The Improvement of Product Sustainability by the Development of 'Whole life' Design Methodologies

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Abstract

Sustainability-related legislation has increased over the past 10 years, and this is now having a profound effect on industry which is required to reduce its impacts. Those designing and manufacturing electro-mechanical products must also consider the impacts of the goods they produce. Many of these impacts stem from decisions made early on in the design process, and consequently it is here that effort must be focused.

One of the most significant lifecycle stages of any product is end of life, as it dictates how much of the material and embedded energy are recovered for reuse. Remanufacturing was found to be the only end of life option for electro-mechanical products that returned a product to a like-new quality, without first destroying the form of the component and loosing the embodied energy. Although remanufacture can require a high level of reprocessing, the process can be simplified if products are designed to facilitate this. Current design models in this area, however, offer inadequate assistance to designers, leading to confusion and a lack of real life application.

Through the use of a case study, this study set out to explore whether the impacts of electro-mechanical products could be reduced, by considering products on a component level and designing them to operate over multiple lives, without increasing cost or reducing quality. This proved to be true in the case of a stairlift.

Through life cycle assessment it was demonstrated that the whole life environmental impacts of a stairlift, representing a sample electro-mechanical product, could be significantly reduced by remanufacturing components at end of life. High impact components were targeted for remanufacture using the LCA data in combination with cost, sending the remainder of the product for recycling. Overall, environmental savings of 13% were witnessed. Incorporating sustainability in this fashion not only avoided any increase in cost to the manufacturer, but achieved a 34% reduction in overall production costs.

It was concluded that if the product had been optimised with desirable characteristics for remanufacture and recycling when in design, then these savings would be even more significant. To guide designers with embedding desirable characteristics into products, the end of life optimisation (EOLO) model was developed. This provides a framework for selecting components early in the design process for either remanufacture or recycling. The model goes on to rate current performance and provided guidelines on how to improve the design going forward.

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Nomenclature

AIDC	Automatic Identification And Data Capture
BOM	Bill of Materials
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
DEFRA	Department for Environment, Food and Rural Affairs
DPI	Dye Penetrant Inspection
ECN	Engineering Change Note
EDM	Environmental Design Manager
EOL	End of Life
EOLO	End of Life Optimisation (Model)
GWP	Global Warming Potential
ISO	International Organization for Standardization
KTP	Knowledge Transfer Partnership
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MPI	Magnetic Particle Inspection
NDT	Non-Destructive Testing
NPI	New product Introduction
OEM	Original Equipment Manufacturer
PCB	Printed Circuit Board
PLM	Product Lifecycle Management
RFID	Radio-Frequency Identification
WEEE	Waste Electrical and Electronic Equipment

Chapter 1 – Introduction

The first Industrial Revolution (1760) saw the switch away from hand production towards manufacturing machines, which mechanised industries such as textiles, furniture, and food production. These new machines were powered by steam, produced from the burning of wood and coal. One hundred years later the second Industrial Revolution (1860) further progressed technology and economic momentum. Fossil fuel, now used to generate electricity, powered larger manufacturing machines capable of mass production. Steel was able to be mass manufactured and in the 20^{th} century the automotive industry was developed. Throughout these years of rapid economic development, little thought was given to the environmental impacts of burning fossil fuel, resource use, increased waste generation or of the products produced. Consequently, some see us now entering the third Industrial Revolution - the sustainable revolution. On a global scale sustainability is providing the stimulus for huge changes in industry, to correct the damage caused in the previous two revolutions and ensure our ability to be sustainable going forwards, (Simon, 2013).

Sustainability will become increasingly important, if not critical to businesses delivering products going forward, as indicated by Professor Schmidt Bleek of the Wuppertal Institute, (European Environment Agency, 1997):

"Firms that are not well on the way to developing and selling sustainable products will be cut out of the market over the next 10 to 20 years."

The need to produce sustainable products, coupled with increasing cost and reduced availability of raw materials, legal requirements and customer expectations are starting to pressure design and manufacturing companies to consider the environmental impact of the products they produce. It is estimated that 80% of a product's environmental impacts are decided in the design phase of its life, (European Commision, 2010). Through well thought out design, the impact of a product can therefore be reduced in each phase of its life. Of the lifecycle stages that the designer can influence, the intended end of life route represents one of the biggest opportunities for reducing the products whole life impacts.

1.1 Research overview

To produce sustainable products, businesses must change radically in order to reduce their environmental impacts. This study therefore focused on how the life cycle impacts of electro-mechanical products could be reduced, through consideration of their end of life reprocessing to retain as much value from these assets as possible.

1.1.1 Research question

The following research question was devised:

> *How can the environmental impacts of electro-mechanical products be reduced by considering them on a component level and designing them to operate over multiple lives without increasing cost or reducing quality?*

It was proposed that this study would show that if products were considered on a component level, end of life reprocessing back to a Like-new condition could be optimised. This would bring significant environmental savings, as well as lower production costs for future product lives.

1.1.2 Gaps in current literature

This research identified a number of gaps in prior literature, and improved the knowledge in these areas to assist designers in optimising products for end of life reprocessing.

Design for end of life models offered top level guidance on assisting designers with optimising products for different end of life disposal routes. It was evident however that more detailed how-to guides were required within the models to assist the designer in practical application. Where more specific design rules did exist, these often conflicted with one another, depending upon the chosen end of life disposal route. There was little guidance available on which design philosophy to use in which situation leading to confusion.

When considering the end of life route of remanufacturing, whole products are rarely remanufactured. Despite this, to date little guidance was identified to assist the designer in selecting end of life routes on a component level, ensuring all components were optimised for predefined disposal routes.

1.2 Case study: Stannah Stairlifts Ltd

To answer the question proposed above, cases study research was undertaken. This method was chosen due to the real world complexities of every product having a unique lifecycle, and the close link between a product’s design and the design process that created it.

This research programme was derived from a Knowledge Transfer Partnership (KTP) between Stannah Stairlifts Ltd and Oxford Brookes University in 2010. The KTP was established to investigate how Stannah could improve the sustainability of its products and services going forwards. As such the research described in this thesis was co funded by Stannah Stairlifts Ltd and Oxford Brookes University.

1.2.1 Stannah Stairlifts Ltd- electro-mechanical product producer

Stannah Stairlifts Ltd represents a typical British engineering company with an increasing interest in the sustainability of its business and the products that it produces. Stannah was used as the case within this study, providing a typical electro-mechanical product and new product development process for assessment.

The Stannah family own the business based in Andover Hampshire, UK. The business was established in 1867 and the business today consists of a number of companies specialising in the movement of goods and people between the floors of buildings. Stannah Stairlifts Ltd is concerned only with the design and manufacturing of stairlifts of which there are two key product categories, curved and straight staircases, Figure 1.1.

a) b)

Figure 1.1 - Stannah‘s curved (a) & straight (b) stairlifts, (Stannah Stairlifts Ltd, 2014).

With their largest markets residing in Europe, Stannah supply over 40,000 units per annum to over 40 countries worldwide. Major customer groups are private sales to end users, local authority contracts and selling to independent distributors.

Stannah's local authority customers are showing an increasing interest in the business's environmental performance. To demonstrate Stannah's commitment to becoming a more socially and environmentally aware organisation the business achieved ISO 14001 (Environmental Management System) in 2008 and the business intends to continue moving in this direction.

The Stannah brand sits at the premium end of the market offering excellence in design, safety and quality. Stannah's goal is to 'deliver to the Business a continuously improving range of stairlifts that enable Stannah to achieve and sustain true product leadership resulting in growth of turnover and earnings.' As part of this mission Stannah will embed sustainability as a key element in the design process, developing new business models based on eco design, which will enhance the company's efficiency, reputation and profitability. In turn, this will help the company to maintain its global lead as its markets become increasingly sensitive to environmental issues.

Stannah wished to look at the whole life cycles of its products and identify how it could change its methods of design and production to ensure that the company had considered all possible economic, social and environmental factors, not only in the design and manufacture of its products, but also in disassembly and disposal.

The stairlift industry has typically sold new products and refurbished models into second hand markets. A joint investigation between the Centre for Remanufacture and Reuse and the North East Improvement and Efficiency Partnership examined the potential of increasing the use of remanufactured products by local authorities in the North East of England, (Centre for Remanufacturing and Reuse, 2011). This would present potential for Stannah to enter new markets and gain a competitive advantage. The report reviewed 717 spend categories and highlighted 17 initial categories of interest, where remanufactured products could be of interest to public procurement. Each was scored against total spend, market readiness and acceptance and ease of substitution.

Stairlifts were highlighted as a potential, ranking joint 13th (along with two other products) out of the 17 initial categories. Overall spend on stairlifts was deemed to be low, but it was felt that stairlifts could be reasonably easily substituted with a remanufactured variant. The readiness of the stairlift industry however, was not currently deemed to be in a position to respond to a large increase in demand for remanufactured products. If the market readiness had achieved the top score, this would push stairlifts up the ranking to joint 5th (along with four other product categories). This potential untapped market offers new opportunities and additional element of specific industrial relevance to the case study within this research.

Chapter 2 – Review of Existing Literature
Designing for Product Sustainability

2.1 Product sustainability and assessment

All products, including electro-mechanical, follow a basic lifecycle which takes it roots from biological sciences. Products are born, develop, mature and ultimately die, (Ashby, 2009). For a product, the most basic flow translates as the extraction of raw materials, manufacturing, product use and end of life.

In each stage of the lifecycle positive or negative effects on financial performance, human health, safety and the environment will be associated with the various activities undertaken, (Fiksel, 2012). Every product is unique and where the greatest impacts occur will vary on the lifecycle in question, (Bhamra, et al., 2007). In Figure 2.1 a product lifecycle can be seen with typical activities for each product lifecycle stage listed below:

Figure 2.1 - Product Lifecycle Diagram, (Verdoorn, 2013)

Product lifecycle diagram key:

1. Raw materials – Extraction and processing.
2. Manufacture – Processing of the raw materials into a product .
3. Packaging – Transit and point of sale packaging applied to a product.
4. Distribution – Transport of component parts to manufacture and products to the user.
5. Use – Power and consumables needed over the product's operating life.
6. Maintenance – Replacement components to maintain the product in operation.
7. & 8. Disposal – End of life route including reuse, remanufactured, recycled, landfill and energy recovery.

2.1.1 Linear to circular product lifecycles

The way in which product lifecycles have been perceived has changed over time and as concern for the environment has grown. We have moved from a linear perception with a start and an end to a position of circularity.

‘Cradle to grave’ is a linear, one-way methodology where products are designed to minimise their impacts on the environment at each stage of their expected life. At end of life though, everything (with the exception of what we actually consume eg. food) is ultimately designed to be thrown away. In some cases obsolescence is even built into the product to encourage the user in upgrading to a newer model. Traditionally disposal has been through incineration or landfill where the resources are wasted. Despite its failings and short outlook, the “cradle to grave” methodology still dominates modern manufacturing today, (Braungart, et al., 2008).

The ‘cradle to cradle’ methodology is an upgrade on the previous approach and is a circular model. This new approach moves away from looking to harm the environment less and focuses on the elimination of waste altogether. This is achieved by the recovery of resources at end of life, which are reprocessed and become an input to another lifecycle, (Braungart, et al., 2008). Eco-effectiveness, another one of the “cradle to cradle” philosophies, looks to create products that actually have a positive impact on the environment working in harmony with natural systems, (Fiksel, 2012). Products should be broken down and systems need to be established to cost effectively and safely recover materials at end of life. Recovered materials should bio-degrade into healthy soil or be captured and returned to high value uses. Operations should be powered by renewable sources, water should be efficiently and cleanly used and people and eco systems respected, (McDonough Braungart Design Chemistry (MBDC), 2010).

The ‘Circular economy’ takes the above circular lifecycle approach but looks more closely at the economics of the various material/energy loops and flows. Where the smallest loops exist is where the biggest financial, social and environmental benefit exists, (Making It , 2013). Products and services should be restorative by intention, with the aim to rely on renewable energy, eliminate the use of toxic chemicals and eradicate waste through careful design, (Ellen MacArthur Foundation, 2012a). Systems thinking looks to understand how processes and products do not operate in isolation, but all influence one and other within a larger system, in much the same way as in nature. Materials should cascade through multiple uses in different applications, each time extracting value before reaching the end of the cascade. One approach being taken in the ‘circular economy’ is to redefine the relationship between objects and consumers, selling a level of performance as a service rather than products themselves. Examples could range from renting tools in order to complete a task, or buying a defined light level in an office, where the actual light is purchased rather than the light fixtures themselves, (Making It , 2013).

The circular economy stands to benefit economies by substantially reducing material consumption and mitigating volatility in material supply. The circular economy should also generate jobs and bring long term resilience to the economy. Companies should benefit from the circular economy by reduced spend on materials and lower warranty risks. Customer interaction and loyalty should improve and less product complexity should lead to more manageable life cycles. Consumers should benefit from the circular economy by reduced total ownership cost, through reducing premature obsolescence of products, improved choice and convenience through renting products rather than buying, catering for their changing needs. Secondary benefits may also be seen by the customer from well designed products that deliver more than their basic function, (Ellen MacArthur Foundation, 2012b).

Currently however, we still mainly operate linear methodologies for production and consumption products, (Ellen MacArthur Foundation, 2012b). To make the shift from a linear to a circular model, it is key that lifecycle thinking is implemented throughout any organisation. It needs to become part of its philosophy, mission and day-to-day operations, rather than only thinking about the impacts that occur within the businesses gates (e.g. materials and/or manufacturing), (European Environment Agency, 1997).

2.1.2 Product lifecycle assessment

In designing electro-mechanical products to become more sustainable, it is first necessary to understand the lifecycle in question and measure how big the environmental impacts are in each stage of life. This data can then be used as a benchmark for future design activities, making product comparisons or customer marketing and labelling claims.

Assessment can be split into two categories, quantitative or qualitative. Quantitative data is preferable when considering continuous improvement and benchmarking, but can be difficult to collect, resource intensive and requires large investment. Qualitative data in many cases can serve adequately being easier to apply and requiring less data. Results still provide useful information in design phases, despite great uncertainties for example in the final design. The two most common qualitative methods used are checklists and scoring matrices, (Fiksel, 2012).

A method of quantitative assessment is Ecological footprinting. It looks to capture the use of nature’s resources as far as it affects the regenerative capacity of the biosphere and expresses the results in the unit of space (eg. hectare per year). Ecological footprint assessment of products is possible but is the most experimental, partly due to system complexity and a lack of necessary data. What it does allow though is the comparison of different services e.g. nappies and drinks containers, where both are related to a finite unit in order to see what proportion of the world’s resources that product consumes, (Chambers, et al., 2000).

One of the newest methods of quantitatively modelling the lifecycle impacts of a product is using Exergy analysis. The methodology is defined as the available work that can be extracted from a material or energy. Energy, materials, land, air, water, wind, tide and human resource can all be modelled as Exergy flows, making it a universal indicator of eco efficiency, (Fiksel, 2012).

Lifecycle assessment looks at each phase of a product or service’s life and attempts to quantify its impact in terms of energy, resources and waste against a chosen measure or measures (for example global warming potential) over its entire lifecycle, (Chambers, et al., 2000). At each stage of the product lifecycle, there are inputs to and outputs from the product system. Life cycle assessment (LCA) is a quantitative method for assessing these input and outputs against the chosen impact categories for the study. Although there are several LCA standards with slightly different methodologies, each approach follows the same basic approach.

Whilst LCA was originally designed to assess single products, it is now also being used to assess large scale systems such as power stations as well. This has resulted in two sub forms of LCA now being in use; attributional LCA and consequential LCA. Attributional life cycle assessment looks to assess and describe the physical flows to and from a product or process and identify what impact these have on the environment, (Eco-efficiency Action Project, 2010). Consequential life cycle assessment is a decision making tool and describes what impact making a change to flows will have on the environment, (Eco-efficiency Action Project, 2010).

2.1.2.1 LCA in product development

80% of the environmental impact of a product is determined by the designer, (European Commision, 2010), consequently using LCA in product development is a powerful tool. Considering a lifecycle approach, also helps minimize the environmental impacts associated with the whole product life, rather than just materials or manufacture traditionally considered by design and manufacturing companies.

Attributional LCA can be used at many different stages when developing products. Initially similar products can be assessed to give a benchmark. This gives a first off view of the product lifecycle and where the greatest opportunities for improvement exist, (Sprout Design Ltd., 2013). In the concepts stage, LCA can be used to assess different designs, evaluating them against the required performance and identifying where their hotspots lie, in order to go about designing these out. Considering these impacts early on in the design cycle minimises the impact on the development process. As the design becomes more mature the ability to make changes become harder, (Gregory, 1993). As the design develops, LCA can be used to evaluate the expected benefits of potential design improvements optimising the design, (Fiksel, 2012).

