Development of sustainable and recyclable footwear for children

SME

The Dubs Universe

by

Dr Abdullah Qaban

Line managers

Dr Finian McCann and Dr Ruoyu Jin

The School of the Build Environment and Architecture

London South Bank University

Sustainable Innovation

10/06/2022

Table of Contents

1 Introduction

The environmental crisis is causing ice caps to melt into oblivion while over 4 million people die each year due to air pollution. One of the main sources of pollution is factories which release toxic emissions at a terrifying rate. Footwear in general, and sneakers in particular have their contribution in which over 25 billion pairs of running shoes are made annually, most are made from plastic that end up in the landfill, according to climate scientist Angela Terry. The footwear market is vase, Nike’s global profits soared by 196% in the first quarter of 2021 and beat pre-pandemic sales by 42%. Two thirds of those profits come from sneaker sales.

The problem is that most shoes, especially sneakers, are not made to last as producers tend to prioritise profitability over sustainability. However, due to the increasing demand in environmental footwear, there are more sustainable options than ever before. The World Footwear 2030 report predicts that sustainability will drive innovation in the footwear industry. Currently, big brands are working on the development of biofabrication, for example, using mushrooms to grow the materials for of the sneakers. In addition, the use of 3D printing, which significantly reduces waste during the manufacturing process. One of the main issues with sneaker recycling is the separation of materials, which makes the process more complex. Therefore, using the minimum number of materials improves the recyclability rate, in which the sneaker can be directly ground up, taken back to pellets, melted again, then turned back into the same material that the sneaker was originally made of.

Adidas has introduced the FutureCraft shoe, which is made using natural, lighter and at least 50% recycled materials. The shoe has the lowest carbon emissions that the company has ever created. Moreover, the shoe function, performance and style are not compromised by carbon reduction, in which 63% less emissions are met by 100% performance.

Dub-Universe has introduced a planet-friendly sneakers for kids that support their daily activities like running, jumping, playing and other activities. The sneakers have appealing appearance and are comfortable, while made of environmental and recycled materials.

In this project we aim to understand Dubs Universe sneakers in more detail, explore the market and develop recycling procedure that can help Dubs Universe promote their product. This report covers the carbon footprint life cycle assessment of the current footwear, which is compared with traditional footwear. Moreover, detailed procedure of sneaker recycling process with providing analysis on technical and environmental aspects are included. Furthermore, recommendations on the end-of-life options for the current sneaker materials and proposition of alternative materials are presented.

This statistic below shows the value of the sneakers market worldwide from 2012 to 2025 (**Figure 1**). In 2020, the total global sneakers market revenue was valued at approximately 70 billion U.S. dollars and was forecast to reach a value of 102 billion U.S. dollars by 2025.

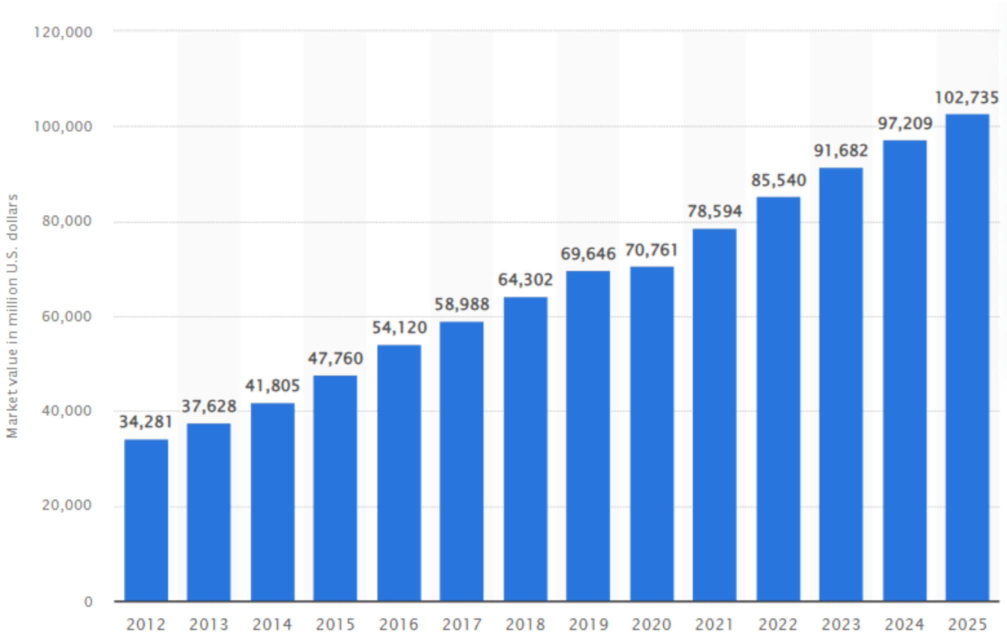


Figure 1. Value of the sneakers market worldwide from 2012 to 2025 (Value of the sneakers market worldwide from 2012 to 2025) (https://www.statista.com/).

2 Life cycle assessment of Dub-Universe sneakers

2.1 Introduction

The sneaker market has been increasing gradually and expected to increase by 5.7% annually (**Figure 1**). This is associated with an increase in the carbon emissions at a similar rate, so it is important to estimate the carbon footprint of traditional sneakers and compare it with Dubs Universe sneakers footprint to explore any potential improvement in using alternative sustainable manufacturing or materials.

2.2 Methodology

The current life cycle assessment compares the carbon footprint of a pair of sneakers supplied by Dubs Universe against traditional pair of sneakers. **Figure 2** shows a schematic of a traditional sneaker component used for assessment while **Table 1** shows each component material and mass for both sneakers.

