially sustainable. The remaining design requirements need to be further tested in order to satisfy them fully.

Further Work

Various properties of the material need to be further characterised and tested to enable a industrial manufacturing of the product. Including thermal expansion and viscosity. Before scaled manufacture, mechanical testing of a full scale model would be a neccesary quality assurance. This would make sure the fence post stands up to theoretical predictions. Further prototyping of the mould design is required to get the product ready for deployment. The long term mechanical behaviour of the material when experiencing UV degredation needs to be explored in order to understand the lifespan and recyclability of the product. Further research into the risks of this product releasing micro-plastics into the environment needs to be undertaken too.

Although the design achieves a low environmental impact, the impact of sand mining has become a serious social and environmental issue (26). Therefore, the exploration of altenative aggregate sources should be considered For instance, the waste behaviour patterns in Gunjur, The Gambia (Appendix 5) suggest that glass is buried instead of being recycled. If this data reflects a larger demographic then crushed glass could be a potential replacement for sand.

Reflection

One of the hardest parts of this project was finding the best application for the material. Initially, I wanted a single product idea that would transform peoples lives. In the end, I paid closest attention the material properties and local markets. Instead of forcing the material into a product that it simply wasn't suited to. Part of the difficulty was trying to design for a demographic that I had very little access to. Learning to embrace the ambiguity of a vast problem space is a skill I am glad to have developed over the course of the project.

Another key point is that the physical prototyping phase proved more time consuming and problematic than expected. Experimenting with a new material from the bottom up meant a lot of learning through 'failure'. Successfully prototyping the mould took a lot of iteration and expert knowledge which I recieved from the workshop technicians. I am glad that the work that I have put in to the prototyping phase can be used by others who continue to work on Polysand. I believe that if I had locked in a design concept earlier I would have given myself more valuable time to progress on prototyping.

Polysand has shown a lot of potential as a sustainable building material and I hope to see it develop further. I have been invited to the WasteAid workshop in The Gambia where I hope to help manufacture the first batch of optimised Polysand Fenceposts. A community of people continue to work on understanding this material and its applications and I am glad to have contributed to it. So far, this project has been focused on developing countries. However, LDPE is often not recycled in countries like the UK and I see potential for its use globally.

PART EIGHT Project Management

Project Management

Time
A gannt chart of work (Appendix 1) was created at the start of the project and updated when required. The general design approach is outlined in Appendix 2. The gannt chart allowed careful time-management of the project. A logbook was updated on a weekly basis, clearly identifying completed work and achievable objectives for the next week. Regular scheduled meetings with my primary tutor or other stakeholders were used to monitor progress.

Budget
A spreadsheet of expenditures (Appendix 3) was kept and used to keep track of remaining budget. As much of the equipment needed for the project was readily available at college £125 remains of the £250 budget given at the start of the project. Receipts have been kept for reimbursement.

Equipment & Facilities
During the project I have used various equipment and facilities at Imperial College London and external organisations. At Imperial I have used the Design Engineering ACE workshop of which I was already inducted. However, I used the furnace which required special training and supervision from the technicians. I also filed the appropriate risk assessment and followed the correct safety procedures. I have also used lab facilities in the department of Civil Engineering. To gain access I connected with the right people and completed the appropriate inductions.