LCA can also be used when improving on an existing product. Conducting an LCA is an easier and faster task than assessing concept ideas as the previous model has already been established, (European Environment Agency, 1997).

As the design progresses and eventually moves from concept right through to the implementation phase, the information required will vary. Appropriate environmental information must be supplied to decision makers throughout each phase of the development process. Obtaining this information from an LCA will support decision making with scientific data and competence. This will help distinguish between scientific fact (as far as possible) and sets of values, (European Environment Agency, 1997).

Whilst LCA provides a methodology for measuring product impacts it is not without limitations. The biggest of these is that conducting an LCA at the beginning of the design process will be unlikely to reveal useful results due to a lack of available information on the product. At the end of the process, however, the information is available but the product is at a point where its maturity prevents the ability to make significant changes to the design, (Gehin, et al., 2007).

Another limitation to using LCA in product development is that it can be a costly exercise both financially and in time. Full assessments can take days, weeks or even months to assess making it difficult to justify the investment. To address this fact, a number of streamlined lifecycle assessment tools have been developed. These do not provide the same level of detail, but look to identify the major environmental impacts over the product lifecycle. Effort can then be prioritised to eliminate these in the design process, (Lewis, et al., 2001).

Conducting full impact assessments is also fraught with scientific difficulties. The precision of a great deal of eco data is low. Some data sets are known to be within 10%; others are even less accurate. Whilst this is a limitation, only enough data is needed to distinguish and make a judgement between the various alternatives being assessed, so 100% accurate data is not always necessary,(Ashby, 2009). Obtaining the required level of data is tricky especially when assessing processes and even more so when considering new technologies, (Fiksel, 2012).

Looking at multiple impacts can provide a more rounded study and stops the shifting of environmental impact from one area of impact (e.g. global warming) to another (e.g. human/eco toxicity), (University of Bath, [no date]). Many designers however, find it hard to use the results of a LCA study that presents them with several sets of results. How are improvements to global warming to be balanced against resource depletion or energy efficiency, (Ashby, 2009)? It is also easy to confuse human health and ecological health when looking at results, (Chambers, et al., 2000). To help get round these issues, an aggregated single score can be generated. This process requires a large amount of value judgement and is an area of significant debate, (Lewis, et al., 2001). The main limitation to using a signal value score is that there is no agreement on normalisation or weighting factors. This can obscure results and prevent fair comparisons being made to other products, (Ashby, 2009).

In practice the current success of using LCA in product development depends on the nature and complexity of the product system (e.g. new versus established), the product development cycle (time-to-market constraints), availability of technical and financial resources, and the design approach (integrated vs. serial). For this reason, many corporate initiatives have focused more on 'design for environment' and 'lifecycle design' approaches rather than comprehensive LCA techniques, (Gregory, 1993). These streamlined approaches to LCA are especially suited to the early stages of product development where rapid design iterations are made but environmental evaluation does not need to be exhaustive in detail, (Fiksel, 2012).

2.2 End of life and Remanufacture

One of the most significant lifecycles stages in terms of defining the product lifecycle and its overall associated impacts is end of life (EOL). One of the key decisions to be made by the designer early on in the design process is therefore is how the product will be disposed of.

There are many forms of disposal for end of life products, as can be seen in Figure 2.2. The most preferable of these is not creating the waste in the first place, negating the need for the product. If the product is needed, then recovering it at end of life in an operable state for reuse is the next best option. If the product is no longer operable then the next priority is to disassemble it allowing for component recovery, (Fiksel, 2012). Following this is material recycling and then recovering the embedded energy through material incineration. The least preferred option of disposal at end of life is one incorporating no form of recovery, such as landfill, (DEFRA, 2011).

[redacted]

Figure 2.2 - The waste hierarchy, (DEFRA, 2011)

2.2.1 EOL options for electro-mechanical products

There are several disposal methods for electro-mechanical products at end of life, impacting the product lifecycle and surrounding environment in differing ways. Figure 2.3 demonstrates the points at which some of the possible end of life routes feed back into the product lifecycle, or are released into the surrounding earth/ecosystem.

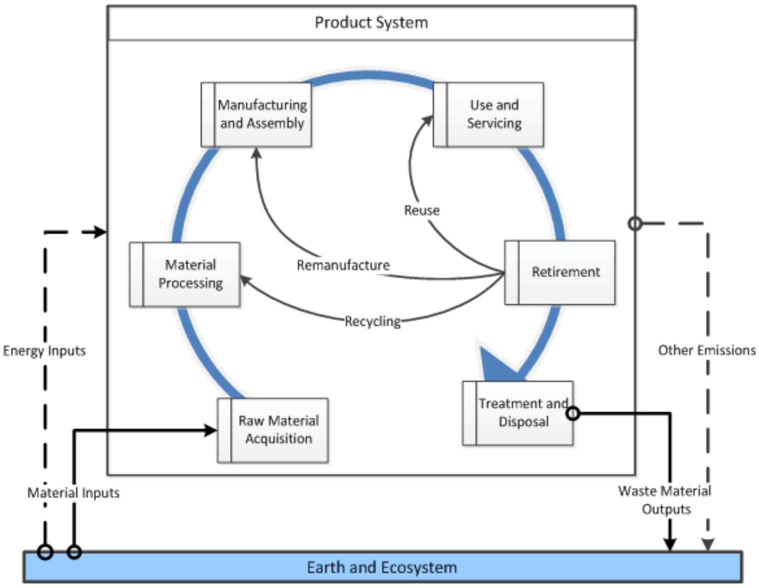


Figure 2.3 - Closing the loop on material flows, (Nasr, et al., 2006)

Exploring the end of life options available for electro-mechanical products in turn:

Landfill – Disposing of end of life products in the ground does not allow for any direct recovery of materials, loosing these resources forever.

Energy Recovery – Energy recovery is the process by which a waste is incinerated to recapture its embedded energy and generate electricity, (Bhamra, et al., 2007). Energy recovery is seen as an economically and environmentally viable approach to dealing with the recovery of heavily mixed waste or materials that are inseparable, (Farrow, et al., 2011). Incinerating plastics is also preferable to landfill based on resource recovery, (Bhamra, et al., 2007). The process is however inefficient and carbon dioxide (CO_2) emissions are 540g/kWh of energy produced higher than the UK grid average. Considering climate change, it is therefore better to landfill plastic waste if it cannot be recycled. Emissions are regulated from these facilities and the risk to health is seen to be undetectable, (Farrow, et al., 2011). The major downside to incinerating waste and only recovering the energy is that the material is lost and cannot be recovered a second or third time as it can be with recycling.

Recycling – Recycling is the recovery of materials from waste for reprocessing back to a raw material ready for reuse, (Ashby, 2009)**.** For recycling to be undertaken material separation is required. This can be done either manually through product disassembly or mechanically by shredding and material separation achieved using magnets and density baths, (Bhamra, et al., 2007).

Power is required to recycle materials at end of life, but this is often less than the power required to extract virgin materials. Recycling aluminium uses up to 95% less energy than primary production and is infinitely recyclable without degrading quality, (International Aluminium Institute , 2011).

Reuse – Reuse of products or components in their current application or a new application is a cost effective and environmental use for products at end of life. Reuse is particularly effective for high value, durable, unseen and static parts, (Bhamra, et al., 2007). Components that have been previously used will retain any problems that developed in previous lives. Where repair is undertaken before reuse, a warranty will typically only cover the repair itself and not the rest of the product, (Charter, et al., 2007).

Reconditioning – reconditioning products returns them to a satisfactory working condition by rebuilding or repairing major components that have failed or are close to failure, even where there are no reported or apparent faults in those components, (Ellen MacArthur Foundation, 2012b). Products may be taken to an almost new condition, but are not disassembled or cleaned on a component level. Any warranty given on the product may not match that of a new product, (Charter, et al., 2007).

Remanufacturing – Remanufacture returns a used product to at least its original performance with a warranty that is equivalent or better than that of the newly manufactured product, (British Standards, 2011). This allows components to be reused whilst maintaining their original quality, value and the embedded energy associated with that part in its original manufacture, (Charter, et al., 2007). This saves much of the energy associated with manufacture, from ore smelting, assembly, and refining, through to test. When comparing the total energy consumption from original manufacture to a remanufactured component the ratio is in the order of 4:1, (Ijomah, et al., 2007). For remanufacturing to be successful is should be considered for high value items with a low evolution rate and established return channels at end of life, (Morley, 2006).

Of the different disposal routes, landfill is arguably the worst for electro-mechanical products, losing the material content and filling limited landfill space with things that could be reprocessed in a more sustainable fashion. Energy recovery allow the recovery of embodied energy but lose the material content in the process. Reuse and refurbishing take the product and reuse it in its current state or with a small amount of reprocessing. Remanufacture takes end of life products and subjects them to a much higher level of reprocessing, but the product is taken back to a like-new condition. This is the only end of life option that achieves the like-new condition, without first destroying the component and recycling the raw material and re-making the component again.

2.2.2 A detailed review of remanufacture

In recent years there have been major strides made in improving resource efficiency and exploring new forms of energy. Many of today's systems are still however, based on consumption based models rather than using materials in a restorative manor. This leads to 'material leakage' and disposal over the product lifecycle,(Ellen MacArthur Foundation, 2012b). Remanufacturing looks to address this 'material leakage' by maintaining them in high value uses, maintaining the 'as new' level of quality.

On the surface standard component reuse may seem more attractive with less overall material and energy consumption. Remanufacturing, however, retains the component to its original value and conformance. This enables component reuse without compromising the durability or reliability of the final product, (Nasr, et al., 2006). By keeping components in circulation for multiple lifetimes it has been suggested that remanufacturing might be twice as profitable as traditional manufacturing, (Charter, et al., 2007). Despite its low uptake, in 2004, remanufacturing was estimated to be worth £5bn a year in the UK (all manufacturing in the UK valued at £447bn in 2004) which is equal to that of the recycling industry, (Oakdene Hollins, 2004).

Not all products however are suitable for remanufacturing, either because it is not cost effective or the most environmental product disposal method, (Hatcher, et al., 2011). If newer more efficient products have since come on to the market then keeping old inefficient models running might be counterproductive when considering the whole product lifecycle, (Ijomah, 2010). This can often be the case for products such as motors, where their use usually has significantly larger impacts than the materials and manufacturing phases of life. In this instance it would therefore be better to recycle than remanufacture, (Boustani, et al., 2011).

For remanufacture to be successful there must be a reverse flow of product at end of life made up of high value and durable components to remanufacture. There must be customer demand for a remanufactured product, stability in the design to limit changes and the potential to upgrade products into newer models, (Hatcher, et al., 2011). There must also be a significant difference between the price of obtaining end of life cores and the selling price for remanufactured products, so that the remanufacturer can make a profit, (Amezquita, et al., 1995).

The remanufacturing of electro-mechanical products comprises of a general process flow in returning them back to an 'as new' condition. This can be seen in Table 2.1.

	Reman. Stage	Description
1	Core collection	The end of life product (the core) needs to be returned to the remanufacturer.
2	Initial inspection	Products intended for remanufacture should be initially inspected for damage and wear.
3	Disassembly	The product is disassembled back into its component parts or manageable subassemblies ready for remanufacturing processes to be undertaken.
4	Cleaning	Parts are cleaned to remove dirt grease and oil form their surface.
5	Detailed inspection	Further inspection for signs of wear, fatigue or damage is required before the component can be deemed suitable for value adding activity.
6	Storage	Parts not required immediately will be stored prior to adding any value to them.
7	Reprocessing	Some components may require reprocessing to bring them back to an 'as-new' quality.
8	Recording component history	Tracking of components which have been remanufactured to record their multiple life history is important is ensure that components do not continue to be used past their designed operating life expectancy.
9	Reassembly	Reassembly of the remanufactured components in combination with new components back into products.
10	Testing	The product should be tested to ensure that it operates to a standard that is equal or better than a new product.
11	Issuing of the new warranty	The remanufactured products must be issued with a warranty that is equal or better than that of a non-remanufactured new product.

Table 2.1 – Remanufacturing process flow

There are three different parties that are currently remanufacturing end of life products, (Hatcher, et al., 2011):

1. The original equipment manufacturer (OEM) can have the cores returned to them and be responsible for remanufacturing their own used products.
2. A contract can be set up with a third party to remanufacture used product on behalf of the original equipment manufacturer.
3. An independent third party can buy cores the from the market and remanufacture these to resell, having no connection with the original equipment manufacturer.

OEMs would prefer model one or two in the above list of potential remanufacturers, as this allows them to maintain control. Incentivising the customer to return their product to the OEM also reduces the number of second hand products on the market helping to protect brand name and unauthorised reuse or remanufacture of their products, (Ijomah, 2010).

There are several factors that affect the take up of remanufacturing in different sectors. If the OEM is not going to undertake the remanufacture then there have to be independent firms willing and able to undertake the work. The engagement of the OEM however is still important to optimise the process. Where legislation exists controlling end of life products (such as the End of Life Vehicle Directive), availability and engagement of these two parties often improves. Customers are also needed who have an awareness and willingness to accept remanufactured products. This will especially be the case when cheap replacements often from developing countries, offer new products which may be more attractive to the consumer, (Matsumoto, et al., 2011).

One of the main challenges for remanufacturing is having cores available to remanufacture. One way to achieve this is to move away from the selling of products to the customer and move to renting or leasing agreement. This enables ownership of the product to be maintained and core retention at end of life. If products are to be sold then the customer should be given incentives to return the product,(Ellen MacArthur Foundation, 2012b). Another benefit to leasing products is that a larger share of the market can be achieved by controlling a greater share of the product value chain, (Sundin, et al., 2008).

With the manufacturer maintaining control over the product's life, there is greater incentive to optimise the whole product lifecycle. This promotes designing durable and reliable products as well as considering end of life treatment processes. This is particularly important in a lease model because any repair needed to the product becomes the responsibility and cost of the provider, not the user. Features such as warning systems can be built into the product to report on part conditions. This can reduce the chance of breakdowns and give service teams information on the optimal point to service or bring the product back in for remanufacture, (Sundin, et al., 2008). A negative that can be observed in operating a lease model is the removal of the maintenance and spares market, which are often very profitable, (Sundin, et al., 2008).

Once the core has been returned, there are two main remanufacturing models,(Matsumoto, et al., 2011):

1. Remanufacturing at a component level and then incorporating these into new products with no distinction between new and old components. This model typically sees the highest ratio of remanufactured components, but customers against remanufacture may be put off buying the brand.
2. Remanufacturing components into dedicated remanufactured products, but component reuse will be driven by the demand for remanufactured products.

If operating model two, new and remanufactured products should be targeted towards different markets so not to affect the sale of new products, (Matsumoto, et al., 2011). Remanufactured components can often be offered at a discounted rate, between 30-70% of their new equivalent's cost. Conversely, research has shown that remanufacturing works best when there is no reduction in cost as this demonstrates that the product offers no reduced functionality or quality compared to new**,** (Charter, et al., 2007)**.**

2.2.2.1 Drivers for remanufacturing

With business volatility due to resource depletion and price fluctuations increasing, the call for new economic models is growing. More businesses have started to explore ways to reuse products or their components and restore more of their precious material, energy and labour inputs through the superior design of materials, products and systems,(Ellen MacArthur Foundation, 2012b). As well as easing material volatility, producers can effectively meet their environmental, legislative and competitive needs by changing their design and manufacturing methods for remanufacture, (Ijomah, 2010).

Remanufacturing is typically cheaper than primary production and increased profits can be achieved due to the reduced material, processing and energy required. The proportion of a product's cost associated to labour might increase but the amount of skilled labour will often reduce, (Ijomah, 2010). A remanufactured product of comparable quality to a new equivalent will require 85% less energy to produce,(Steinhilper, 1998). This can equate to providing a 20-85% production cost saving compared to new product manufacture, (Ijomah, et al., 2007).

Recycling end of life products should be seen as a 'reduction' process, as components are taken and energy used to reduce them back to raw materials. With the highest impacts arising from the raw material production and subsequent shaping in most products, this is then needed again to turn it back into a new product. Remanufacturing therefore has great benefits to offer when compared to traditional recycling models as much of the original manufacture as possible is saved and value added to components with 'addition' processes to bring them back to an as new condition. Energy can therefore be saved twofold by neither destroying nor recreating the component, (Ijomah, 2010).

One area of uncertainty is the quality of traditionally recycled material, often putting designers off using it. Remanufacture negates this problem by maintaining the material in the component where its quality is known. Products that cannot be recycled would traditionally end up in landfill. The remanufacturing of these components diverts this waste from landfill and reduces the need for further non recyclable components to be produced, (Ijomah, 2010).