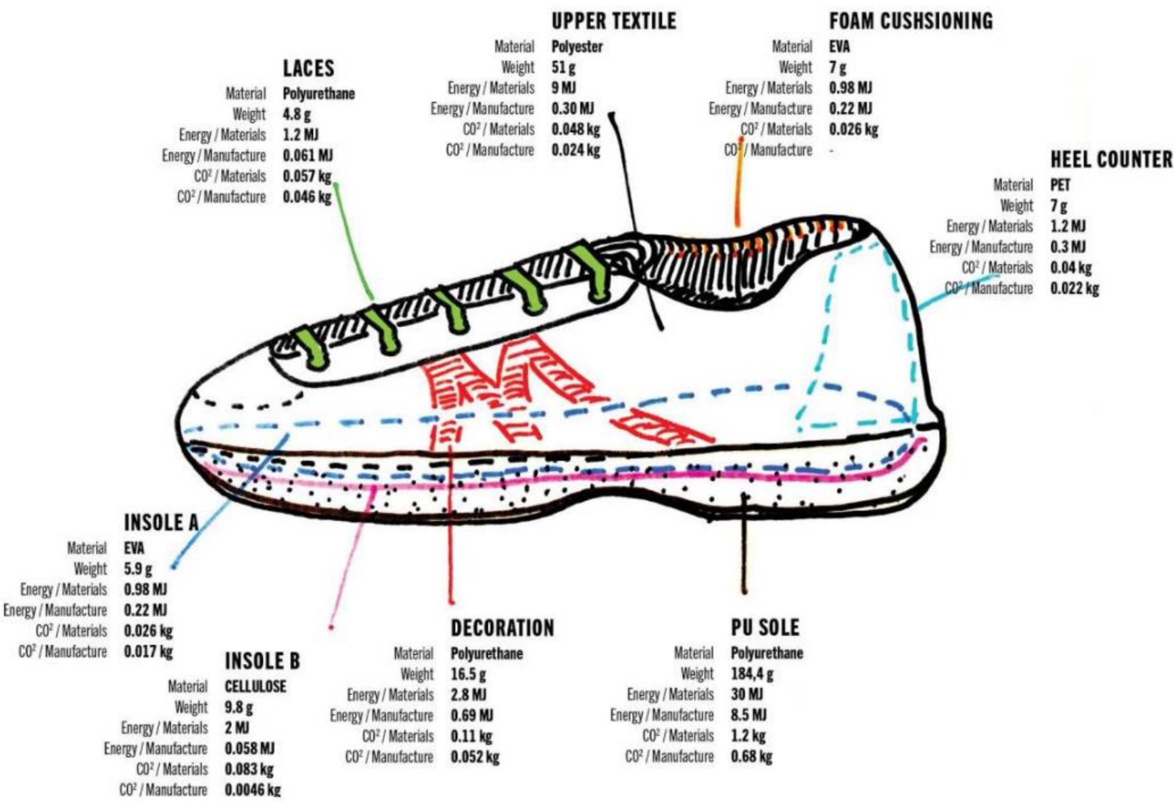


Figure 2. A schematic showing the breakdown structure of a traditional sneaker including materials, masses energy and carbon footprints.

Table 1. A summary of each component material and mass for Dubs Universe sneaker against a traditional sneaker

Component	Sub-components	Dubs Universe	Traditional
Lace	**Lace**		
	Material	Polyester	Polyurethane
	Density	1.38 g/cm^3	1.05 g/cm^3
	Mass	6.3 g	4.8 g
Sole	**Midsole**		
	Material	EVA	Polyurethane
	Density	0.96 g/cm^3	1.05 g/cm^3
	Mass	168.6 g	184.4 g
	Pad		
	Material	Rubber	EVA / Cellulose
	Density	0.95 g/cm^3	0.96 /1.5 (g/cm^3)
	Mass	15.5 g	5.9 / 9.8 (g)
Upper	**Knitted upper**		
	Material	PET	Polyester / PET
	Density	1.38 g/cm^3	1.37 / 1.38 (g/cm^3)
	Mass	51.4 g	51 / 7 (g)
	Insock		
	Material	PU foam	EVA foam
	Density	0.1 g/cm^3	0.96 g/cm^3
	Mass	4.2 g	7 g

The transport was based on a combination of land transport, based on an 8 axle truck, and sea transport, based on ocean freight as shown in **Table 2**.

Table 2. A summary of the transport method and distance

Stage name	**Transport type**	**Distance (km)**
Land	55 tonne (8 axle) truck	25
Sea	Ocean freight	1.8e+04

2.3 Results

The life cycle consists of the following stages: material, manufacture, transport, use and end-of-life. **Figure 3** shows the energy consumption while **Figure 4** shows carbon footprint at each stage of the life cycle of traditional sneakers against Dubs Universe sneakers. In general, there is a relationship between energy consumption and carbon footprint. Most energy and carbon can be observed at the material stage, followed by the manufacture then the transport stage. This can be observed in both sneakers (traditional and Dubs Universe).

Table 3 and **Table 4** show the detailed values of energy consumption and carbon footprint of traditional and Dubs Universe sneakers, respectively, in addition to their fraction at each stage of the life cycle. Results show that the total energy consumption is 20% higher in the traditional sneakers, 61.2 MJ vs 49.3 MJ, and carbon footprint of the traditional sneakers is 65% higher, 2.94 kg vs 1.93 kg (**Table 3** and **Table 4**). Considering carbon footprint, almost two-third is observed at the material stage and around the third at the manufacture stage while transport did not exceed 6% for both sneakers (**Table 3** and **Table 4**).

End-of-life (EoL) phase splits into two components: Disposal and EoL potential, they both represent the influence of expected end-of-life recovery rate on the benefit that can be obtained in subsequent life cycles. In other words, the components that can be recycled will have negative carbon footprint at the end-of -life stage because the material phase at the next use will be zero.

For the Dubs Universe sneakers, the total carbon footprint is 1.93 kg (**Table 4** as we have already mentioned, but this value does not take into account the end-of-life potential). We have assumed that Polyester, EVA and PET will be recycled while rubber and PU foam will be downcycled based on the materials datasheets (**Table 6 – 11**). In this case, there is a potential of 0.639 kg reduction in carbon footprint (**Table 4**), almost one-third of the original carbon footprint, 1.93 kg, can be offset at the end-of-life stage so giving a total carbon footprint of 1.29 kg.

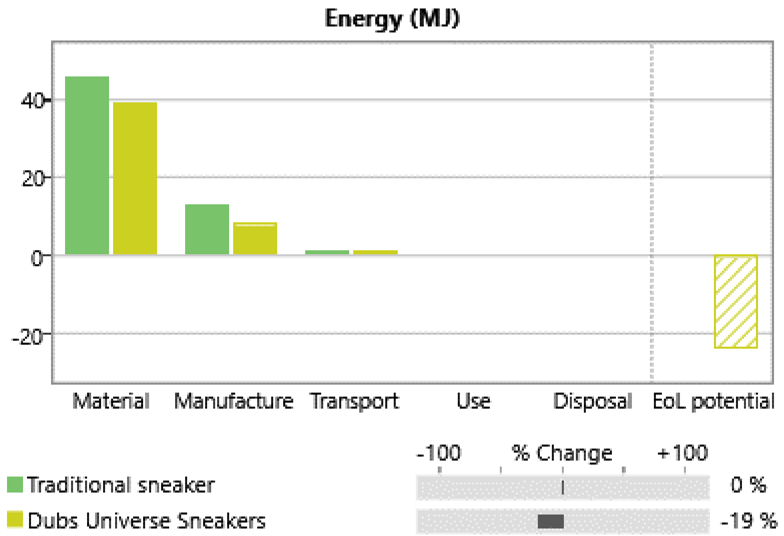


Figure 3. Energy consumption throughout the life cycle of traditional vs Dubs Universe sneakers