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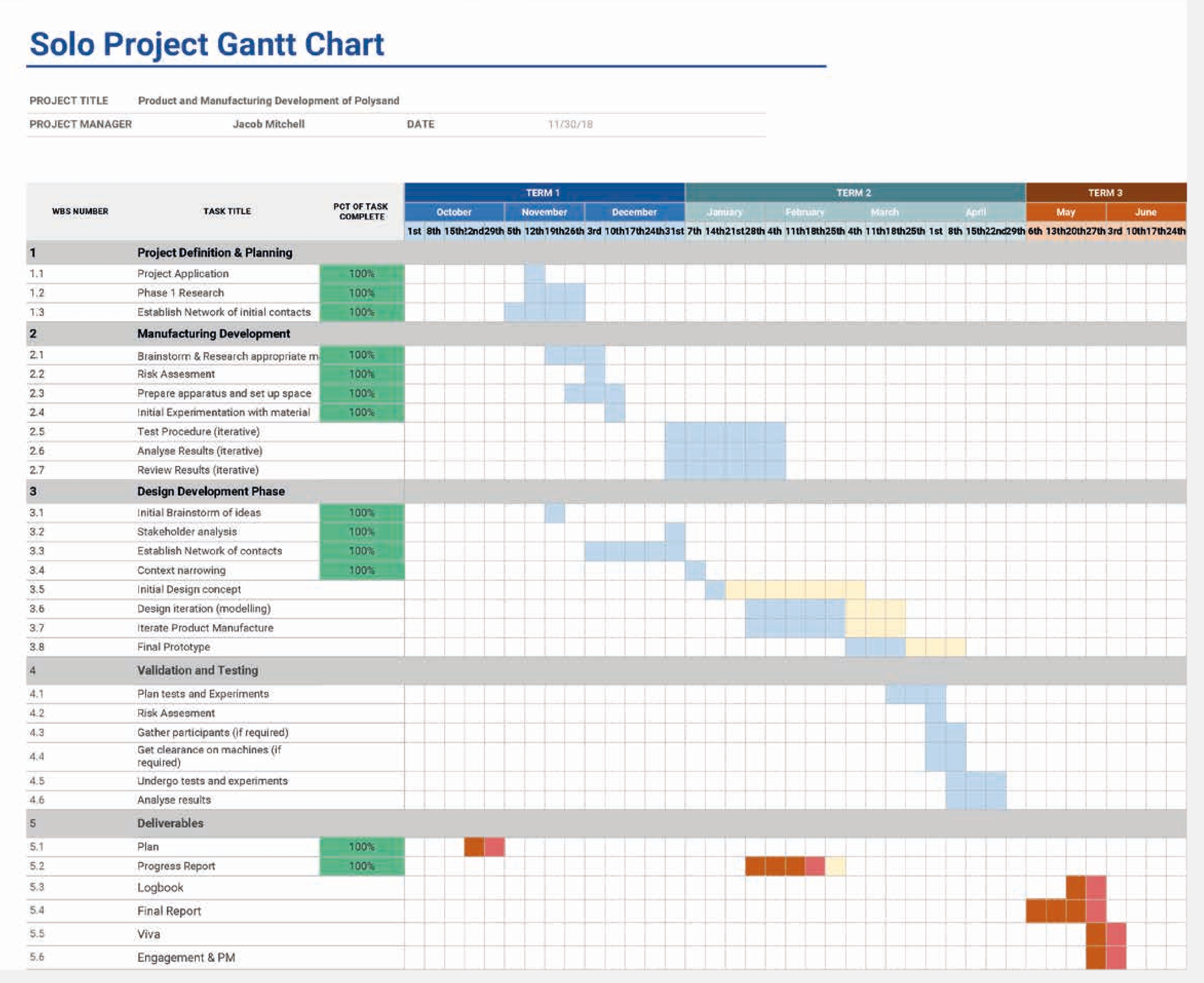
PART NINE

Appendices

Appendix 1 - Gantt Chart



Appendix 2 - Design Approach

This project has taken a divergent-convergent double diamond method as demonstrated below.

Term 1

Discover
- Waste landscape secondary research
- Exploring different project directions
- Meeting with Chris Cheeseman and his research group
- Exploring sustainable materials and product design
- Researching new materials and applications
- Comparing applications to mechanical properties of the material

Define
- Meeting with stakeholders from Waste Aid, PLOC and Loop Innovation
- Insights into life in the Gambia and the manufacturing process
- Defining appropriate applications for the material.
- Selecting fencing as application to explore

Term 2

Develop
- Prototyping with material and manufacturing processes
- Ideation and iteration of fence post design using FEA and optimisation tools.

Term 3

Deliver
- Refine design prototype
- Validate designs with testing of LCA tools and cost analysis
- Deliver Report

Appendix 3 - Budget

Item	Date of purchase	Description	Cost
Biodegradable p	12/11/2018	Plastic samples for original project idea	£4.80
Crushed Glass	02/01/2019	Crushed glass for creating an experimental material	£27.24
Kitchen ware	06/01/2019	kitchen ware (wooden spoon, sauce pan, and glasswar	£25.00
Coloured Sand	13/02/2019	Coloured sand for experimenting with aesthetics	£15.01
Plaster of Paris	24/05/2019	Plaster of paris for creating a mould	£11.99
PID controller	02/03/2019	Digital PID Temperature Controller for controlling DIY c	£10.78
Tile Cutter	25/03/2019	Tile Cutter for finishing up the prototype	£29.98