This ability to maintain the material in its current form and cut cost, can offer a solution to manufacturers competing with cut price, lower quality alternatives, often manufactured in developing countries. Offering a remanufactured product can allow a business to cut cost without quality, which is valued by 'A class' customers who value the reputation of service and brand name above low prices, (Ijomah, 2010). This was the case in the automotive industry, where OEMs meet their customer's demand for low cost replacement components and fulfilled their own warranty obligations through remanufactured parts, (Hatcher, et al., 2011). Another benefit seen by the automotive industry was remanufacturing their own end of life components, reducing the number of cores available to independent remanufactures. This reduced the risk of low quality independent remanufacturers damaging their brand reputation. For the automotive industry, the motives of maintaining market share, supplying low cost warranty components and limiting risk were stronger drivers than ethics, legislation or profit, (Hatcher, et al., 2011). OEMs can also benefit from feedback that can be obtained from end of life cores. These may highlight design weaknesses, and areas for improving durability and reliability in future product design, (Matsumoto, et al., 2011) .

Examples of the benefits that have been achieved through remanufacture in many products and sectors are detailed in Table 2.2. These clearly demonstrate the opportunity to reduce material, energy consumption and waste, leading to cost savings and greater profit.

Sector/Product	Observed Benefits of Remanufacturing
Disposable cameras	82% by weight of the camera is reused or recycled,(Matsumoto, et al., 2011).
Starter motors	New starter motors require 7 times the energy and nine times the quantity of new materials when compared to a remanufactured unit, (Matsumoto, et al., 2011).
Photocopiers	Ricoh, 93% by weight of a typical remanufactured photocopy machine is composed of reused parts, its price is 50% to 70% less than prices of new products, and profits from remanufactured machines are larger than those from newly produced machines, (Matsumoto, et al., 2011).
Caterpillar engine cylinder head	Compared with making a new cylinder head, a remanufactured one requires 61 percent less greenhouse gas, 93 percent less water, 86 percent less energy and 99 percent less material use. This also resulted in a 99% reduction in waste to landfill, (Nasr, 2011).
Electricity meters	In replacing 800,000 electricity meters, a saving of £7 million was achieved by installing 15% remanufactured meters instead of new. A £90,000 saving was achieved via metal reclaim and avoiding waste disposal costs. This demonstrates the clear economic benefit of remanufacture over recycling, (Ijomah, et al., 2007).

Table 2.2 - Observed benefits of remanufacturing

2.2.2.2 Challenges to implementing remanufacture

Despite all the observed benefits, there are still challenges to implementing successful remanufacturing at end of life. These are especially apparent if it is not the OEM conducting the remanufacturing, Figure 2.4.

By far the biggest challenge is the availability of components that require replacing as part of the remanufacturing process. Unless available as customer spares, these may not be made available to an independent remanufacturer. For technical products, specifications might also be required to aid in remanufacturing the product back to an as new condition. It is not in the interest of the original manufacturer to make these available, as competition in the market place would increase. Before any remanufacture can take place, systems need to be set up to recover the cores at end of life. Without having any influence on the product or literature when the product is sold, communicating product recovery options is difficult. These factors all increase the complexity and cost for third parties and discourage them remanufacturing products that might otherwise be viable, (Hammond, et al., 1998).

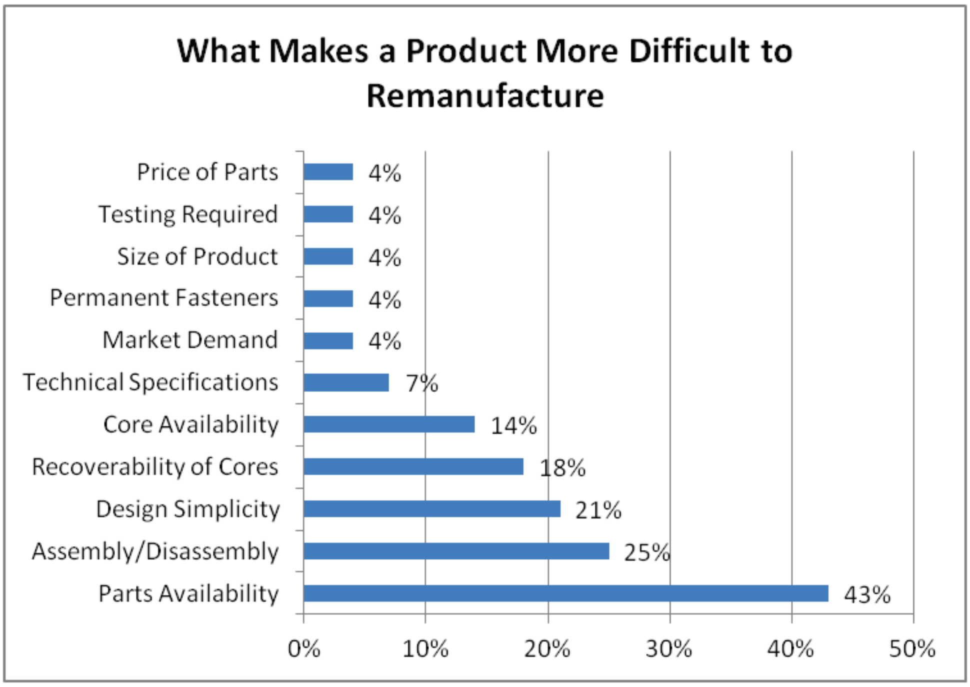


Figure 2.4 - Product remanufacturing difficulties, (Hammond, et al., 1998).

If it is not the OEM remanufacturing the product, then there is also no incentive to optimise the product through design for remanufacture, as the OEM will see no benefit, (Charter, et al., 2007). In some cases where independent remanufacturer is being undertaken, the OEM may even deliberately make the design hard to remanufacture in order to reduce competition on the sale of new products, (Hatcher, et al., 2011).

If it is the OEM undertaking the remanufacturing process then many of these challenges can be overcome. They have the knowledge, data, equipment and access to suppliers and replacement components in order to undertake the process. Intellectual property does not become an issue as it might with an independent remanufacturer, (Matsumoto, et al., 2011). Conflicts can however, arise between efficient assembly processes such as adhesives and ultrasonic welding and efficient remanufacturing processes, (Ijomah, 2010). If it is the OEM remanufacturing the product, there may be benefit in designing the product to optimise remanufacture even if this adds some initial cost, as net whole life savings will be achieved, (Charter, et al., 2007).

Implementing remanufacture can be a costly process whoever undertakes it, with high initial investment and often long paybacks of greater than 10 years, (Matsumoto, et al., 2011). Remanufacturing can also be costly to undertake, with high labour, resources and testing costs, (Ijomah, 2010). Remanufactured XEROX products require double the labour, compared to the manufacture of their new equipment, (Charter, et al., 2007). When materials have a high recycling value, remanufacturing can become less financially attractive, (Ijomah, 2010). As such some OEMs design new products for recycling rather than remanufacture, (Nasr, 2011).

The true meaning of remanufacture is often misconceived by some original equipment manufacturers who often still view remanufactured products as “used” or “old”, (Nasr, 2011). This needs to be addressed with better policing of standards within the industry and description of products in terms of their quality rather than their ‘newness’, (Ijomah, et al., 2007).

From the customer prospective this ambiguity creates a barrier to purchasing remanufactured products. Ambiguity gives the perception of poor product quality and as such, the willingness of the customer to pay for remanufactured products reduces, (Hazen, et al., 2011). There is also currently a prosperous, throwaway culture in existence with a demand for newness that remanufactured products have to overcome, (Ijomah, et al., 2007). If remanufacturers and those who sell remanufactured products are more transparent and explain the rigors of the remanufacturing process, they may convince the public that remanufactured products are ‘as good as new’. The stigma associated with product reuse should reduce and the sale of remanufactured goods should rise, along with a customer willingness to pay more, increasing the profitability, (Hazen, et al., 2011).

Customers also buy into rapid development of technology, resulting in remanufactured components no longer being compatible with newer models. Designing with a modularization strategy across a family of products and for successive generations of components allows for design commonality. Each module can then either be reused or upgraded to a newer revision in remanufacture. Each module could be a single part or an assembly but it is the functionality of the module which should dictate its boundaries, (Kimura, et al., 2001). Where this is not achieved consumers will purchase recovered products only if they are significantly less expensive than new alternatives, (Ijomah, 2010).

For some products however, it is the customer who has driven remanufacture due to criticism of the current wasteful business model. This was the case for disposable cameras where consumers accepted the remanufactured products, with no distinction being made between new and those products that are remanufactured, (Matsumoto, et al., 2011). These are however short life products that customer will have no real connection to before passing them back to the manufacturer to have the photos developed. Aversion to remanufactured industrial products is also often less than towards consumer products, as they are not owned by the individual purchasing them, (Matsumoto, et al., 2011).

It is clear that for remanufacture to be successful, the process of transforming the product back to 'as new' needs to be as efficient as possible. The best way to achieve this is through design for remanufacture. Remanufacture is not currently fully appreciated or widely educated as a design discipline. It is also not seen as a priority issue by many industries or to the normal designer, where traditionally focus has been placed on design for production and use. The principles of design for remanufacture can in some cases be in direct opposition with these traditional focuses, creating conflict and confusion for the designer, (Hatcher, et al., 2011).

2.3 Designing more sustainable products

The decisions made by the designer when designing any product can have widespread impacts around the world; these include where materials come from, how and who extracts them and under what conditions they are working. Designers need to understand the sustainability impacts of the products they design and understand how to develop products which better contribute to a sustainable business, (Bhamra, et al., 2007)

Eco design aims to minimize environmental impacts throughout the product's life cycle, without compromising other essential criteria such as performance and cost, (Pigosso, et al., 2013). It is therefore clear that professionals involved in designing new products are key to designing a more sustainable future, (Lewis, et al., 2001). In the past good design has considered the materials and components used, health and safety, function, ergonomics, style and legislation. Eco design goes further aiming to reduce the impacts at each stage of the product life from materials right through to disposal. The designer may even consider if indeed the product is needed at all, (Bhamra, et al., 2007).

Environmental design only makes up one of the three pillars of sustainability, and designers should also consider society and economics. The social impacts of the product should also be looked at on a whole life basis, from the manufacturer providing employment, to the impacts of industry such as the creation of noise or odour or pollution. The product itself should also have positive social impacts, enriching the life of the user. At the end of life, the disposal of the product should not have a negative impact on the lives of others locally or on a global scale, (Fiksel, 2012). Economic capital refers to the businesses ability to make money. Process reliability, safety and security should be improved. Business continuity and supply chain resilience should be improved and assets better utilised to increase productivity. Reputation and brand should be protected, (Fiksel, 2012).

Considering each stage of the product life cycle in turn, designers should look to design out associated impacts by integrating concepts of pollution prevention and energy efficiency, (European Environment Agency, 1997). Lifecycle thinking helps avoid merely shifting burdens onto any other life cycle stage, (University of Bath, [no date]). Through an iterative design and assessment approach, net savings can be achieved over the whole life cycle of the product.

In order to deal with the growing amounts of waste, it is important that waste minimisation and recovery be designed into the product from the start. This brings responsibility back to the design and manufacturer of the product, Bjerregaard cited in (RRC Training, 2010).

Today recycling is the most common and well understood EOL strategy by designers, but this is far from meeting the goal of sustainable development. With designers having to meet multi criteria requirements, the environment, not being understood, is often considered too complex and easier ignored than time spent only to achieve poor results, (Gehin, et al., 2007). Therefore, if design for EOL is to be successful, there also needs to be tools and methodologies to help designers implement it into the product development cycle.

2.3.1 Design for end of life methods and tools

Designing products so that they can be sustainably disposed of at end of life has always been a key focus of eco design, (Bhamra, et al., 2007). Currently many manufacturers do not have a focus on eco design and as such have considered the problems of waste management someone else’s issue.

The first challenge is defining when to apply which end of life strategy for the product in question. Looking at each product with a whole life perspective will indicate whether the product should have its life extended through reuse or remanufacture or if in fact it should be cut short through recycling. For many products extending the product’s life will reduce its overall impact on the environment, but for some high energy use products extending the product’s life may have a negative effect if newer models are more efficient.

Product durability (physical, emotionally, aesthetically, functionally, technological) will also play a factor in the length of time a product can stay in service. Some technology products have rapid replacement cycles and so designing them for extended life may not be desirable, and when it is desirable the ability to upgrade them becomes important such as through modular design.

The current waste management hierarchy is of limited use in this situation as different products require different hierarchies of product life extension and product recycling strategies, based on product characteristics (i.e. lifespan, technological maturity, resource intensity) and business constraints (i.e. market dynamics, legislation), (Bakker, et al., 2014).

With end of life being such a significant lifecycle stage, engineers need tools for the evaluation of the possible recovery options. These tools need to evaluate and indicate the prospective potential for reuse, recycling and remanufacturing of products, (Gehin, et al., 2007).

The models in literature for selecting the most appropriate end of life option for products currently make a large assumption. They assume that the whole of the product should be designed for the same EOL reprocessing route. When designing for recycling this methodology works, but it becomes a weakness for other EOL routes such as remanufacture. This is because it is unlikely products would be remanufactured in their entirety. It would therefore be more beneficial to consider these products on a component level. The components identified for remanufacture would then be optimised for this process and the remainder of the product would be optimised for recycling. This however does require early identification of the desired EOL route on a component-by-component level by the designer.

2.3.1.1 Design for remanufacture

It is possible to remanufacture products that are not designed specifically for this end of life route, as demonstrated by independent third party remanufacturers, (Sundid, 2004). If it is the original equipment manufacturer or a partnership with a third party that is undertaking the process, there are clear advantages to designing products to be remanufactured if this is the intended end of life route.

The concept of design for remanufacture looks to address many of the technical barriers to remanufacture which relates to how the product was originally designed, (Hatcher, et al., 2011). Ensuring these are not overlooked in design means products complement the remanufacturing process and in turn improve the efficiency in which they can be bought back to a like-new condition, (Ijomah, 2010).

Design for remanufacture considers both the product and the remanufacturing process, (Hatcher, et al., 2011). The RemPro Matrix, Figure 2.5, considers which of nine product properties are important for each of the remanufacturing process stages, in order to simplify and maximise the efficiency of the process, (Sundin, et al., 2008).

Figure 2.5 - RemPro Matrix, (Sundin, et al., 2008)

Of the nine product properties, the matrix identifies four as being particularly significant. Ease of access is the most significant property being important in all but two of the remanufacturing processes. This is because if the ability to easily carry out work is hindered by a lack of access, then the whole remanufacturing process will become less efficient/viable. Ease of identification is important in the four stages where components are being inspected, or information about them recorded. Whilst not listed, it was also felt this property would be important in the reassembly stage of remanufacture. Without easy identification, similar parts may be reassembled incorrectly or time have to be spent distinguishing between them. Ease of handling components becomes important in every stage from disassembly through to reassembly of the product. This is because if parts are hard or fiddly to handle this will slow the process down. Wear resistance is important in all stage where work is being undertaken on the product. This might be in disassembly, cleaning, reprocessing or reassembling the product. This is because if the components are fragile and break they will no longer be suitable for remanufacture and require replacing.

Whilst the RemPro matrix identifies important product properties, it does not however provide guidance to help the designer achieve each of these desired properties. Some researchers have attempted to create specific design guidelines that promote the remanufacturing process and these have been pulled together in Appendix A.

The REPRO^2 (REmanufacturig with PROduct PROfiles) is a tool created for use in the early stages of design. The remanufacturable product profiles consider both the remanufacturing context and remanufactured product properties of exactingly remanufactured products. To create the product profiles successfully remanufactured products were evaluated against criteria such as economy, technology, market, environment, remanufacturing, valorisation, and tests. The positive remanufacturing characteristics were then divided into the two groups, internal (technical properties of the product) and external (properties of the context of the project). These then assist designers by allowing them to compare their design against the profiles. This in turn should result in improving the reliability of remanufacturing as an end of life strategy and products designed with properties that are adapted to remanufacturing.

It was hoped that the $REPRO^2$ will incentivise designers to make a better compromise between remanufacture and other design criteria while designing the product. (Gehin, et al., 2007).

Whilst the $REPRO^2$ does assist the designer in designing products which are optimised to the internal and external characteristics of remanufacture, it does first assume that remanufacture has been identified as is the correct EOL option over straight reuse or recycling for instance. Again the same as the RemPro matrix there is limited assistance for the designer in achieving the desired outcome.

The same as any other design activity, design for remanufacture should also take a whole life approach and not just consider the stages of the remanufacturing process in isolation, (Hatcher, et al., 2011). Design for remanufacture however seldom integrates this approach as it requires 'life cycle thinking' with closed-loop life cycles. Design for remanufacture should therefore be considered as a culmination of two activities. Firstly, definition of the target or desired product characteristics to promote remanufacturing. Secondly LCA should be used to consider not only the remanufactured product, but also the remanufacturing process and the product lifecycle (e.g. number of reuses). (Goepp, et al., 2014). This gives the designer the ability to assess the impact on the product lifecycle of increasing product durability to increase the number of reuses and then estimate the maximum impact that can be added to the component in making it more robust without having an overall negative effect, (Goepp, et al., 2014).