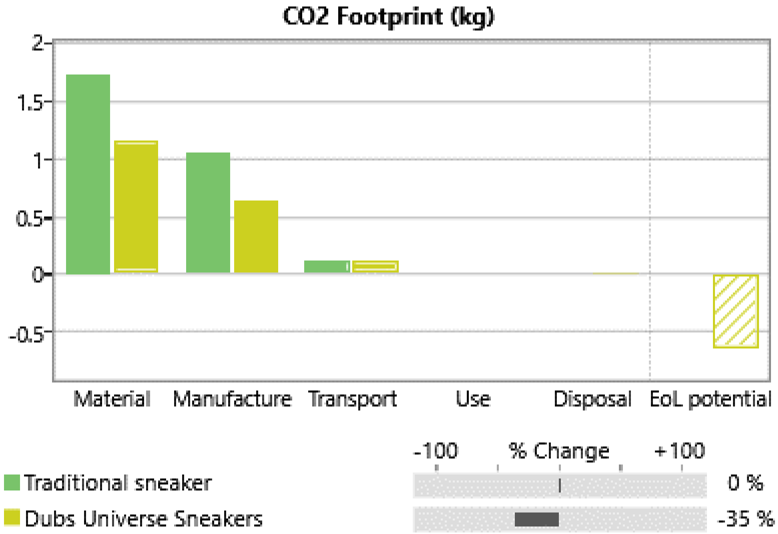


Figure 4. Carbon footprint throughout the life cycle of traditional vs Dubs Universe sneakers

Table 3. Energy consumption and carbon footprint throughout the life cycle of traditional sneakers

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	45.9	75.0	1.74	59.0
Manufacture	13.3	21.8	1.06	36.1
Transport	1.87	3.0	0.134	4.6
Use	0	0.0	0	0.0
Disposal	0.115	0.2	0.00802	0.3
Total (for first life)	**61.2**	**100**	**2.94**	**100**
End of life potential	0		0	

Table 4. Energy consumption and carbon footprint throughout the life cycle of Dubs Universe sneakers

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	39.2	79.5	1.14	59.3
Manufacture	8.19	16.6	0.645	33.5
Transport	1.6	3.2	0.115	6.0
Use	0	0.0	0	0.0
Disposal	0.336	0.7	0.0235	1.2
Total (for first life)	**49.3**	**100**	**1.93**	**100**
End of life potential	-23.8		-0.632	

Carbon offsetting

If Dubs Universe is interested to provide a carbon neutral sneaker, we would recommend buying carbon credit in offset projects to compensate for carbon emissions. This is normally done in case the carbon footprint of a product can be reduced but not fully eliminated as the case in the current sneakers. Carbon Neutral Britain has carbon offset projects which Dubs Universe can consider https://carbonneutralbritain.org/products/carbon-neutral-small-business?variant=39301139792041&selling_plan=393904297. Carbon offset projects provide the opportunity for companies to compensate for carbon emissions through, for example, afforestation efforts and the expansion of renewable energies. Independent organisations monitor the precise amounts of carbon saved, which are then sold in the form of CO_2 reduction certificates, which in turn finance the project. Dubs Universe may consider adding the carbon credit cost on the sneakers sale price and promote its product through “Carbon Neutral” label which will help in the marketing efforts.

2.4 Summary

Figure 5 shows a detailed illustration of a Dubs-Universe sneaker including the components with their carbon footprint contribution, the most feasible end-of-life option and its estimated potential in carbon reduction as well as the net carbon footprint.

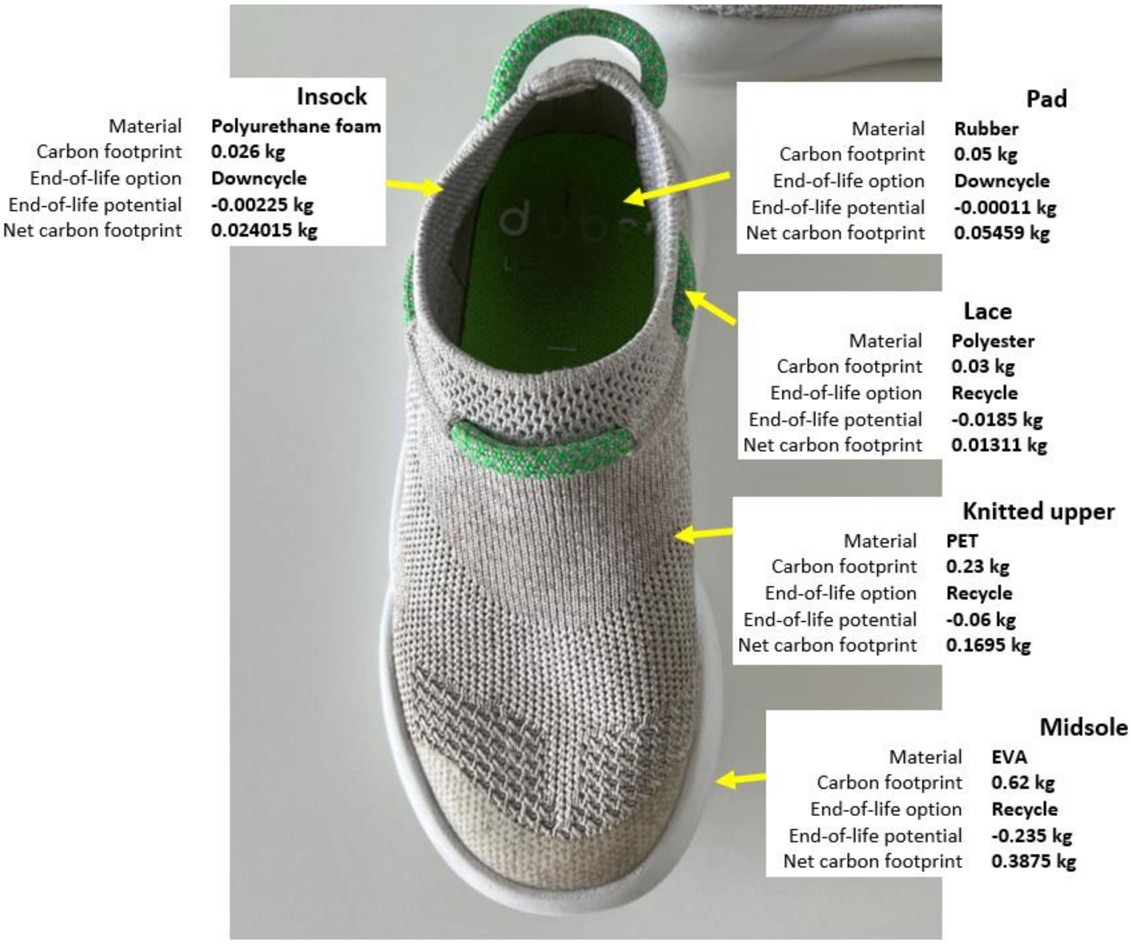


Figure 5. A summary of Dubs-Universe sneaker component materials, carbon footprint, end-of-life option, end-of-life potential and net carbon footprint

A summary of the comparison between a traditional and a Dubs-Universe sneaker showing 240% save in energy consumption and 226% reduction in carbon emissions is presented in **Table 5**.

Table 5. A summary of the comparison between a traditional and a Dubs-Universe sneaker showing energy and carbon footprint

	Traditional Sneaker	**Dub-Universe Sneaker**	**Improvement**
			
Energy consumption	**30.6 MJ**	**12.75 MJ**	**240%**
Carbon footprint	**1.47 kg**	**0.65 kg**	**226%**

2.5 Case study of sneaker recycling in Singapore schools

Singapore is one of the world's leaders in sustainable development in which sustainability is the country's new engine for jobs and growth. Sneakers, similar to the rest of the world, was one of the environmental issues in Singapore in which they most ended up in landfill or through combustion. A recent project aimed at creating a circular economy by recycling used sneakers in schools and use the recycled materials in sports infrastructures including jogging tracks fitness corners and playground back.