Appendix 4 - LCA Data

A - LCIA Inputs

	Flow	Category	Amount	Unit
Wooden Post	Occupation, shrub land	Resource/land	2	m^2
	Pine Wood	Materials Production	18	kg
	Small Lorry	Transport Services	3150	kg*km
	Landfill of untreated wood	End-of-life treatment	18	kg
Polysand (Original)	Very fine milled silica sand	Materials Production	65	kg
	Polymer Moulding	Manufacturing	20	kg
	Small Lorry	Transport Services	1600	kg*km
	Landfill of plastic waste	End-of-life Treatment	20	kg
Polysand (Optimised)	Very fine milled silica sand	Materials Production	11.25	kg
	Polymer Moulding	Manufacturing	3.75	kg
	Small Lorry	Transport Services	320	kg*km
	Landfill of plastic waste	End-of-life Treatment	3.75	kg
Concrete	Pre-cast concrete	Systems/Construction	6	kg
	Container ship	Transport Services	7.57E+04	kg*km
	Small Lorry	Transport Services	4.16E+04	kg*km
	Landfill of Concrete	End-of-life Treatment	6	kg

B - Energy and CO2 data

	Polysand (Optimised)		Polysand (Old)		Concrete		Wood	
Phase	Energy (MJ)	CO2 footprint (kg)	Energy (MJ)	CO2 footprint (kg)	Energy (MJ)	CO2 footprint (kg)	Energy (MJ)	CO2 footprint (kg)
Material	7.5	0.45	21	1.26	32.82551459	5.100828179	75	4
Manufacture	30	0	90	0	0	0	0	0
Transport	0.3	0.02	2.58	0.19	74.976	5.398272	4.725	0.3402
Use	0	0	0	0	0	0	0	0
Disposal	3.25	0.23	3.25	0.23	3.2	0.224	3.6	0.252
Total	41.05	0.7	116.83	1.68	111.0015146	10.72310018	83.325	4.5922

C - LCIA impact category output data

Impact Category	Concrete	Polysand (Optimised)	Polysand (Original)	Wood	Unit
Ecosystems - Agricultural land occupation	0.00E+00	0.00E+00	0.00E+00	2.79E-07	species.yr
Ecosystems - Climate Change	1.85E-05	-1.52E-07	-7.48E-07	-9.31E-07	species.yr
Ecosystems - Freshwater ecotoxicity	2.61E-10	1.36E-11	7.48E-11	-1.04E-11	species.yr
Ecosystems - Freshwater eutrophication	2.36E-09	-4.68E-11	-2.34E-10	-1.22E-10	species.yr
Ecosystems - Marine ecotoxicity	1.06E-10	1.04E-12	6.01E-12	-4.22E-12	species.yr
Ecosystems - Natural land transformation	0.00E+00	0.00E+00	0.00E+00	0.00E+00	species.yr
Ecosystems - Terrestrial acidification	6.06E-08	-5.12E-10	-2.55E-09	-2.44E-09	species.yr
Ecosystems - Terrestrial ecotoxicity	1.54E-08	5.25E-09	2.85E-08	-6.09E-10	species.yr
Ecosystems - Urban land occupation	0.00E+00	0.00E+00	0.00E+00	0.00E+00	species.yr
Ecosystems-total	1.86E-05	-1.47E-07	-7.23E-07	-6.56E-07	species.yr
Human Health - Climate Change	3.26E-03	-2.68E-05	-1.32E-04	-1.64E-04	DALY
Human Health - Human toxicity	1.34E-04	-1.10E-06	-5.46E-06	-5.34E-06	DALY
Human Health - Ionising radiation	3.03E-06	-6.14E-09	-2.20E-08	-1.21E-07	DALY
Human Health - Ozone depletion	2.71E-07	-2.18E-09	-1.08E-08	-1.08E-08	DALY
Human Health - Particulate matter formation	6.49E-04	-5.84E-06	-2.91E-05	-2.80E-05	DALY
Human Health - Photochemical oxidant formation	1.67E-07	-1.34E-09	-6.63E-09	-7.20E-09	DALY
Human Health-total	4.05E-03	-3.37E-05	-1.67E-04	-1.98E-04	DALY
Resources - Fossil depletion	1.12E+02	-8.99E-01	-4.45E+00	-4.51E+00	$
Resources - Metal depletion	1.09E+01	-9.65E-02	-4.82E-01	-4.34E-01	$
Resources-total	1.23E+02	-9.95E-01	-4.93E+00	-4.94E+00	$

Appendix 5 - Waste Behaviour in Gunjur

The data used to generate this graphic was obtained from an attitude towards waste survey undetaken by WasteAid UK, in Gunjur, The Gambia.