Designing purely for remanufacture has in the past been criticized as a more remanufacturable product that may be inferior in terms of cost effectiveness, environmental performance, manufacturability and assembalability, when compared to a less remaunfacturable design, (Hatcher, et al., 2011). The increased cost associated to design for remanufacture can sometimes be offset against the multiple remanufacturing and use cycles of the product, (Shu, et al., 1999). Economic considerations must however, remain at the forefront of the design process, as there is little point in making a product remanufacturable if it is no longer cost effective, (Hatcher, et al., 2011). Design for remanufacture therefore needs to be considered simultaneously alongside other design requirements and not in isolation, (Hatcher, et al., 2011).

The design for remanufacture models reviewed from current literature offer high level guidance rather than practice ‘how to’ assistance for designers looking to implement design for this end of life route. The first decision that needs to be made by the designer is which end of life option will be applied. Whilst independent tools exist for this, with the design for remanufacture models this initial stage is missed out. There is therefore an assumption that the designer has the required skills to have previously selected the correct EOL option, which may not be the case.

Current design for end of life models traditionally apply one methodology across a whole product. With products rarely remanufactured in their entirety, optimising remanufacturability across a whole product is a weakness in current methodologies.

Desirable product characteristics are specified in a number of models reviewed, but they don’t provide the designer with strategies for achieving the characteristics recommended.

2.3.1.2 Design for recycling

Not all products, or indeed components within remanufactured products, are however suitable for remanufacture and recycling may be the most desirable EOL option. In this case strategies also exist to aid the designer in improving their recyclability. Several guidelines have been developed to aid the designer in improving recyclability of products based on the recycling process stages, these have been pulled together in Appendix B.

For designers to improve recyclability they need to consider both the product and the recycling treatment processes. This poses the first problem as recycling scenarios are different by regions based on the legislation, policy, recycling technology, recycling cost, and required quality of materials in the region,(Umeda, et al., 2013).

One quantitative method developed, quantifies the recyclability of products based on different EOL scenarios. Five performance factors of components were formalised that need to be maintained, Rotational Stiffness, Axial Strength, Yield Strength, Thermal Conductivity and Electrical Resistance. The effect of design, material end EOL processing changes can then be assessed against the recyclability of the product,(Umeda, et al., 2013).

For recycling to be beneficial there needs to be a use for the material generated, impacting on the lifecycle stage of material selection. Replacing virgin materials with post industrial/consumer waste is good option, especially important with non-renewable resources. Recycled materials are however often of a lower grade, presenting a challenge for designers who are used to the well-characterised properties of virgin materials from precise manufacturing processes, (Fiksel, 2012). One approach is to use only virgin materials for critical components and recycled materials for less demanding applications. As well as not compromising the quality of the final product with their potential impurities, recycled materials must also be a cost effective choice, (Fiksel, 2012).

Resource cascading sees a sequence of resource uses, where each time waste is used for a lower quality application. An example of this would be solvents used in degreasing electronics could be used again for degreasing metals once they become too contaminated for their current purpose. Similarly materials can be cascaded where plastics are first used for customer facing parts, then internal structure, before being recycled into a commingled recycling stream. Design for cascadeability has been considered but presents a number of challenges. The main challenge is that it is difficult to anticipate requirements of future cascade levels when designing the first product, (Fiksel, 2012). Where inspiration is required to solve engineering problems, businesses should look to nature where the resilience of natural systems have evolved over millions of years (known as biomimicry). In all cases, materials and energy are transformed generating no waste, only an input to another system, (Fiksel, 2012).

End of life design principles, more often than not, have to be suggestive guidelines rather than hard and fast rules. This is down to the fact that they are in a field that is constantly developing. Setting hard and fast rules is also difficult when sustainability often requires trade offs to be evaluated, with results differing depending on the system being studied. For example, guidelines can often conflict with one another, requiring tradeoffs to be made. Comparing various ‘design for end of life’ requirements in Appendix A & B, it can be seen that they conflict with one another depending on the choices made. Several authors have made note of this and given examples, Table 2.3.

Design for Recycling	Design for Remanufacture	Reference
Design joints for speed of assembly and recycling, such as the use of snap fits.	The product must be disassembled without causing component damage such as snap fits that may become damaged.	(Ijomah, et al., 2007)
Don't cross contaminate components with different materials. Metal inserts in plastic parts for example, will contaminate recycling and may damage plastic reprocessing machinery.	Threads in plastic components can become worn. Screw inserts are favourable in plastic components as they can be replaced when damaged.	(Shu, et al., 1999)
Design for assembly by reducing the number of parts through part-consolidation.	Design in features that indicate component wear. These should be separable, so they can be easily replaced.	(Shu, et al., 1999)
Welding is a good joining method for like materials and won't introduce contaminants when recycled.	Design parts to be easily separable so they can be reprocessed/replaced.	(Sundin, et al., 2008)

Table 2.3 - Examples of conflicting end of life design requirements

Whilst there is often an awareness of eco design strategies among designers, when faced with non-prescriptive rules and conflicting guidance, the use of guidelines can be confusing making application difficult without formal training or education. Strategies for implementing eco design guidelines into design and engineering departments are therefore needed.

2.3.2 Implementing eco design methodologies

Implementing eco design does not have to be complex and many of the benefits can be achieved using tools checklists and rules of thumb, (Lewis, et al., 2001). Product sustainability also needs to be built into the design process and included in "stage gate" reviews. This will promote its importance alongside cost and other design requirements currently considered at review stages. This in turn will make designers more likely to consider eco design and give it a greater influence in developing new products, (Fiksel, 2012). Business that operate environmental decision making in a product lifecycle perspective are still however deemed state of the art. There is clearly a need for environmental decision making, but the methods and tools to assist the process lack application and have a low degree of implementation in ''real life'' industry, (Bey, et al., 2013).

2.3.2.1 Implementation issues

Current approaches to implementing design for remanufacture are laborious, time consuming and poorly applied down to a lack of skill and education in design teams, (Ijomah, et al., 2007). Designers need educating in design for remanufacture. Courses in eco design are limited and design students are not receiving enough training in these areas, leading to a lack of awareness, (Charter, et al., 2007). Design tools such as databases or knowledge-based systems are needed to assist them in integrating environmental considerations into design activities, (Nissen, 1995). These should include quantitative decision metrics to allow the designer to assess different concepts and design to increase suitability for end of life reprocessing, (Amezquita, et al., 1995).

Education must start in design schools and with young designers. Designers must be educated to go beyond what they traditionally consider the boundaries of design and consider the product lifecycle impacts alongside requirements such as cost and functionality, (Walker, 2006). The extent of today's designers' environmental awareness however, is highly variable and more often than not reflects awareness of regulations and the need to comply with them. As such eco-design is in actuality largely confined to maintaining the minimum legal requirements and as such, engagement in sectors such as automotive and electronics, which were influenced by EU Directives such as End of Life Vehicles and Waste Electronic and Electrical Equipment (WEEE), (Deutz, et al., 2012). This regulation has however, driven eco design to focus on design for recycling, rather than the broader consideration of whole life sustainability, (Deutz, et al., 2012).

Larger companies are significantly more likely to consider the environment but design focuses on reduced energy consumption in production, waste, pollution prevention and a reduction in hazardous materials. These are all factors that influence within the factory gates rather than the performance of the product. Design for repair is far more likely for products sold to companies than products intended for consumers. Regulatory and customer requirements are therefore paramount in driving a change towards companies considering eco design, (Deutz, et al., 2012).

As can be seen in Figure 2.6, there are several barriers to manufacturing companies implementing environmental strategies into exiting design/engineering departments with designers who traditionally don't consider the environmental impacts of the products that they are designing.

The most common barrier is in finding relevant environmental impact data in order to base discussions on. The additional work of considering the environmental impacts of designs is also under resourced, and where resource is allocated lacks specialist knowledge. It was also felt that there was a lack of collaboration and sharing relevant information within companies preventing successful implementation, (Bey, et al., 2013).

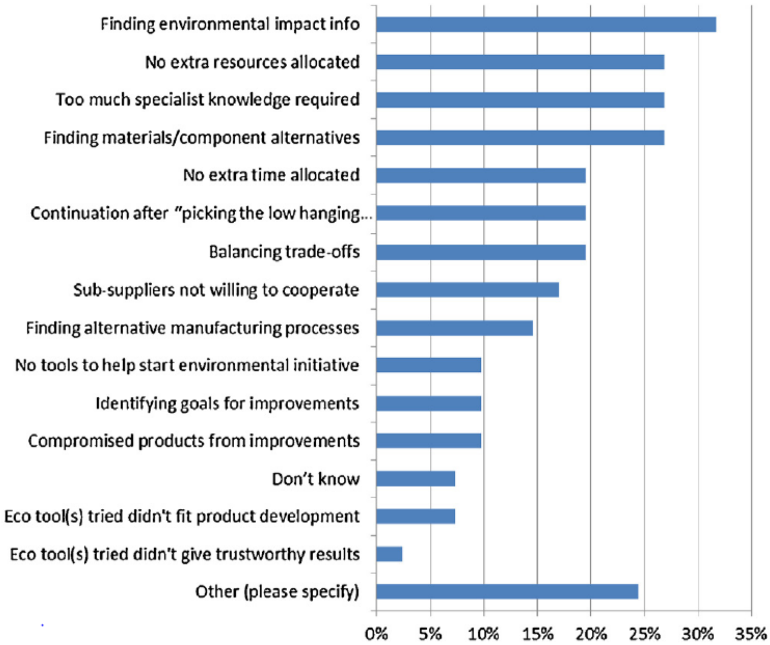


Figure 2.6- Barriers to implementing environmental strategies, (Bey, et al., 2013)

There are currently two lifecycles operating within design and manufacturing companies, Figure 2.7. One looking at the design development cycle and the other looking at the life cycle of the products developed.

Figure 2.7 - Dual Life Cycles Associated with Product Development, (Fiksel, 2012)

Both have different focuses and can distract the designer. The product lifecycle looks to optimise the environmental impacts and the design lifecycle focusing on issues like cost and performance trade-offs, (Fiksel, 2012). Considering and optimising the environment alongside the sheer diversity of these existing pressures, Figure 2.8, is a barrier in itself, being seen as extra pressure for an already stretched design resource, (Knight, et al., 2008).

Figure 2.8 - Diversity of existing design pressures, (Knight, et al., 2008)

In stretched design teams, knowledge of previous design tasks will be brought forward, favouring familiar solutions to problems over revolutionary ideas. This will greatly restrict the possibility of a concept that breaks from current practice and delivers a truly sustainable solution, (Deutz, et al., 2012).

The culmination of these factors is that the strongest focus currently within most design teams is on the design life cycle. Traditionally the focuses of the design cycle are what define the success or failure of a product based on the product requirements. Any conflict between the eco design strategy and customer requirements would usually be over-ruled by the latter. This results in a lack of freedom in applying eco design and a challenge to implementing it as a strategy, (Knight, et al., 2008).

The lack of prescriptive rules around eco design making their use difficult, especially for designers not educated in the field, (Fiksel, 2012). With the wide range of techniques and guidelines that are in existence they are not generically applicable, with some guidelines more appropriate than others in different situations, e.g. Longevity verses recyclability. A level of understanding is therefore needed by the designer.

With a required level of understanding clearly needed to apply eco design successfully, there is often no clear direction as to who on the design team is going to represent the environmental aspects of the product's development. There are three main options available, each with positives and drawbacks, (Dufrene, et al., 2013):

1. A new environmental expert is recruited on the design team to handle this element of the development. The expert brings with them detailed knowledge, but design teams cannot ever expand to bring in experts for every new discipline.
2. Train designers to be multi skilled in different areas of expertise limiting numbers. Whilst designers can represent several disciplines, they will be unlikely to achieve the same level of detailed knowledge as an independent expert.
3. Use tools and methods to integrate environmental knowledge across the team. In reality, these tools often do not achieve the expected performance because of their difficulty to use.

2.3.2.2 Implementation strategies

For eco design to be successfully implemented into a business it needs to be implemented on a strategic perspective. To assist businesses in developing a strategic perspective, eight key elements of consideration have been derived, (Hallstedt, et al., 2013):

1. Ensure organisational support from senior management.
2. Efficiently bring in a sustainability perspective early in the product innovation processes.
3. Utilise knowledge and experience of procurement staff in the earliest phases of the process
4. Include social aspects across the product life cycle and its value chain.
5. Assign responsibility for sustainability implementation in the product innovation process.
6. Have a systematic way for knowledge sharing and competence building in the sustainability field to inform decisions taken in future product development projects.
7. Utilise tools for guiding decisions as a complement for assessment tools.
8. Utilise tools that incorporate a backcasting perspective from a definition of success.

Looking more closely at the design or engineering department there were three general recommendations made by Goepp, et al. Firstly, it is clear that eco design needs to be considered as early on in the design process as possible in order for it to be most effective. Secondly, there needs to be the tools, design principles, rules and standards available and these needs to be effectively implemented. Finally, there needs to be the required information and knowledge appropriately shared within the business requiring cross-functional teamwork, (Goepp, et al., 2014).

Initially when implementing eco design the existing design process should be evaluated and its 'eco design maturity' evaluated against best practice. Once improvement opportunities have been identified and a roadmap developed towards achieving the desired outcome, thought needs to be given to how the implementation will be anchored into the company's business as usual. From this point, continuous improvement methods should be utilised in order to reach higher levels of 'eco design maturity'. (Pigosso, et al., 2013).

Wider engagement with the environment is needed within the company beyond the design department, (Deutz, et al., 2012). Once an environmental strategy has been established it needs implementing into daily business routines around the business. A managerial framework should be developed setting out common language and a description of a shared vision across the organisation, including culture and hierarchical structure and financial modelling. A clear framework to define, evaluate and monitor the performance of the improvement projects should be created with the reporting of key performance indicators (KPIs). (Pigosso, et al., 2013).

Environmental performance indicators should be chosen by the business and aligned with customer needs and corporate environmental goals. Once chosen the indicators should be communicated to engineering and manufacturing staff who are striving to meet operational targets and used to guide product development decisions. Every indicator should have a rigorous quantitative tool or verification method, to assess acceptability, weigh up tradeoffs and guide design decisions, (Fiksel, 2012). A measure such as resource efficiency should be measured over the whole system, not just the product produced. Both upstream (raw materials, producing components and the supply chain) and downstream (distribution, use and disposal) choices can influence the overall environmental performance. This approach will help ensure the needs and expectations of the stakeholders are met in the most resource efficient manner, (Fiksel, 2012).

Clear management structures and business procedures need to be established with senior management agreeing the main direction for product development, assuring that suitable methods and tools are actually used, allocating resources appropriately, and assuring communication through all levels of the organization, (Hallstedt, et al., 2013). The position of an 'environmental design manager' (EDM) should work both on projects and as well as at a corporate level to define the strategy for that particular organisation and record and communicate environmental Key Performance Indicators (KPIs), (Bey, et al., 2013). Eco design should also be communicated out to suppliers, helping to spread the philosophy down to the next tier of businesses. This in turn ensures that not only internal, but externally manufactured components have undergone the same design process and had efforts made to reduce their impact on top line environmental indicators.

Ideally the environmental design manager (EDM) sits as part of the project management team. The EDM is responsible for providing guidance on the objectives and constraints of the environmental elements of the design. They provide guidance tools, which are used on the project by designers to facilitate the knowledge transfer from the environmental design manager to the whole design team. The concepts generated are reviewed by the EDM. Any adaption to the guidance tools can then be made to assist the designers going forward. The different viewpoints of the respective experts in each field should then be viewed simultaneously to develop the final solution, (Dufrene, et al., 2013).

Successful implementation of eco design will have to incorporate it as a discipline amongst the existing design requirements, and not be seen as an additional pressure. (Knight, et al., 2008). To assist businesses in integrating Eco design into their existing product development process, various standards and guidelines have been developed. These are detailed by design stage in Appendix C.

Linking the implementation of these standards and the resulting design process to the businesses environmental management system, ties the design process and the products produced to the business's top line environmental objectives. This generates a greater consistent approach to meeting the business's top line indicators. Design briefs and other project documentation should reference targeted environmental reductions and technical design solutions developed to meet these requirements.