In 2019, a pilot project was initiated to collect used sneakers in schools. General public were also welcomed to contribute. Twenty one thousand pairs of shoes were collected. The rubberised soles and midsoles were then ground into rubber granules that are used as materials to build sports infrastructure. The project delivered a 100 metre jogging track at a football hub which is now the Singapore's first running track that is made from recycled sneaker granules that is water-based and based on solvent-free binder technology creating environmentally friendlier and safer sports infrastructure for users (**Figure 6**).

In 2020, the project expended outside schools to include the nationwide. The project succeeded in collecting over seventy five thousand pairs of shoes so enhancing circular economy. In the long term, the project was successful in establishing partnership with sport organisations and other value chain partners and now formed a permanent collect for recycling waste stream in Singapore since July 2021. Moreover, rubber and elastomer are expected to be extracted from at least 170,000 pairs of school sneakers every year, instead of moving them to landfills, they are expected to contribute markedly into infrastructure materials and sports facilities such as jogging tracks playgrounds and fitness cons, which aligns with the country's long-standing commitment to tackle sustainability challenges. It is advisable that Dubs Universe promote theirs brand through targeting schools and partnering with the downstream and upstream stakeholders to maintain circular economy of their sneakers.

Figure 6. The sequence of sneaker recycling showing sneaker collection, shredded particles and a jogging track playground made using the recycled particles in Singapore

2.6 Sneaker waste mechanical recycling ecosystem

Recycling can be a complex process and to have an optimum recycling the process must not be generic but optimised based on the existing product, in this case Dubs Universe Sneakers. When searching for a technical recycling solution we need to break down the sneaker into components, assess the end-of-life options of each component material then choose the most reasonable option and find the most suitable technique to achieve it. The full datasheets of all the materials used in the Dubs Universe Sneakers are given in **Tables** (**6** - **11**). The end-of-life options of the material are presented, including Recycle, Downcycle, Combust, Landfill and Biodegrade. In addition, the energy consumption and carbon footprint for Recycle and Combust options are provided.

In general, Dubs Universe sneakers are easy to recycle as they do not contain a complex mixture of materials, for example, leather and metallic materials. This makes it less difficult to perform complete separation and reclamation of material streams in an economically sustainable manner.

The proposed recycling process has been developed by the Centre for Sustainable Manufacturing and Reuse/Recycling Technologies (SMART) at Loughborough University. The process uses bespoke air-based separation technology that separates granulated shoe particles based upon the difference in size and weight (**Figure 7)**.

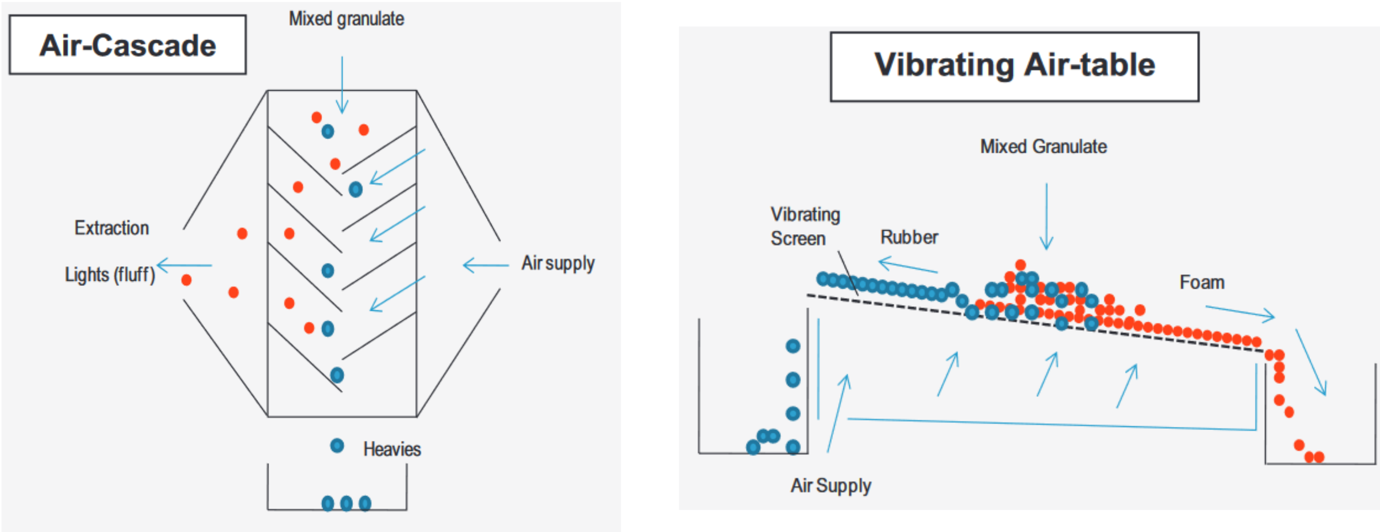
The first stage in sneaker recycling is material separation. It is not economically viable to separate components individually or manually for recycling, re-using….,etc. It is important to have an automated system, based on fragmentation and separation processes, that can recognise the materials and sperate them into separate containers. In this process, the system uses mechanical shredders to slash the sneaker into smaller fragments, sorting the results automatically. The challenge is how can the system distinguish the materials to separate them, the answer is by looking at a unique property of each material that the system can use, the most feasible property is density. When the sneaker is shredded into small particles, ideally 3-4mm size range is required, these practices are fed into a container. The separation process takes place inside the container in which air zigzag separators are used for this purpose, each air separator is adjusted at a particular speed based on the material density (**Figure 7a**). To make this clearer for non-technical experts let us take a general example to explain the principal. Assuming we have steel particles and plastic particles, when blowing air at low speed the plastic particles can move due to their low density but the steel particles would require higher air speed to move. This is the mechanism used in the current system which adjusts the air speed based on the material density.

In our case, the particles are introduced from the top, and as they fall down some sort of air jet is introduced from the side where all of the lighter materials are more or less taken to a different dropping zone while the heavier particles just fall down (**Figure 7a**).

Foam and rubber separation

Although the air-cascade is expected to provide high purity material separation, further processing maybe needed to separate foam from rubber. Therefore, an extra separation step is necessary in which a vibrating air-table is used ((**Figure 7b**). In this process, the air-table uses air and vibration to separate the heavier rubber that moves up the table from the lighter material (foam in our case) that stratifies on top and slides down the table. Separation efficiency depends on the following process parameters

- Angle of the vibrating deck
- Vibration frequency; the air speed
- Surface characteristics of the deck



(a) (b)

Figure 7. Air separation technologies **(a)** air-cascade separator and **(b)** vibrating air-table separator

Thereafter, the sorted particles are then taken into a vibrating table which uses the typical process of sieving, using different mesh sizes, the vibration process helps separating the smaller particles form the bigger particles.

The result is a quantity of different waste particles that have been separated (**Figure 8**), depending on the type of material, they can be recycled or downcycled. Downcycle is a process that is used in case recycling is not possible, in this operation the material losses many of its features, for example, marked drop in strength, but the material is still suitable for other applications. Recyclable materials can be used in sneaker re-manufacture while downcycled materials have a variety of other uses, for example, surfacing of playing grounds and an underlay for carpets which is a common use.

Figure 8. Small particles of footwear during the recycling process

One of the challenges with sneaker recycling is the lack of communication between the suppliers and recycling organisations. As a result, footwears are poorly designed, for recycling to be effective and to ensure the entire sneaker can be recycled/downcycled, the initial design should consider the end-of-life stage of the sneaker, for example, avoiding the use of glue is suggested to make components dismantling easier, and in this case weaving can be a better option.

2.7 Applications

To ensure circular economy is maintained for Dubs Universe sneakers, we include the most common applications for end-of-life stage of the sneaker materials with the manufacturers and suppliers in the UK that Dubs Universe is recommended to collaborate with.

2.7.1 Polyester

Applications	Companies
Pipe lining	Pipe Lining Services
Vessels	Vessco Engineering, Spirotech Group, John King

2.7.2 EVA

Applications	Companies
Shoe soles	Dubs Universe
Stretch film for wrapping	Kite Packaging
Medical equipment	3M Healthcare, Baxter, Blatchford and Sons, JRI Orthopaedics
Flexible toys	Plushie, Peterkin, Wow Toys, Playmonster

2.7.3 Rubber

Applications	Companies
Car tires	Michelin, Pirelli, Bridgestone, Avon, Goodyear
Seals	Butser Rubber, M Barnwell Services, COH Baines, Delta Rubber
Belts	Conveyor Belting, Vulcatech Belting, UK Rubber Belting
Anti-vibration mounts	AV Mounts
Electrical insulation	UKi Insulations, Mekufa, RH Nuttall
Gloves	Synthomer, Unigloves, Aurelia, Just Gloves, Gloveman
Adhesives	Alpha Adhesives, Anglo Adhesives
Carpeting	Cormar Carpets, Axminster Carpets, Brockway Carpets
Textiles	Coruba, Baltex
Rubber bands	Calibre Rubber Bands

2.7.4 PET

Applications	Companies
Blow moulded bottles	Weltonhurst. ENL Group, Bolton Plastic Components & Bettix
Packaging film	Aintree Plastics, Polystar, Multiplastics
Industrial strapping	Fortris, Fromm Pack, Plastex
Fibres	James Robinson Fibres, Fibres Direct

2.7.5 PU foam

Applications	Companies
Insulation	Isothane, Custom Foams
Packaging	Advanced Packaging, Advanced Protective Packaging
Crash protection	Munsch & Co/PTM, Polymax
Impact pads	GB Foam, PAR Group
Shock isolation pads	Acoustaproducts, Gel Mec

3 Alternative materials

Plant contribution in sneaker manufacturing has the benefit of reducing landfill plastic waste due to the biodegradability of plant-based materials in addition to making use of the agricultural waste that normally left for incineration. In this section, we give some of the most sustainable plant-based materials that can be used by Dub-Universe to replace some of the plastic components.

3.1 Upper

3.1.1 Pineapple

Ananas Anam uses pineapple leaf fibre as an agricultural waste to produce textile that can be used for fashion, accessories, upholstery, clothing and footwear. These leaves are a by-product from existing pineapple harvest, so the raw material requires no additional environmental resources to produce. The material has passed ISO international textile testing standards for the following properties: Tear & tensile strength, Flexing endurance, Seam rupture, Finish adhesion and Colour fastness.

The process starts with pineapple harvesting, the suitable plant leaves which are left behind are collected in bundles and the long fibres are extracted using semi-automatic machines. The fibres are washed then dried naturally by the sun, or during the rainy season in drying ovens. The dry fibres go through a purification process to remove any impurities which results in a fluff-like material. This fluff-like pineapple leaf fibre (PALF) gets mixed with a corn based polylactic acid (PLA) and undergoes a mechanical process to create a non-woven mesh which forms the base of all Piñatex collections. The rolls of non-woven mesh are then processed under specialised finishing. Then, the non-woven mesh is coloured using GOTS certified pigments and a resin top coating is applied to give additional strength, durability and water resistance. A foil is heat pressed on to create the Metallic collection and a high solid PU transfer coating is used to improve the performance (**Figure 9**). This textile is fit for use in the upper part of the Dubs Universe sneaker to replace the PET knitted upper, which will reduce the total carbon footprint considerably. Piñatex's website offers various product categories for sale.

(1) Leaf collection (2) Fibre extraction (3) Washing/Drying (4) Purification

(5) Non-woven mesh (6) Finishing (7) Piñatex (8) Final product

Figure 9. The Production stages of the pineapple leaf fibre-based textile

3.1.2 Corn

Ecoalf has introduced corn-starch based biopolymer known as "Sorona". The material can be used as a fabric material and it has similar properties to nylon. Unlike nylon, corn-starch based biopolymer has many environmental advantages such as reducing energy consumption by 30% and carbon footprint by 63%. The properties of this material are suitable for the upper part of the sneaker because it is soft and it can dry quickly as well as their high comfort.

3.2 Lace

Currently, organic cotton is the best option for the lace part, ideally without plastic tip covers. Sustainable cotton is therefore grown in a way that can maintain levels of production with minimal environmental impact, can support viable producer livelihoods and communities, and can do so in the face of long-term ecological constraints and socioeconomic pressures.

3.3 Insole

Cork fabric is the best insole alternative, providing a healthy environment for feet due to its antimicrobial properties and foot moulding capabilities (**Figure 10**). This relieves joint pressure, provides cushion, and wards against foot odor.

One of the main benefits of using cork, or most tree-based materials for that matter, is its ability to absorb CO_2 from our atmosphere. With cork, harvesting keeps the tree intact, meaning it can continue sequestering carbon dioxide. Moreover, the primary production of cork consumes low energy, around 3.9 MJ/kg, giving 0.2 kg/kg carbon footprint, see **Table 11**. This is very low in comparison with: polyurethane having 82 MJ/kg - 3.2 kg/kg, rubber having 87 MJ/kg - 1.95 kg/kg and PET having 84 MJ/kg - 2.7 kg/kg. Cork fabric is 100% vegan, making it a great leather alternative, thus giving it one of its main sustainability benefits. Sustainable Jungle can be a valuable source of cork information and communication support with potential suppliers.

Figure 10. Insloe made using cork

3.4 Midsoles

This component still presents the largest problem for sustainability. Most still incorporate non-biodegradable, plastic-based materials in the midsole due to their performance properties.

EVA is currently the almost sustainable option for running sneakers to give them a combination of supportive and light cushioning. Therefore, Dub-Universe sneakers use the optimum midsole material, as we will explain in the Datasheet section.