There can be a feeling amongst designers that eco design stifles creativity. It is argued however, that eco design guidelines in requirements can be mistaken for dictating the solution and designers effectively by-passed the divergent design stage. Many of the eco design tools such as LCA are to assist decision making, providing convergence in the design process. Reliance on these tools to improve sustainability, however, results in sustainability being imposed on the design process as a limiting factor rather than as part of the process of developing concepts. Tools such as LCA do not aid the creation of concepts and if the divergent stage of design is missed then choices have to be made between sub-optimal alternatives and true opportunities for innovation are likely to be missed, (Deutz, et al., 2012).

Design guidelines and indicators need to be communicated through training to design teams. These will promote repeatable innovation rather than anecdotal success based on the receptiveness and ingenuity of an individual, (Fiksel, 2012). Where possible they should be integrated into the computing software that designers are routinely using. Whilst this is a rapidly developing field and software does exist, environmentally orientated tools are not as developed as other areas of engineering such as fluid dynamics.

Life cycle thinking needs to be embedded into the product development process. This will ensure that broader consequences are considered rather than just those that apply locally to the design or manufacturing business. Product Lifecycle Management (PLM) software is gaining popularity amongst production and engineering companies to manage a product from conception through to discontinuation. Using the PLM framework to assist eco design, provides a structure and essential functions facilitating collaboration and a focus on the product lifecycle. Collaboration across the various departments of a business is important for eco design as it enables management to identify and evaluate a greater selection of design solutions in order to reach the best whole life outcome for the product. Examples of these are cross-departmental and cross-company processes harmonization, data handling, people, technology and complexity reduction, (Gmelin, et al., 2014).

There is no one-size-fits-all solution to eco design. As such, in each case process specific customisation is needed to suit the eco design needs of the design team. If this is not undertaken then designers may not relate to eco design in the context of their design work, in turn acting as a barrier to adoption. Customisation will firstly be in the form of specifying the right tools and secondly the adaption of these tools to specifically meet the requirements of the design process in question, (Knight, et al., 2008). This customisation will help designers to relate and emphasise with the tools.

Chapter 3 - Defining the Study

3.1 Gaps in existing literature

After reviewing a range of literature, the benefits of product sustainability are undeniable for both the environment as well as for businesses.

Life cycle assessment can help identify the lifecycle stages and product components with the highest impacts and where to direct effort in making reductions. Using LCA in early product development where it could have the largest impact on the design of the product is however difficult with too many variables outstanding to achieve detailed results.

Considering the product lifecycle there are environmental impacts that act upon each stage. Of these, end of life represents one of the biggest opportunities for reducing the product's whole life impact. Designing for lifecycle circularity is important to ensure that resources are recovered and reused at end of life in the most beneficial fashion.

Remanufacture is the only end of life reprocessing option that returns the product to a 'like-new' condition without first destroying the component itself. The remanufacturing process can present challenges to the remanufacturer both technically and economically if products are not optimised for the process. These challenges can be reduced by designing the product with the remanufacturing process in mind. Design models exist offering high level guidance to the designer on selecting the most desirable end of life route, and desirable characteristics for optimising the design. Engaging the designer with these tools and successfully implementing them into the existing and familiar design process is however difficult.

Gaps have been identified in the current literature surrounding design models for optimising products for end of life:

- Despite whole products rarely being remanufactured in their entirety, current tools tend to apply the remanufacturing philosophy across the whole product rather than consider them with a component- by- component perspective.
- The current guidance is all high level support offering overviews, not detailed practice advice on how to achieve the desired design outcome.
- No models have been found to initially select the desired EOL route for a product and then go through to helping the designer optimise the design of that product. These stages tend to exist in separate models.

- Whilst optimisation tactics such as ‘durability’ are given in design for end of life models, these are not expanded to aid the designer in how to achieve these.
- The more detailed guidance that is available in some guides, offers non-descriptive design rules, which can conflict with one another depending on end of life route chosen. There is only limited guidance on when to apply which rules, with the potential to lead to confusion.

With limited knowledge of design for end of life existing in most design departments, these gaps will hamper optimisation of products for end of life.

3.2 Defining the Study

The aim of this research was to identify and evaluate methods for improving the sustainability of electro-mechanical products, focusing on improving the product through design, for end of life reprocessing

3.2.1 Research question and proposition

In order to help fill the gaps identified in the literature review, the following research question has been raised:

How can the environmental impacts of electro-mechanical products be reduced by considering them on a component level and designing them to operate over multiple lives without increasing cost or reducing quality?

It was proposed that this study would show that if products were considered on a component level, end of life reprocessing back to a like-new condition could be optimised. This would bring significant environmental savings, as well as lower production costs for future product lives.

3.2.2 Research objectives

To fulfil the above research question, the following objectives were set:

1. Review current literature to identify current methodologies and guidelines for improving the sustainability of electro-mechanical products, maximising the recovery of assets at end of life and tools to aid the designer in creating more sustainable products from the outset.
2. Conduct a case study undertaking a comprehensive life cycle assessment on an electro-mechanical product, to highlight the lifecycle stages and component parts with the highest environmental impacts.
3. Review options for recovering electro-mechanical products at end of life to make maximum use of these assets.
4. Conduct a case study undertaking the chosen reprocessing option, highlighting the potential benefits to the product lifecycle and reprocessing issues that arise.
5. To develop a framework to aid designers in improving the suitability of electro-mechanical product for end of life reprocessing, whilst still in the new product introduction process.

3.2.3 Novelty and original contribution

This research brings together and builds upon much of the existing knowledge in design for end of life, particularly when considering remanufacture. It provides a framework which assists designers in predetermining a lifecycle, in order to achieve the best possible outcome for each of the product's components at end of life.

The methodology breaks from current literature in a number of distinct areas:

- A strategy was devised using the available life cycle assessment data, along with other drivers such as cost to select components from a product specifically for remanufacture or recycling in the design phase.
- The framework offers a practical approach to design for end of life, which was intended to aid designers in optimising products for end of life, even if they were not skilled in the knowledge of eco design.
- How-to guides within the model were provided to assist the designer with achieving the desirable characteristics for both remanufacture and recycling.

The outcomes of this research will help the designers of electro-mechanical products to meet the challenges and environmental demands of today's commercial world. The interpretation of the data in this framework demonstrates how LCA can not only be used to assess the environmental impacts of a product, but can also be used iteratively in a cross disciplinary fashion around many aspects of the business, guiding decision making. It is anticipated that using LCA and cost to target effort in this way will improve the efficiency of sustainable business, whilst still achieving significant environmental savings.

3.3 Study Methodology

3.3.1 Case study methodology

A case study approach was chosen for this research. The definition of case study research is defined as an empirical research method used to investigate a contemporary phenomenon focusing on the dynamics of the case, within its real life context, (Yin, 2014).

The justification for using this methodology is routed in the fact that it is not possible to control the behavioural events and manipulate these (as in an experiment) when looking at the lifecycles of products, which are also in every case unique. With much of a product's environmental impact being defined in the design phase of life, there may also be contextual conditions between the product's design and the design process that created it. These could not be replicated or the two contexts separated as would be required in other research methodologies.

The case study is therefore an appropriate method for investigating the contemporary, real world challenge of creating more sustainable products within this research.

3.3.2 Research plan

Figure 3.1 lays out the structure of the study and thesis.

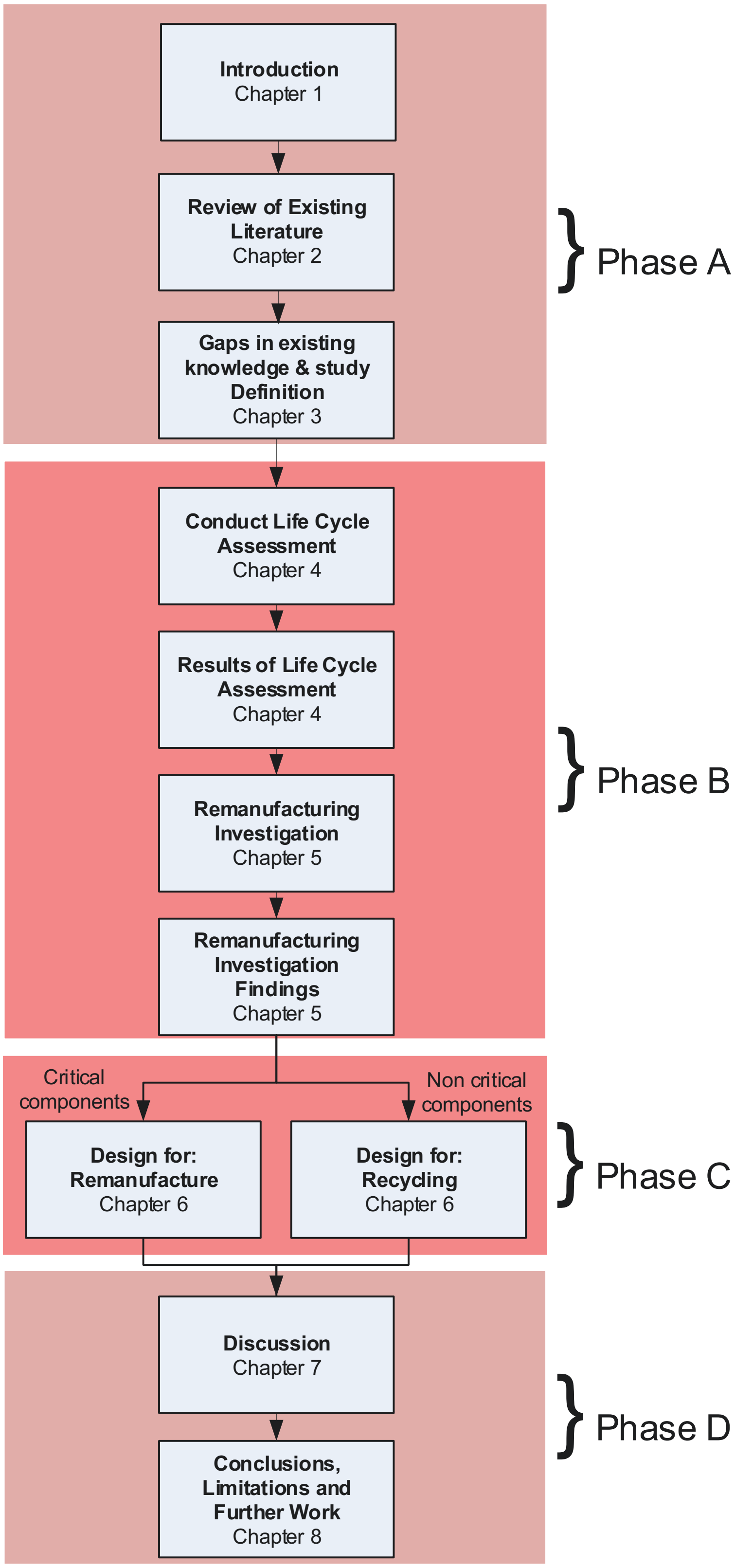


Figure 3.1 - Structure of work undertaken

The review of existing literature (Phase A) highlighted the gaps that existed within current literature. Consequently, a programme of practical work was undertaken to better understand how considering electro-mechanical products' design on a component level might improve their end of life optimisation, ideally without increasing cost or reducing quality.

The first phase of practice work, a case study (Phases B), was to undertake a full lifecycle assessment on one of Stannah's products. The results from this highlighted which phases of life had the highest impacts and in which components the greatest scope lay for making improvements. The second stage of the case study looked to reduce the impacts of the product through better recovery at end of life. This was done by remanufacturing the stairlift and assessing the benefits of doing so on whole life CO_2e and cost.

The final stage of practice work (Phase C) was to develop a design framework to aid the designer in developing products that are optimised for end of life recovery. This was based on splitting them into critical and non critical groups and applying appropriate design philosophies for each.

The outputs from the case study and practice work were then used to evaluate and discuss the findings in relation to the previously reviewed literature (Phase D).

3.4 Unit of Analysis – The Case

The Unit of analysis for the case study in this research will be the 260SL Stannah stairlift, which is thought to represent a typical electro-mechanical product.

3.4.1 The Stannah 260SL Stairlift

Figure 3.2 - 260SL Stannah Stairlift, (Stannah Stairlifts Ltd, 2014)

The Stannah 260SL stairlift, Figure 3.2, was released in 2001, designed to meet the curved staircase segment of the market. The stairlift consists of a chair, carriage and footrest which travels up the staircase on a fixed rail.

Sold into every one of Stannah's markets, 13,000 units are sold annually (2013 data). The 260 model was selected for this work as it is expected to have a higher environmental impact than the straight stairlift models, due to the bespoke nature of the curved rail.

There are a number of chairs in Stannah's range that can be added to the 260 carriage. The SL chair used in this study was developed in 2005, but not made compatible for the 260 carriage until 2006. Five thousand units are currently sold per annum (2013 data). This chair was added to the range to offer the customer a premium product with enhanced aesthetics, features and benefits. This chair was chosen as it was expected to have the greatest environmental impacts in the Stannah range. This is due to the large aluminium castings that makes up the majority of the chair's structure.

The product travels up and down a rail which is fixed to the staircase. The rail is a twin tube design, which mechanically levels the product by varying the distance between the two rails. With the rail designed to exactly fit the staircase in each instance they are bespoke products.

Product Specification:

- Max load capacity: 135 Kg.
- Speed:0.12 m/sec.
- Warranty: 24 months (motor gearbox 60 months).

There is a large second-hand stairlift market for carriages and chairs. For Stannah to resell products they must be under five years old and have been maintained by Stannah with a service contract. Rails are recycled when removed from a property and cannot be reused due to their bespoke nature.

3.4.2 Stannah's new product introduction process

The new product introduction (NPI) process operated by Stannah is shown as a flow diagram in Figure 3.3. The NPI process is broken down into three distinct phases, Concepts, Engineering and Pre production.

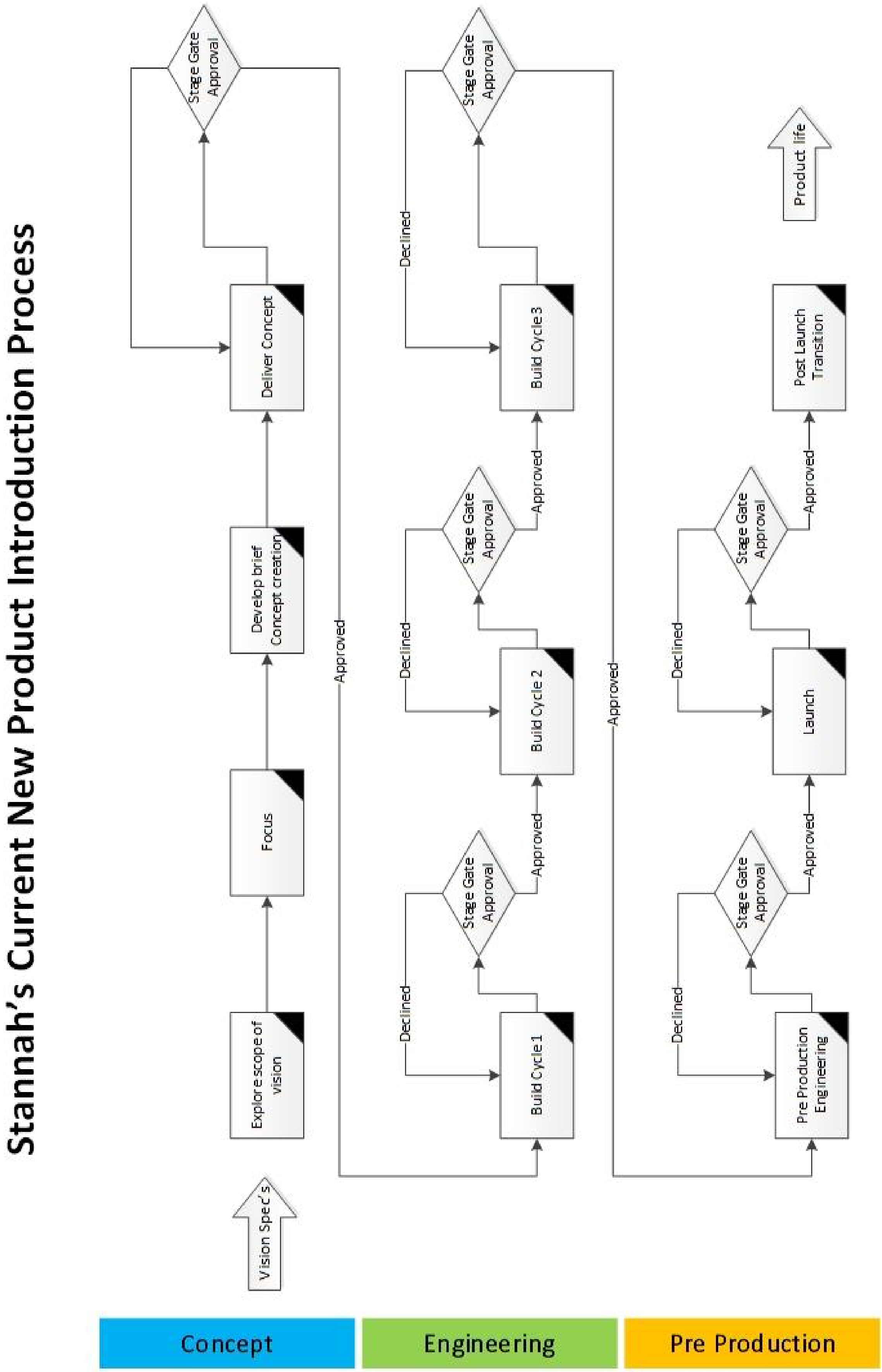


Figure 3.3 – Stannah's current NPI process

The Concepts stage of the process begins with a vision specification produced by the Product Marketing Department. This specification is explored, defining the scope of the project and planning research and testing requirements. Next the project is focused after conducting research, and testing insights. Following the research, a product brief and specification is developed and concept creation and selection takes place. The final stage within Concepts is concept development and testing and delivery of a design ‘proof of principle’ to take forward. The first stage gate review then takes place and if approved the concept moves forward into Engineering.

The Engineering stage of the NPI process is made up of three build cycles. The first cycle resolves any snags from the stage gate review and develops the product to a point where soft tools are used to create a bare product (no covers) in an engineering environment. This is then used for life and fatigue testing of all major components. The second build cycle is to create the product in a production environment off jigs where possible. All snags from the first build cycle must be resolved. Early iteration tooled parts are used to create a product for further life and fatigue testing. The final build cycle, resolves the snags from the previous build. Final tooled parts from the correct supplier are used and batch production is undertaken. Life and fatigue testing must be passed with no more than routine product servicing. The design is frozen and the engineering change note (ECN) is released.

After the release of the ECN, the product moves into pre production when component orders are placed to stock the system with parts. A full order fulfilment trial is undertaken and test shipments made. Finally, the launch readiness review takes place and pending approval the product is available for sale.

3.4.3 Relating this research to Stannah's current position

Relating the reviewed literature back to Stannah Stairlifts, the whole life of products are not considered currently, and the business model would be considered more linear than circular. It is thought that the linear system is at least partly driven by the structure of the Stannah group, where-by one business is responsible for the design and manufacture of the stairlift. This is then sold on to a sister service company that sells and maintains the product. As with all systems designed to pass product in one direction, this hinders the ease of return flows or circular business models.

With a lack of lifecycle thinking, no prior lifecycle assessment had been conducted by Stannah on any of their products. A review of the available literature has found no evidence to suggest that any assessment has ever been carried out by, or on behalf of, any other stairlift manufacturer either.

Currently Stannah is reconditioning products, which meet a stringent set of requirements for reuse in a second hand market. Only those components necessary to maintain the product in working order are replaced as part of this process. Products are not returned to a like-new condition, as they would be in remanufacture, resulting in an inferior product offering. Products not reused are recycled where material choice permits and landfilled where not.

A report into local authority procurement highlighted stairlifts, among other products, as a potential area where buying remanufactured products may be advantageous, (Centre for Remanufacturing and Reuse, 2011). Stairlifts however, scored badly in their analysis, due to the perceived lack of industry readiness to deliver a remanufactured product. With a potential market for remanufactured stairlifts not being fulfilled, there is the potential for new business models in this area.

Stannah's engineering department currently show little consideration in the design process for whole life thinking on environmental grounds. The sustainability of concepts does not feature in product requirement documents or form part of the design review processes, such as at stage gate reviews. It is thought that there is currently a lack of understanding and little to no application of whole life eco design philosophies. Historically, with the reuse of products sitting with the service division of the Stannah group, design optimisation for reuse has not been in the forefront of the designer's mind working within the manufacturing company.

Chapter 4 – Life cycle assessment of Stannah's 260SL Stairlift

The initial phase of this study was to conduct a life cycle assessment using a Stannah 260SL Stairlift as a case study. It was possible to see which life cycle stages have the largest environmental impacts. The results were also broken down to explore which of the product's components contributed the most towards the overall environmental impact.

4.1 Defining the Scope and Methodology of the Study

The flow diagram, Figure 4.1, produced by the author, indicates the stages of the LCA undertaken and discussed in this chapter. The blue arrows represent the iterative nature of conducting life cycle assessments.

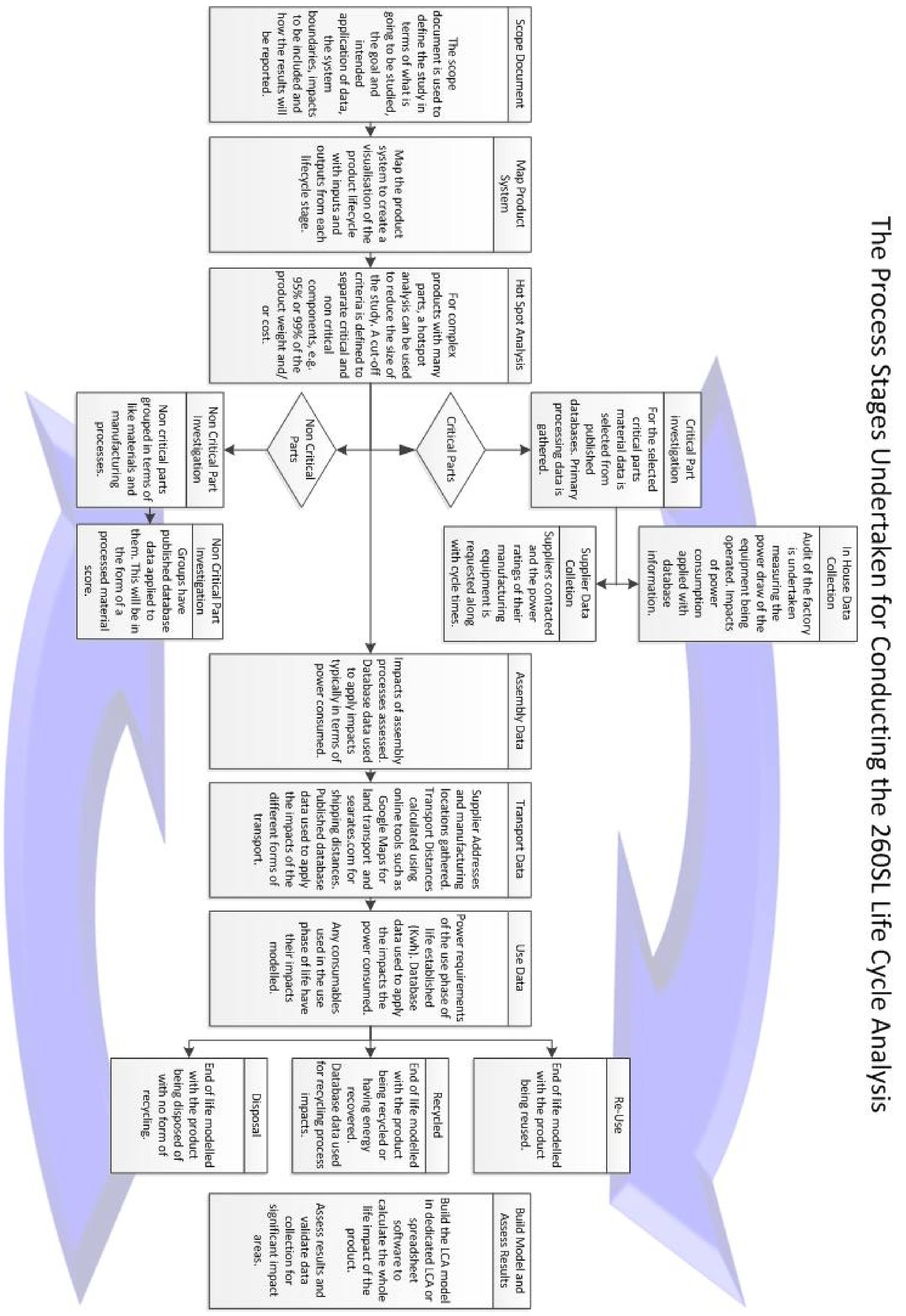


Figure 4.1 - Flow diagram of LCA process stages

4.1.1 The product system

The product system being studied in this assessment is Stannah Stairlifts standard 260SL Curved Stairlift. The stairlift is made up of the following modules (weight includes all associated packaging), Table 4.1:

No.	Stairlift Module	Mass
1	260 carriage	39Kg
2	260 manual swivel chair	19.5Kg
3	Upholstery	3.96Kg
4	260 footrest assembly	4Kg
5	260 carpet	0.13g
6	SL seat belt	0.34g
7	Batteries (X2)	2.50Kg each
8	Charging kit	0.88Kg
9	260 infrared controls	0.56Kg
10	260 rail (per m)	12Kg
11	Rail kit box (6m rail)	8.25Kg
12	Labels kit	0.01g
13	Handbook – 6x A4 double sided pages	0.04g
14	Installation Manual – 96x A4 double sided pages	0.26g

Table 4.1 - 260SL product modules

4.1.1.1 Product function

Stannah offer premium products to the stairlift market that are reliable, durable, safe and aesthetically pleasing. The 260 stairlift fulfils a number of different functions to the customer:

- A mechanical chair that transports the user up and down stairs.
- A mechanical aid that can be used to carry a load up and down stairs.

4.1.1.2 Functional unit

The functional unit for this study was based on a standard 260 Curved Stairlift manufactured in 2009, with maximum load capacity of 135 kg and a lifetime of 20 years.

Much of the stairlift is the same for every contract sold. There are however, some stairlift modules such as the rail which are bespoke with the size and shape of the module being dependent on the customer's property and therefore needing to be defined. The level of use was also defined as a product installed into. For example, a nursing home would have a far higher level of use than a product installed in a private residence. It was decided that a typical private residence would be studied; which required an average rail length of 6m including one

90 degree bend. It was estimated that, on average, products in a private residence made 14 journeys a day, either up or down the stairs and are installed for four years.

At end of life the stairlift could follow a number of different routes. These can be characterised as sold on into a second hand market, recycled or sent to landfill. It was decided that scrapping the product into a recycled waste stream, where ever material selection permitted, would be the most likely end of life route after four years. This is due to the expiry of the warranty on the motor gearbox preventing reuse in a second hand market, (Stannah Stairlifts Ltd, 2010).

Defined of functional unit:

One standard 260SL stairlift manufactured in 2009 with a maximum load capacity of 135Kg and a maximum life of 20 years. The product will be used for 4 years in the UK, after which it will be recycled. The product will make 14 journeys per day (being either up or down the stairs) travelling along a six meter rail with one 90 degree bend.

4.1.1.3 System Boundaries

There are currently no Product Category Rules (PCRs) for the assessment for stairlifts. The LCA considered the whole life of the product from raw materials in the supply chain, to the product's disposal at end of life including associated impacts as depicted in Figure 4.2 (produced by the author).

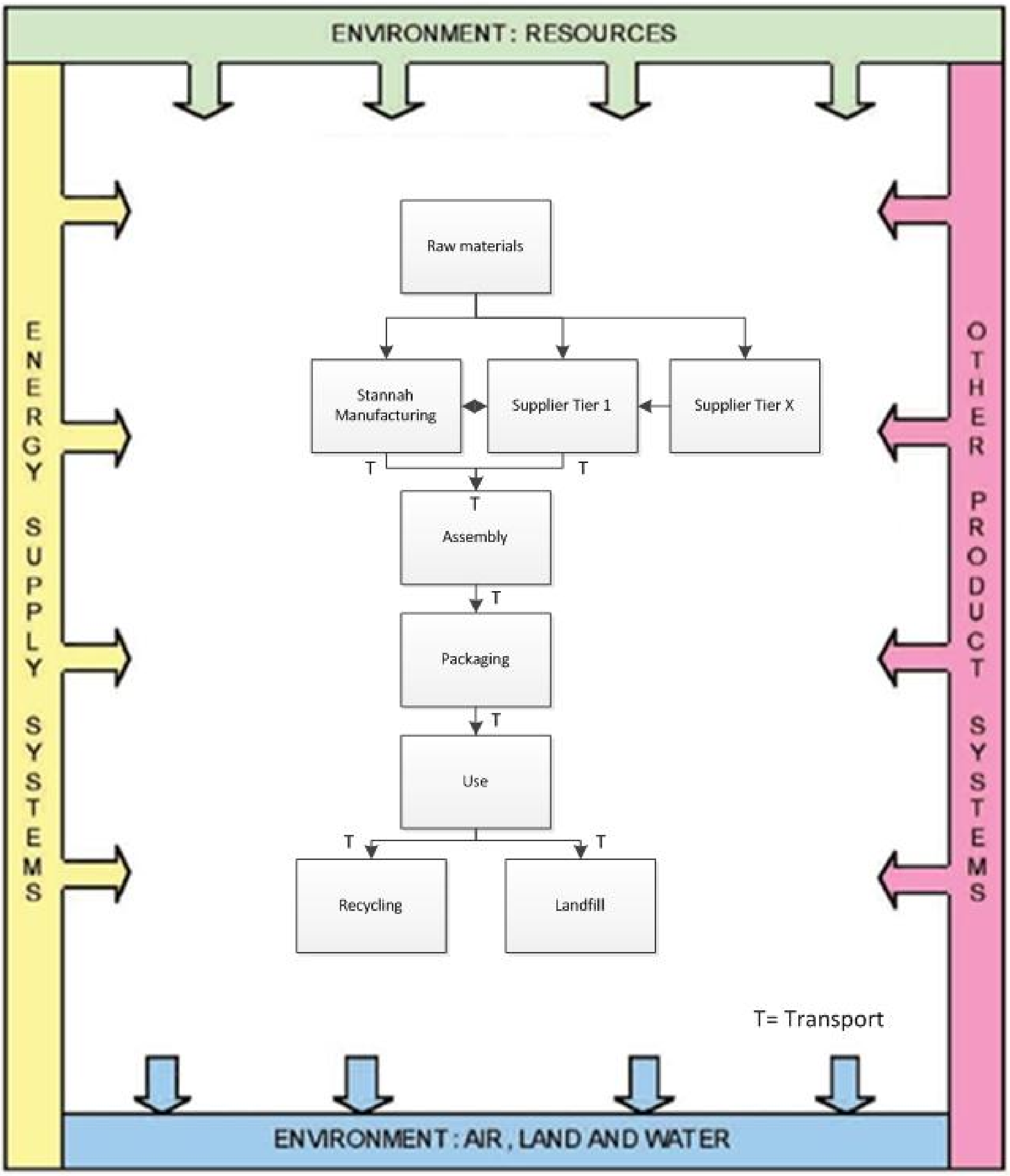


Figure 4.2 - System boundary diagram

Raw materials and components entering Stannah have either had their impacts provided by the supplier or have been worked out using the total inputs/outputs the whole production process. Components manufactured in-house have had their individual processes modelled.

Transportation of the product and components was modelled. Due to the varying transport distances to the end user, an average figure was generated for business activities within the United Kingdom. Packaging was included within the study and its impacts assessed.

The use phase of the product was four years in line with the average time in the first address. Maintenance schedules were not included as these are an extra that can be purchased on top of the basic product sale.

At end of life the expected disposal route for the product was for it to be removed by a Stannah engineer and then recycled/landfilled depending on the material.

In accordance with PAS 2050 (British Standards Institute, 2011) the emissions associated with the production of capital goods were excluded from this study.

4.1.2 Assessment Methodology

A consequential LCA was performed so that the impact of changes made to the product system later on in the study could be evaluated against the current performance.

The study was performed in accordance with PAS 2050 and captured the full lifecycle of the 260SL stairlift using a consequential life cycle assessment. This assessment encompassed raw materials, manufacturing, transport, use and disposal of the product at end of life. Each of these lifecycle stages have had inputs and outputs modelled and the impacts of these assessed. This built up a picture of the product's overall environmental impact.

4.1.2.1 Recycling Methodology

It was assumed that primary material was used for the manufacture of the stairlift. Recycling credits were applied at end of life for the components that are recycled. It was felt that building the model in this fashion (and not including the recycling credit in the raw material) would better demonstrate the impact of different end of life options.

4.1.2.2 Allocation

Where allocation of impacts was required, the inputs and outputs to the system were split between the different products produced, transported, etc. This was done to reflect the true proportion of each product produced in terms of the most appropriate measure, be that time, mass or financial value.

4.1.2.3 Hotspot analysis and Cut-off criteria

Whilst the study endeavoured to assess the whole product thoroughly, critical components that make up the largest impacts were identified and these were assessed in the most detail. An initial hot spot analysis was undertaken using database data, to gain an understanding of where the largest material impacts lay. The results for each of the stairlift main modules

(Carriage, chair, footrest, kit box and rail, Table 4.1) were assessed separately and components were highlighted as critical if they:

- Make up >5% of the CO_2 in all metal components.
- Make up >5% of the CO_2 in all plastic components.
- Make up >5% of the cost.
- Were thought to have a significant impact on the environment.