4 Datasheets

Detailed datasheets of the materials used in the components of the Dubs Universe Sneakers are given in **Tables 6 - 11**. Each datasheet includes the composition of the material, which is important when considering recyclability, for example, some materials are coated with non-recyclable coatings which may affect the end-of-life potential of the entire material or may require an additional step before recycling is possible. The list also includes energy consumption, carbon footprint and water footprint at the primary production stage and at the processing stage in detail. Finally, the end-of-life options of the materials are presented, including Recycle, Downcycle, Combust, Landfill and Biodegrade with their energy consumption and carbon footprint.

Midsole contributes over 55% of the total mass of sneakers so it has a considerable impact on the sneaker sustainability. The midsole of traditional sneakers is made of polyurethane while Dub Universe uses EVA. EVA is around 10% less dense than polyurethane, densities are 1.05 g/cm^3 for polyurethane and 0.96 g/cm^3 EVA, resulting in a mass reduction from 184.4 g in polyurethane to 168.6 g in EVA. This also represents around 10% decrease in carbon footprint due to mass reduction.

Furthermore, it is not only the mass, but the type of material is of importance as different materials consume different levels of energy during processing even for the same mass. At the primary production process polyurethane results in 3.21 kg/kg carbon emission while EVA emission rate is 2.11 kg/kg, around 35% carbon reduction. In general, all secondary processing techniques require less energy for EVA, for example, in injection moulding polyurethane consumes 23.1 MJ/kg, equivalent to 1.85 kg/kg carbon footprint, while EVA consumes 6.39 MJ/kg resulting in 0.511 kg/kg carbon footprint, more than 3 times emissions reduction.

Considering the end-of-life potential, EVA is recyclable while polyurethane can only be downcycled. This means that EVA maintains its properties and can be used repeatedly in sneaker production while polyurethane properties degrade so it can be used in less property requiring products. In summary, EVA would be the ideal candidate for midsole manufacturing due to its low density, low carbon footprint during processing and good recyclability which contributes to maintaining circular economy.

Dub Universe uses polyurethane post-industrial waste off foam for the insock component of the sneakers. Polyurethane foam materials are used widely, inevitably leading to a large number of polyurethane foam wastes production that need to be disposed of. Polyurethane foam wastes mainly come from the production process of leftover materials and product scraps. Polyurethane foam wastes belong to the white pollution, and it affects the living environment. Due to its low density and high volume, polyurethane foam waste is difficult to treat and dispose of in landfills, even incineration will produce poisonous gas. In addition, its ecological environment degradation can lead to adverse effects. Therefore, polyurethane foam wastes recycling has become an urgent need to resolve one of the major industrial sustainability issues. The use of polyurethane post-industrial waste off foam by Dub Universe contributes in minimising its negative impact on the living environment, reducing space occupation in landfills and avoid poisonous gas during incineration. Since the sneakers are made in China, this would be advantageous in a country that has the largest polyurethane foam wase in the world.

Table 6. Datasheet for Polyester

General information

Designation ⓘ

Polyester cast

Tradenames ⓘ

Ad-Tech; Ampal; Aropol; Atlac; Bakelite; Corezyn; Dion; Envirez; Enydyne; Glastherm; Glastic; Hetron; Norsodyne; Palatal; Plenco; Polaris; Polylite; Polyrite; Premi-Glas; Ralupol; Silmar; Synolite; Varimat

Included in Materials Data for Simulation	ⓘ	✓			

Composition overview

Compositional summary ⓘ

Cross-linked copolymer of unsaturated polyester (typically from maleic anhydride, phthalic anhydride, and a polyol) and styrene

Material family	ⓘ	Plastic (thermoset)
Base material	ⓘ	UP (Unsaturated polyester resin)
Polymer code	ⓘ	UP

Composition detail (polymers and natural materials)

Polymer	ⓘ	100			%

Price

Price	ⓘ	* 1.39	-	1.65	GBP/kg
Price per unit volume	ⓘ	* 1.4e3	-	1.98e3	GBP/m^3

Primary production energy, CO2 and water

Embodied energy, primary production	ⓘ	67.9	-	74.8	MJ/kg

Sources

64.5 MJ/kg (Patel, 2003); 78 MJ/kg (Song, Youn, Gutowski, 2009)

CO2 footprint, primary production	ⓘ	2.41	-	2.66	kg/kg

Sources

Data reported by sources are for CO2, values were converted to CO2 footprint using the relationship: CO2 footprint = CO2 * 1.06. Relationship taken from Hammond and Jones, 2008. Note that this is only captures fuel use (i.e. not including any process related emissions). This is for the average mixture of fuels used in the UK industry.

2.39 kg/kg (Patel, 2003)

Water usage	ⓘ	* 190	-	210	l/kg

Processing energy, CO2 footprint & water

Polymer molding energy	ⓘ	* 25.9	-	28.6	MJ/kg
Polymer molding CO2	ⓘ	* 2.07	-	2.29	kg/kg
Polymer molding water	ⓘ	* 15.6	-	23.4	l/kg
Coarse machining energy (per unit wt removed)	ⓘ	* 0.594	-	0.657	MJ/kg
Coarse machining CO2 (per unit wt removed)	ⓘ	* 0.0446	-	0.0493	kg/kg
Fine machining energy (per unit wt removed)	ⓘ	* 1.67	-	1.84	MJ/kg
Fine machining CO2 (per unit wt removed)	ⓘ	* 0.125	-	0.138	kg/kg
Grinding energy (per unit wt removed)	ⓘ	* 2.86	-	3.16	MJ/kg
Grinding CO2 (per unit wt removed)	ⓘ	* 0.215	-	0.237	kg/kg

Recycling and end of life

Recycle	ⓘ	✗			
Recycle fraction in current supply	ⓘ	0.1			%
Downcycle	ⓘ	✓			
Combust for energy recovery	ⓘ	✓			
Heat of combustion (net)	ⓘ	* 27.9	-	29.3	MJ/kg
Combustion CO2	ⓘ	* 2.49	-	2.62	kg/kg
Landfill	ⓘ	✓			
Biodegrade	ⓘ	✗			

Table 7. Datasheet for Ethylene Vinyl Acetate

General information

Designation

Ethylene Vinyl Acetate

Tradenames

Alcudia; Apizero; Appeel; Ateva; Bynel; Certene; Cosmothene; Elevate; Elvax; Escorene; Evatane; Evateno; Evathene; Exceval; Fainplast; Flexaren; Fusabond; Greenflex; Hanwha; Icorene; J-Rex; LG; Marpol; Melthene; Microthene; Nipoflex; Novatec; Orevac; Polene; Polymer-E; Samsung Total; Sanren; Seetec; Taisox; Toler; Tritheva; Ultrathene

Included in Materials Data for Simulation	✓

Composition overview

Compositional summary

Copolymer of 67% ethylene (CH2CH2)n and 33% vinyl acetate (CH2CHOCOCH3)m

Material family	Elastomer (thermoplastic, TPE)
Base material	EVA (Ethylene vinyl acetate copolymer)
Polymer code	EVA

Composition detail (polymers and natural materials)

Polymer	100			%

Price

Price	* 1.08	-	1.13	GBP/kg
Price per unit volume	* 1.01e3	-	1.08e3	GBP/m^3

Primary production energy, CO2 and water

Embodied energy, primary production Sources 78.9 MJ/kg (Ecoinvent v2.2)	75.1	-	82.7	MJ/kg
CO2 footprint, primary production Sources 2.11 kg/kg (Ecoinvent v2.2)	2.01	-	2.21	kg/kg
Water usage	* 2.66	-	2.94	l/kg

Processing energy, CO2 footprint & water

Polymer extrusion energy	* 6.08	-	6.7	MJ/kg
Polymer extrusion CO2	* 0.486	-	0.536	kg/kg
Polymer extrusion water	* 4.93	-	7.39	l/kg
Polymer molding energy	* 15.5	-	17.1	MJ/kg
Polymer molding CO2	* 1.24	-	1.37	kg/kg
Polymer molding water	* 11.3	-	16.9	l/kg
Coarse machining energy (per unit wt removed)	* 0.63	-	0.696	MJ/kg
Coarse machining CO2 (per unit wt removed)	* 0.0472	-	0.0522	kg/kg
Fine machining energy (per unit wt removed)	* 2.02	-	2.24	MJ/kg
Fine machining CO2 (per unit wt removed)	* 0.152	-	0.168	kg/kg
Grinding energy (per unit wt removed)	* 3.57	-	3.95	MJ/kg
Grinding CO2 (per unit wt removed)	* 0.268	-	0.296	kg/kg

Recycling and end of life

Recycle	✓			
Embodied energy, recycling	* 25.5	-	28.2	MJ/kg
CO2 footprint, recycling	* 0.682	-	0.754	kg/kg
Recycle fraction in current supply	0.1			%
Downcycle	✓			
Combust for energy recovery	✓			
Heat of combustion (net)	* 39.2	-	41.2	MJ/kg
Combustion CO2	* 2.82	-	2.97	kg/kg
Landfill	✓			
Biodegrade	✗			

Table 8. Datasheet for Rubber

General information

Designation

Natural rubber (unreinforced), Natural rubber / Natural cis-1,4-polyisoprene (NR)

Tradenames

Aquamix; Cariflex; Nipol

Included in Materials Data for Simulation	✓			

Composition overview

Compositional summary

Cis-1,4-polyisoprene, chemical formula (CH2-C(CH3)=CH-CH2)n, vulcanized (crosslinked) by sulfur, peroxide, or bis-phenol. Produced from the latex of the rubber tree: Hevea brasiliensis. Natural rubber is 100% cis, 0% trans isomer. Unless removed by processing, contains small amounts of fatty acid and protein residues. Typical vulcanizate includes 5phr ZnO and 2.5 phr sulfur.

Material family	Elastomer (thermoset, rubber)			
Base material	NR (Natural rubber)			
Renewable content	100			%
Polymer code	NR			

Composition detail (polymers and natural materials)

Polymer	100			%

Price

Price	* 1.14	-	1.35	GBP/kg
Price per unit volume	* 1.06e3	-	1.31e3	GBP/m^3

Primary production energy, CO2 and water

Embodied energy, primary production Sources 67.6 MJ/kg (Hammond and Jones, 2008); 87.4 MJ/kg (Ecoinvent v2.2)	73.8	-	81.4	MJ/kg
CO2 footprint, primary production Sources 1.95 kg/kg (Ecoinvent v2.2)	1.86	-	2.05	kg/kg
Water usage	1.5e4	-	2e4	l/kg

Processing energy, CO2 footprint & water

Polymer molding energy	* 15.3	-	16.9	MJ/kg
Polymer molding CO2	* 1.23	-	1.35	kg/kg
Polymer molding water	* 11.2	-	16.8	l/kg
Grinding energy (per unit wt removed)	* 6.3	-	6.96	MJ/kg
Grinding CO2 (per unit wt removed)	* 0.472	-	0.522	kg/kg

Recycling and end of life

Recycle	✗			
Recycle fraction in current supply	0.1			%
Downcycle	✓			
Combust for energy recovery	✓			
Heat of combustion (net)	* 42.5	-	44.6	MJ/kg
Combustion CO2	* 3.15	-	3.31	kg/kg
Landfill	✓			
Biodegrade	✗			

Table 9. Datasheet for Polyethylene Terephthalate

General information

Designation

Polyethylene Terephthalate

Tradenames

4Tech; Accucomp; Acculoy; Akolyt; Aqua; Arnite; Array; Artenius; Arya; Aspet; Aspira; Astapet; Bangkok; Bapolene; Bestdur; Bondz; Calima; Cazeden; Certene; Chiliad; Cleartuf; Cobifoam; Cobitech; Cobiter; Colorrx; DSR; Durapet; Eastapak; Eastar; Eastlon; Eastman; Ekopet; Ensinger; Exelene; Future-Pet; Genius; Geo; Globio; Hifill; I. Stern; Icorene; Incolor; Indorama; Inelec; Infinite; Jamplast; Kebablend; Kempt; Kopet; Krupet-A; Kurarister; Lamigamid; Laser+; Lighter; Lofex; Lotte; Luvocom; M&G; Madesolid; Marpol; Master; Matrixx; Maven; Mimesis; Mylar; Natureplast; Nemcon; Neopet; Nupet; Octal; Papet; Petlon; Polyclear; PQS; Preformance; Primalene; PTI; Qr Resin; Quadrant; Ramapet; Relpet; Repete; RJM; Rodnsheet; Sabic; Safe; Sealpet; Selar; Selekt; Selfy; Shinite; Skypet; Skyrol; Slovastyr; Strapio; Surespec; Sustadur; Terez; Texpet; Traytuf; Tripet; Tunhe; Umapet; Unipet; Unitrex; Valox; Venuz; Vinpol; Voloy; Wankai; Weezen; Wellpet; World; Xcel; Zedex

Included in Materials Data for Simulation	✓

Composition overview

Compositional summary

(CO-(C6H4)-CO-O-(CH2)2-O)n

Material family	Plastic (thermoplastic, amorphous)
Base material	PET (Polyethylene terephthalate)
Polymer code	PET

Composition detail (polymers and natural materials)

Polymer	100			%

Price

Price	* 0.827	-	1.03	GBP/kg
Price per unit volume	* 1.07e3	-	1.43e3	GBP/m^3

Primary production energy, CO2 and water

Embodied energy, primary production	78.4	-	86.4	MJ/kg

Sources
59.4 MJ/kg (Patel, 2003); 74.2 MJ/kg (Franklin Associates, 2010); 77 MJ/kg (Shen and Patel, 2008); 78.2 MJ/kg (Song, Youn, Gutowski, 2009); 78.8 MJ/kg (Thiriez and Gutowski, 2006); 82.8 MJ/kg (Habersatter et al., 1996); 89.2 MJ/kg (Hammond and Jones, 2008); 96 MJ/kg (Song, Youn, Gutowski, 2009); 110 MJ/kg (Hammond and Jones, 2008); 78.4 MJ/kg (Ecoinvent v2.2)