The components that were excluded in this process (make up <5% of the above criteria) have still been included in the study but in significantly less detail. Each was assigned a category which when combined with their mass, give an approximation of their impact. The chosen categories for non critical components were based on the most likely component scenario after examining the product, Table 4.2.

Category	Description	Kg CO_2e /Kg
Metal Deformation	Steel deformation	2.98
Metal cast	Aluminium cast	13.4
Plastic Moulded	ABS moulded	4.56
Plastic Extruded	Nylon extruded	5.92
Paper/board	Card	1.32
Fixings	Steel deformation	2.98

Table 4.2 - Non critical component categories

4.1.2.4 Impact categories

The impact category considered in the study were limited to Global Warming Potential (GWP). This was measured in the form of Carbon Dioxide Equivalent (CO_2e) focusing on the following emissions and conversion factors, Table 4.3:

Emission	GWP conversion factor
Carbon Dioxide	1
Methane	21
Nitrous Oxide	310

Table 4.3 - CO_2e emission factors considered, (DEFRA, 2010)

4.1.2.5 Data Quality Assessment

Primary data collection

Stannah was able to provide much of the manufacturing process data needed for this study. A complete 260SL stairlift was broken down into individual components, each having their material, mass and manufacturing methods recorded.

The power consumption of in-house manufacturing equipment was measured using an inline power meter. An average was then taken from several hours operation to take into account the warm up and cool down phases of operation. The manufacturing time for each operation was already known at Stannah on a component-by-component basis. The waste generated in manufacture was worked out using the punch and the laser cutter programs.

Several of the manufacturing processes require compressed air. Stannah has two air compressors of different sizes which run alternately. The larger of the two compressors was measured and used for this study. It was not possible to measure the consumption of compressed air for each operation, so total power consumption for the compressor was divided by output of the factory in the same given period of time. This allowed an estimation of the compressed air per product to be determined and applied as a single impact within the model.

Stannah operates an in-house paint plant to paint all but the rail sections (which are painted externally). The electricity consumption of the paint plant was again measured using an inline power meter. An average was again taken over several hours operation. The gas consumed by the paint plant could not be measured directly so an average over three summer months was taken from the utility bill as there was no heating requirement over this period in the factory. This was divided by the output of the corresponding months.

Understanding the impact of externally manufactured components required the engagement of the supply chain. An initial investigation showed that suppliers were unlikely to have a depth of knowledge in LCA and were stretched in terms of resources to carry out this work. Suppliers of critical components were asked to provide the following information for each phase of manufacture:

- Equipment manufacturer and model number.
- The operating energy consumption.
- Time taken to produce a batch.
- Waste produced through the manufacture of this batch and what happens to this waste.
- The number of units in this batch.

In many cases the operating energy consumption of the manufacturing equipment was not known and could not be measured, as the company did not have the resource to install an inline power meter. In these cases, the maximum operating power was taken from the equipment literature. These values will likely over estimate the actual operating power as there is often a spike in power consumption as machines get up to temperature which then drops off and levels out.

The assembly cells at Stannah for the carriage, chair and footrest had their energy consumption recorded using an inline power meter. An average was taken for several hours operation and then divided by the output of that cell. Suppliers deliver many of the components on the cell in transit packaging. This was weighed for each cell in terms of mass of plastic and cardboard and divided by the day's output.

International supplier transport distances were calculated from the closest port to the manufacturer to the closest port to the UK supplier. Shipping distances were worked out using the Searates.com website, (Searates.com, 2010). Road transport distances were calculated using Google maps, (Google, 2010).

Sources of third party / Life cycle inventory data

Where primary data was not available, life cycle inventory (LCI) data was used. LCI data was collected from several sources, Table 4.4. These are ordered in term of the data's perceived quality. The most accurate CO_2e data was used where available. Where it was not, CO_2 data was substituted.

Life Cycle Inventory (LCI)	**Quality (5 high- 1 Low)**	**Impact category**	**Data used**
World Steel Association	5	CO_2e	Material
World Aluminium Institute	5	CO_2e	Material
European Life Cycle Inventory (ELCD)	5	CO_2e	Material
DEFRA DECC	5	CO_2e	Energy Transport
Ecoinvent	5	CO_2e	Material Process
CES Materials and the environment	3	CO_2	Material
Greet 2	3	CO_2e	Material
Bath inventory of carbon and Energy	3	CO_2 & CO_2e	Material
LCA Calculator	3	CO_2	Material Process
Mortimer, N, et al. (2009)	2	CO_2e	Material

Table 4.4 - Life cycle inventory (LCI) data sources

Assumptions made

Where data could not be collected or variables needed to be set, assumptions had to be made. The assumptions made throughout this study are detailed below:

- Stannah's average staircase dimensions of six meters long with one 90 degree bend is a fair representation of the average staircase.
- A 4 year service life is a fair representation of the time at any one address.
- 5110 trips taken per year is a fair representation of average use.
- The stairlift has not had a service contract taken out.
- The product is sold from the Stannah factory in Andover rather than transported to an instillation branch first.
- The rail is manufactured in the UK.
- Shipping was always between closest ports to manufacturer and supplier and the road transport took the most direct route.
- Vehicles were returned empty unless otherwise stated and were only delivering to Stannah.
- The customer lived 100Km away from Andover.
- Average power consumption of manufacturing equipment was representative of the manufacturing process for the specific component in question.
- The stairlift remote batteries will require one change in a 4 year period. Actual longevity is based on use patterns.
- Non critical part categories are a fair representation of the parts they are assigned to.

Quality, Representativeness and Sensitivity of data

The data in this study has been represented in an open, comprehensive and understandable form, that does not look to hide or misrepresent the system being studied. Completeness checks were used to try and ensure that the data collected represented the full system being studied within the system boundary. Where data was not available the closest available data was used. Sensitivity analysis was used on any assumptions made throughout the study to qualify their impact and to ensure that they did not significantly affect the overall results.

4.2 Mapping the product system

The product lifecycle was mapped, Figure 4.3, plotting the product flow along with all the process inputs and outputs for each lifecycle stage. The process flow diagrams generated were used to not only understand the full product system, but also direct where data needed to be collected in order to conduct the life cycle assessment.

Process Flow Diagram Key for Figure 4.3:

- Black Lines- Product flow
- Red Lines – Electricity
- Orange Lines – Gas
- Blue Lines – Compressed air
- Green Lines – Recycling
- Brown Lines – Landfill

To allow greater clarity and analysis, Figure 4.3 was split up into the major lifecycle process stages, Appendix D.

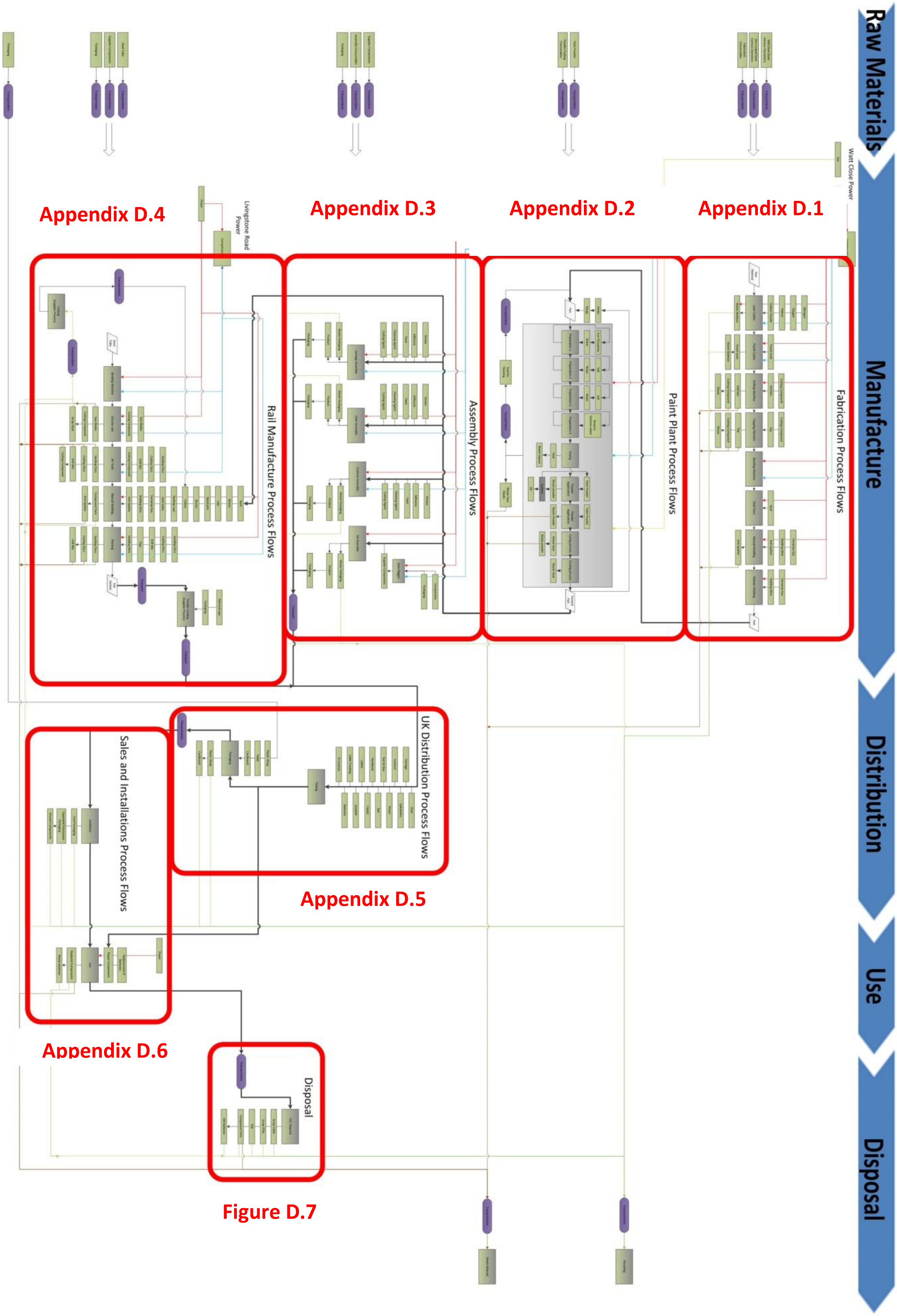


Figure 4.3 - Stannah 260SL stairlift lifecycle process map

4.3 Performing the Hotspot analysis

To narrow down the data collection requirements of the full study, a hotspot analysis was carried out. This determined which components in each stairlift module, would be most significant to the outcome of the study and should therefore be allocated the most data collection resource.

The initial investigation indicated that the 260SL stairlift consisted of over 600 components. In the allocated time, this number of components was too great for a full life cycle analysis on the whole product. To reduce the size of the study, a number of options were considered along with the impact each would have on the validity of the assessment, Table 4.5.

Component selection criteria	No. of components left to be assessed	Advantages	Disadvantages
Exclude the fixings from the study	441	Would maintain a high level of detail in the study	No significant reduction in data collection required
Only assess Stannah's internally manufactured components	127	Successfully cuts the scale of the data collection and does not rely on third party involvement	Would not be a fair representation of the whole product, as Stannah only fabricate the steel components
Assess anything greater than a 5% mass cut off criteria	5	Provides a clear criteria for selection	Narrows study too much to provide detailed results
Assess 80% of the cost (£) cut off criteria	14	Provides a clear criteria for selection	Narrows study too much to provide detailed results

Table 4.5 - Initial component selection options for the LCA hotspot analysis

None of the initial selection criteria fitted the requirements to reduce the size of the study whilst still maintaining sufficient clarity of data.

It was decided that a hybrid approach would be taken using a cut off criteria of >5% in each case, but with multiple selection criteria:

- Make up >5% of the CO_2e in all metal components.
- Make up >5% of the CO_2e in all plastic components.
- Make up >5% of the cost.
- May have a significant impact on the environment.

After performing a basic LCA on the product bill of materials (BOM), approximate component CO_2e impacts were known. Components were selected from each stairlift module if they made up 5% or greater of the plastic CO_2e, metal CO_2e or cost. Any components that were not highlighted and selected, but were thought to be environmentally significant, were also included so they were not overlooked. An example of this would be the electronic components within the stairlift, which were known to have significant environmental impact but were not highlighted under cost or metal/plastic content.

4.3.1 Results of the Hotspot Analysis

The hotspot analysis identified significant components from the carriage, chair, footrest, kit box and rail and the proportion of each selection criteria they make up, Table 4.6 to Table 4.10 respectively.

Carriage Components Selected as Critical	% Total Metal CO_2	% Total Plastic CO_2	% Total Cost	Env. Significant
260 CARR-WELDED ASSY PEARL	30%			
SKATE ASSEMBLY (MECHANICAL)	30%		16%	
CLUSTER HOUSING (CAST VERSION)	5%			
COVER-SAFETY PAD-PEARL-260		36%		
FRONT COVER-260 CARRIAGE-PEARL		22%		
SKATE-FRONT RUBBER		10%		
SAFETY PAD-SKATE ASSY-PEARL		8%		
PINION SHROUD-LH-PEARL		8%		
PINION SHROUD-RH-PEARL		8%		
MOTOR/GEARBOX 250 MK11			33%	✓
PCB 260 CONTROL ASSY COMMS			8%	✓
260 SL CARR P/FOOT MOTOR+ LOOM			5%	✓
LOOM 260 CLUSTER				✓
LOOM 260 SKATE				✓
LOOM 260 CARRIAGE SAFETY PAD				✓
SL LOOM-CARRIGE TO CHAIR				✓
LOOM 260 HWND SWCH TO ISO SWCH				✓
260 CARRIAGE POWER LOOM (CEN)				✓
400/260 SL POWER FOOTREST PCB				✓

Table 4.6 - Hotspot selected components from the 260 carriage

Chair Components Selected as Critical	% Total Metal CO_2	% Total Plastic CO_2	% Total Cost	Env. Significant
SL CHAIR-CHAIRBACK CASTING	30%		28%	
CHASSIS, WELDED - MAN SWIVEL	30%			
260SL CHANNEL TOP M/SWIVEL	12%			
HINGE M/C SL CHAIR	6%		8%	
ARM MACHINED R/H SL CHAIR	5%			
ARM MACHINED L/H SL CHAIR	5%			
SWIVEL COVER		27%		
ARM, EXTENSION, MOULDED		11%		
ARM EXTENSION MOULDED		9%		
LINK BAR PEARL SL CHAIR		7%		
ARM TOP MOULDED-PEARL		6%		
ARM TOP MOULDED-PEARL		6%		
260 SL CHAIR MANUAL SWIVEL LOOM			11%	✓
POD ASSY			9%	
400/260 SL CHAIR ARM PCB ASSY				✓

Table 4.7 - Hotspot selected components from the SL chair

Footrest Components Selected as Critical	% Total Metal CO_2	% Total Plastic CO_2	% Total Cost	Env. Significant
FOOTREST CASTING 260	79%		55%	
STIFFENER SAFETY PAD (CEN)	15%			
SAFETY PAD-FOOTREST-PEARL-260		14%	10%	
SAFETY PAD EXT LONG LH PEARL		83%		
260 FOOTREST LOOM L/H (CEN)			11%	
FOOTREST CLAMP WEBBING				✓

Table 4.8 - Hotspot selected components from the 260 footrest

Rail Kit Box and Sundries Components Selected as Critical	% Total Metal CO_2	% Total Plastic CO_2	% Total Cost	Env. Significant
END STOP WELDED ASSY PEARL LH	32%			
END STOP WELDED ASSY PEARL RH	32%			
CHARGE RAMP FIXING BLOCK	7%		14%	
CHARGE RAMP FIXING BLOCK	7%		14%	
END STOP PLUNGER	6%			
END STOP PLUNGER	6%			
CHARGING RAMP ASSEMBLY (INJ)		36%		
CHARGING RAMP ASSEMBLY (INJ)		36%		
PLUG-RAIL END/PEARL		16%	6%	
SLOWING RAMP		13%		
SLOWING RAMP FIXING			16%	
TOUCH-UP STK PEARL-260 RAIL			13%	✓
BATTERY 12V-7.2/7.6AH				✓
CHARGER / 220-230V / 50/60HZ				✓
IR CONTROLS				✓
POWER CABLE				✓
TOTAL PACKAGING				✓

Table 4.9 - Hotspot selected components from the kit box

Rail Components Selected as Critical	% Total Metal CO_2	% Total Plastic CO_2	% Total Cost	Env. Significant
260 RAIL	78%		✓ not known as bespoke	
260 RAIL LEGS	13%		✓ not known as bespoke	
PROTECTIVE LEG CAP		18%		
CARPET SHROUD PEARL INJ MOULD		15%		
ZERO VOLT RETURN RAMP		7%		

Table 4.10 - Hotspot selected components from the 260 rail

The selected components were assessed in the most detail going forward, assessing materials and manufacturing process stages separately including the waste generated in these processes. Primary data was collected wherever possible from internal and external sources. The components not selected were allocated a more generalised category intended to capture an approximation of these components' impacts.