CO2 footprint, primary production	2.59	-	2.86	kg/kg

Sources
2.75 kg/kg (Franklin Associates, 2010); 2.7 kg/kg (Ecoinvent v2.2)

Water usage	* 126	-	140	l/kg

Processing energy, CO2 footprint & water

Polymer extrusion energy	* 5.82	-	6.43	MJ/kg
Polymer extrusion CO2	* 0.437	-	0.483	kg/kg
Polymer extrusion water	* 4.83	-	7.24	l/kg
Polymer molding energy	* 18.7	-	20.6	MJ/kg
Polymer molding CO2	* 1.4	-	1.55	kg/kg
Polymer molding water	* 12.6	-	18.9	l/kg
Coarse machining energy (per unit wt removed)	* 0.864	-	0.954	MJ/kg
Coarse machining CO2 (per unit wt removed)	* 0.0648	-	0.0716	kg/kg
Fine machining energy (per unit wt removed)	* 4.36	-	4.82	MJ/kg
Fine machining CO2 (per unit wt removed)	* 0.327	-	0.361	kg/kg
Grinding energy (per unit wt removed)	* 8.25	-	9.11	MJ/kg
Grinding CO2 (per unit wt removed)	* 0.618	-	0.684	kg/kg

Recycling and end of life

Recycle	✓			
Embodied energy, recycling	* 26.8	-	29.6	MJ/kg
CO2 footprint, recycling	* 1.45	-	1.6	kg/kg
Recycle fraction in current supply	20	-	22.1	%
Downcycle	✓			
Combust for energy recovery	✓			
Heat of combustion (net)	* 23	-	24.2	MJ/kg
Combustion CO2	* 2.24	-	2.35	kg/kg
Landfill	✓			
Biodegrade	✗			

Table 10. Datasheet for Polyurethane foam

General information

Designation

Polyurethane foam

Tradenames

Last-a-Foam TF & EF, Hyperlast, Foamex

Composition overview

Compositional summary

(NH-R-NH-CO-O-R'-O-CO)n, R from a diisocyanate, R' from a polyol

Form	Foam
Material family	Elastomer (thermoset, rubber)
Base material	PUR (Thermoset polyurethane elastomer)
Polymer code	PUR

Composition detail (polymers and natural materials)

Polymer	100			%

Price

Price	* 5.95	-	6.54	GBP/kg
Price per unit volume	* 446	-	556	GBP/m^3

Primary production energy, CO2 and water

Embodied energy, primary production	80.9	-	89.2	MJ/kg

Sources
62.9 MJ/kg - Bio-based (Institute for Prospective Technological Studies, 2005); 88.7 MJ/kg (PlasticsEurope, 2015); 85.5 MJ/kg (PlasticsEurope, 2015); 84.9 MJ/kg (PlasticsEurope, 2015); 103 MJ/kg (Institute for Prospective Technological Studies, 2005)

CO2 footprint, primary production	3.76	-	4.14	kg/kg

Sources
4.4 kg/kg (Institute for Prospective Technological Studies, 2005); 6 kg/kg (Institute for Prospective Technological Studies, 2005); 3.22 kg/kg (PlasticsEurope, 2015); 3.18 kg/kg (PlasticsEurope, 2015); 2.95 kg/kg (PlasticsEurope, 2015)

Water usage	* 280	-	310	l/kg

Processing energy, CO2 footprint & water

Polymer extrusion energy	* 6.64	-	7.32	MJ/kg
Polymer extrusion CO2	* 0.531	-	0.585	kg/kg
Polymer extrusion water	* 5.16	-	7.74	l/kg
Polymer molding energy	* 17	-	18.7	MJ/kg
Polymer molding CO2	* 1.36	-	1.5	kg/kg
Polymer molding water	* 11.9	-	17.8	l/kg
Coarse machining energy (per unit wt removed)	* 0.478	-	0.529	MJ/kg
Coarse machining CO2 (per unit wt removed)	* 0.0359	-	0.0396	kg/kg
Fine machining energy (per unit wt removed)	* 0.508	-	0.561	MJ/kg
Fine machining CO2 (per unit wt removed)	* 0.0381	-	0.0421	kg/kg
Grinding energy (per unit wt removed)	* 0.54	-	0.597	MJ/kg
Grinding CO2 (per unit wt removed)	* 0.0405	-	0.0448	kg/kg

Recycling and end of life

Recycle	✗			
Recycle fraction in current supply	0.95	-	1.05	%
Downcycle	✓			
Combust for energy recovery	✓			
Heat of combustion (net)	* 21.3	-	22.4	MJ/kg
Combustion CO2	* 2	-	2.1	kg/kg
Landfill	✓			
Biodegrade	✗			

Table 11. Datasheet for cork

General information

Designation

Cork

Typical uses

Corks, stoppers, bungs for bottles, floats, lifebelts, walls, flooring, insulation, shoes, packaging, fancy goods, decoration, gaskets, road surfaces, linoleum, polishing, brake pads, vibration damping.

Composition overview

Compositional summary

40% Suberim/27% Lignin/12% Cellulose/4% Friedelin/17% Water

Material family	Natural			
Base material	Wood (other: monocot, bark)			
Renewable content	100			%

Composition detail (polymers and natural materials)

Wood	100			%

Price

Price	* 2.09	-	10.5	GBP/kg
Price per unit volume	* 251	-	1.88e3	GBP/m^3

Primary production energy, CO2 and water

Embodied energy, primary production	3.81	-	4.2	MJ/kg

Sources
4 MJ/kg (Hammond and Jones, 2008)

CO2 footprint, primary production	0.192	-	0.211	kg/kg

Sources
Data reported by sources are for CO2, values were converted to CO2 footprint using the relationship: CO2 footprint = CO2 * 1.06. Relationship taken from Hammond and Jones, 2008. Note that this is only captures fuel use (i.e. not including any process related emissions). This is for the average mixture of fuels used in the UK industry.

0.19 kg/kg (Hammond and Jones, 2008)

Water usage	* 665	-	735	l/kg

Processing energy, CO2 footprint & water

Coarse machining energy (per unit wt removed)	* 0.525	-	0.58	MJ/kg
Coarse machining CO2 (per unit wt removed)	* 0.0394	-	0.0435	kg/kg
Fine machining energy (per unit wt removed)	* 0.973	-	1.08	MJ/kg
Fine machining CO2 (per unit wt removed)	* 0.073	-	0.0807	kg/kg
Grinding energy (per unit wt removed)	* 1.47	-	1.63	MJ/kg
Grinding CO2 (per unit wt removed)	* 0.11	-	0.122	kg/kg

Recycling and end of life

Recycle	✗			
Recycle fraction in current supply	0.1			%
Downcycle	✓			
Combust for energy recovery	✓			
Heat of combustion (net)	* 19.8	-	21.3	MJ/kg
Combustion CO2	* 1.69	-	1.78	kg/kg
Landfill	✓			
Biodegrade	✓			