Each category was given a likely carbon impact per mass of component. The impact was made up of the impact category for the most likely material and manufacturing process. These categories are inspired by the inventory databases produced by Ashby (2009) to capture an approximation of their materials and manufacturing impacts, be that deformation, cast, moulded or extruded without going into excessive detail.

The approach of using a hotspot analysis was successful in cutting down the scale of the study. The process identified the 80 components that made up the majority of the product's impact. This maintained enough detail in the study for post analysis and identifying areas for making improvements, whilst still narrowing the data collection to an achievable level.

4.4 260SL stairlift Data Collection

Before the LCA could take place data was collected on the inputs and outputs identified on the product system map.

4.4.1 Product Disassembly

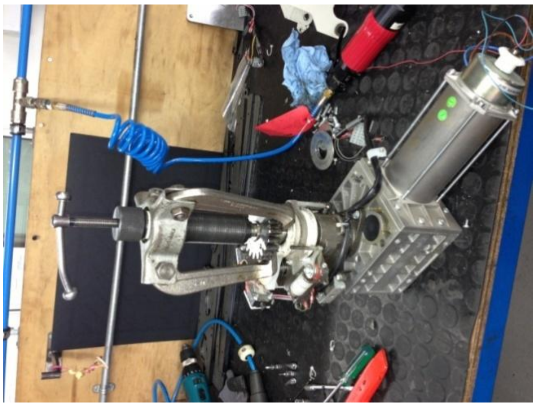
Initially the 260SL Stairlift was broken down into its modules of a carriage, chair, and footrest.

4.4.1.1 260 Carriage

The carriage was then further disassembled on a bench down to its component parts, Figure 4.4.

a)

b)



c)

d)

Figure 4.4 - Carriage disassembly

a) The 260 carriage on a bench pre disassembly.

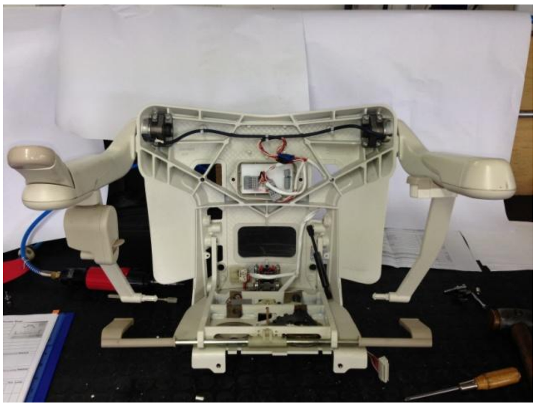
b) The drive mechanism separated from the rest of the carriage with covers still attached.

c) The motor gearbox with drive mechanism still attached mid disassembly.

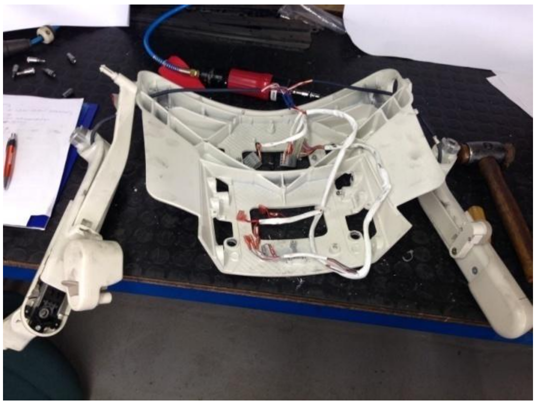
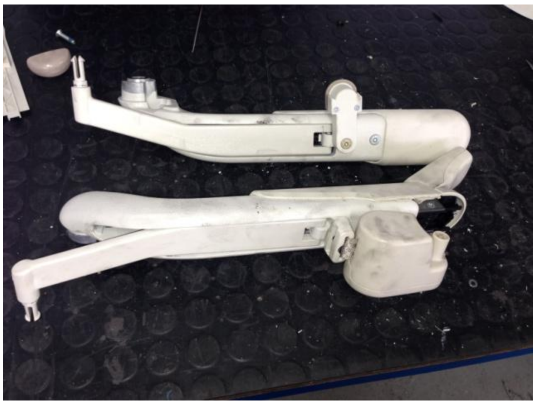
d) The cluster housing which acts as the chassis for the drive mechanism separated from the product.

4.4.1.2 SL Chair

The SL Chair was disassembled on a bench down to its component parts, Figure 4.5.

a) b)

c) d)

Figure 4.5 - SL chair disassembly

a) The SL chair on a bench pre disassembly.

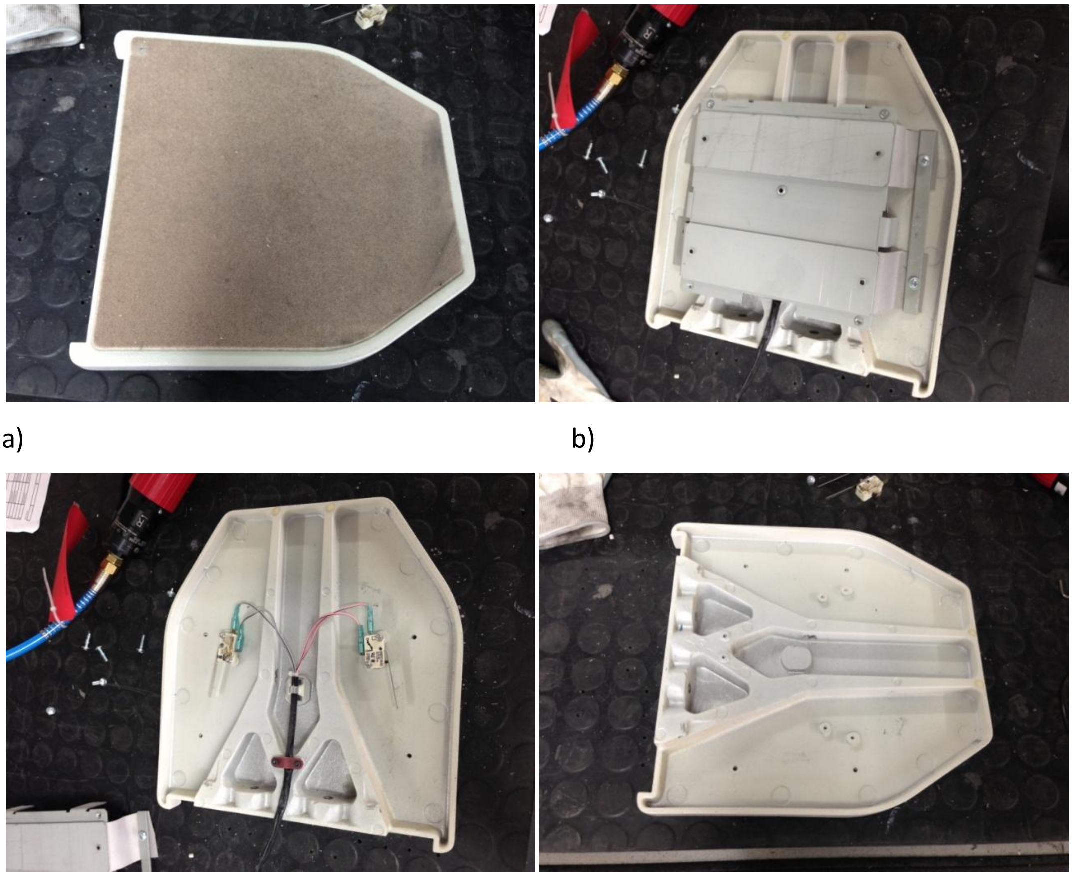
b) The chair with the upholstery removed.

c) The seat back assembly with looms still attaching the arms.

d) The removed arms awaiting further disassembly.

4.4.1.3 Footrest

The Footrest was disassembled on a bench down to its component parts, Figure 4.6.



a) b)

c) d)

Figure 4.6 - Footrest disassembly

a) The 260 footrest on a bench pre disassembly.

b) Footrest with the bottom cover removed.

c) Safety pad mechanism removed showing switches and looms.

d) Bare footrest casting.

4.4.2 Component data collection

After disassembly, every component had its key information for the study recorded. Table 4.11 is an example of the data collected and recorded for components. Items like fixings were set aside after disassembly and weighed as a combined total. In hindsight, more of the small component parts could have also been grouped into categories and had this philosophy applied. This would have made data collection much quicker, without the need for individual weighing and recording.

Stairlift Module: 260 Carriage			
Part No.	2604208002	Part Name	260 CARR-WELDED ASSY PEARL
		Supplier	STANNAH
		Address	n/a
		Cost	£16.40
		Mass	6.554Kg
		No. of	1
		Material	Steel
		Manufacturing stages	Laser cut Post operations (stud, drill, tap) Bending Welding Powder coating

Table 4.11 - Component data collection example

4.4.3 Life cycle stage data collection

Manufacturing process data was collected for the various internal and external (when available) processes. Table 4.12 is an example of the data collected on manufacturing processes. In this example the processing power, waste produced and auxiliaries used are recorded for laser cutting the component parts of the carriage welded assembly.

Stairlift Module: 260 Carriage			
Part No.	2604208002	Part Name	260 CARR-WELDED ASSY PEARL
		Process	**Trumatic 3030 Laser cutter**
		Power kWh	34.4
		Process time	229 Sec per unit
		Process waste	0.052 Kg per unit
		Auxiliaries used	Nitrogen Oxygen Helium Carbon dioxide Compressed air

Table 4.12 - Manufacturing process data collection

Data collection of internal manufacturing processes went smoothly although it was carefully planned to ensure minimum impact on production activities. It was not always possible to stop a process in order to make controlled measurement. This was particularly the case with the powder coating plant where it was not possible to stop and clean through the system prior to gathering data. This was resolved by using an inline power meter for measuring electricity and using the gas utility company data taken from an average summer month, when there would be no other gas consumption in the factory. To measure the paint use, the purchase orders of powder were divided by the factory output over the same period.

Some systems such as the provision of compressed air could not be measured by process, due to the compressor supplying the whole factory. In this case an average hourly power consumption was taken for the compressor and divided by the factory output over this period. This was added to the LCA model in a single stage rather than by individual processes.

For components manufactured by external suppliers, mixed success was achieved in engaging their involvement. For a large number of suppliers the largest barrier to providing the data was knowledge, time and availability of equipment to take power readings. In some instances this resulted in collection of the maximum power ratings of equipment, rather than the power required to produce the component in question. For some processes such as injection moulding, the maximum power rating is only used in the heat up phase of operation, which was significantly higher than the operating power requirement. In these cases data was obtained using a 3rd party database as it was deemed more accurate.

Some suppliers had never considered the environmental impacts of their processes and saw the project as an opportunity to learn new skills. Those who had already looked into making environmental improvements were less willing to be involved or share the data which they had already collected. These businesses had less to gain and so were less willing to put resource towards the project.

Data collection on transport was generally easily established once suppliers' manufacturing locations were established. It was however hard on occasions to determine the manufacturing location of some components. An example of this would be where electronic components are sourced by a UK distributor from several different countries in the Far East. These are then sold on to the printed circuit board (PCB) manufacturer in the UK. Often these components were not critical to the outcome of the study and so an approximation of the distance was used. Transportation distances to a fictional customer were set and maintained constant throughout the study, for stages such as product delivery and removal of the product at end of life.

Whilst it was not always possible to explicitly collect primary data at every stage it was felt that the data quality obtained for the study was sufficient to provide a fair representation of the product lifecycle in this study.

4.4.4 Life cycle impact data

CO_2e impact data for common materials, transport and energy was easily found in freely available impact databases. Less common materials and substances such as electronics, carpet, lubricants and adhesives were only available in the commercial databases. In a few cases carbon dioxide equivalent (CO_2e) data was not available and carbon dioxide (CO_2) data had to be used. Whilst CO_2 makes up the largest impact, not considering the other emissions associated with carbon dioxide equivalent will have a small effect on the results.

4.5 Building the Life Cycle Assessment Model

Several software options were reviewed for building the LCA model. One of the most extensive pieces of LCA software used by LCA practitioners is GaBi by PE International. This software is complex and would require training to build and understand the underlying model. The data within GaBi was thought to have a good level of accuracy, although specialist datasets would need to be purchased to obtain results for the required materials. However, primary data from data collection activities could have been entered into the software where collected.

Eco Audit is a simpler piece of LCA software produced by Granta. The model is built up using pick lists and data input fields. Little training is required as the user is guided through the process of building the model. Only the data which is in Granta can be used so there is no capability to enter any primary data.

Microsoft Excel is available with Windows and can provide all the functionality required to build LCA models. Once an understanding of LCA and how models are built is gained, it is quick and easy to build models in Excel. Excel offers the freedom to structure the model in any way and apply data from any source.

Microsoft Excel was chosen due to the freedom it offered to structure the model and apply data from many sources. This was essential because of the complexity of the study and time available to build the model. The project success observed by building the model in Microsoft

Excel further supports similar claims by Ashby (2009) that life cycle assessment models can be created manually in spreadsheet software.

Appendix E contains figures demonstrating each stage of the life cycle assessment model built in Microsoft Excel .

4.6 Results of Stannah's 260SL Life Cycle Assessment

The purpose of this study was to understand the lifecycle of the Stannah 260SL stairlift and to quantify its impacts in terms of global warming potential (CO_2e).The results are however, a reflection of the functional unit assessed and assumptions made. The functional unit of the study was:

Functional Unit:

One standard 260 curved stairlift manufactured in 2009 with a maximum load capacity of 135Kg and a maximum life of 20 years. The product will be used for 4 years worth of life in the UK, after which it will be recycled. The product will make 14 journeys per day (being either up or down the stairs) travelling along a six meter rail with one 90 degree bend.

4.6.1 Results of the Life cycle assessment – by Life Cycle Stage

In this section the results of the study were broken down in terms of life cycle stages, to understand where impacts were occurring across the whole life of the Stannah 260SL Stairlift.

The total global warming potential of the product was 632 Kg CO_2e across the whole lifecycle. This was broken down by phase of life in Figure 4.7.

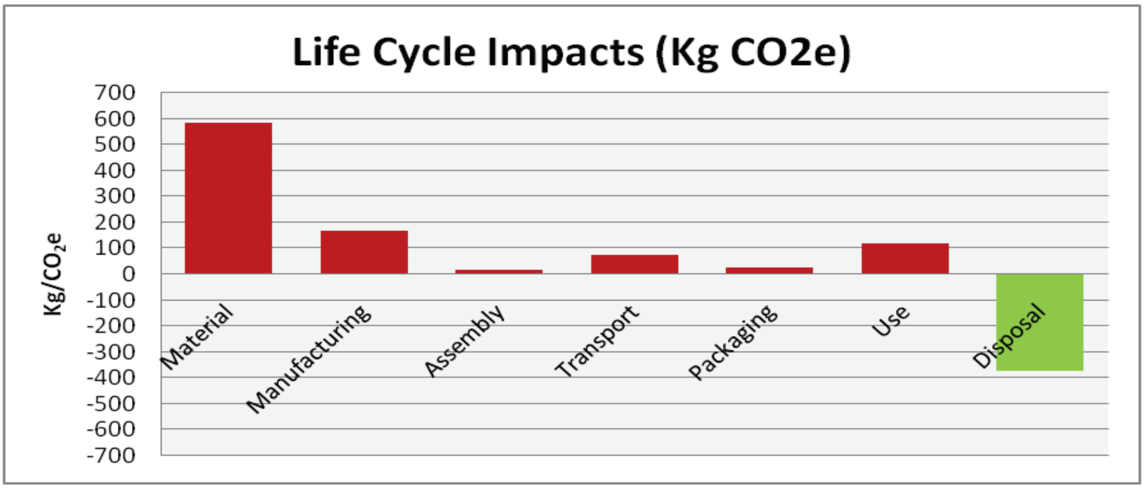


Figure 4.7 - 260SL impacts by lifecycle stage

The stage of life with the largest impact was raw materials, with a total of 583Kg CO_2e (58% of the total life cycle impact). This was predominantly down to the large amounts of metal used. The Stairlift module that had the largest material impact was the Rail (207Kg CO_2e). The Carriage had the second highest material impact (198Kg CO_2e). The electronics in the product were made up of batteries, wiring looms, switches, motors and printed circuit boards (PCBs). The electronics had a total impact of 141Kg CO_2e so contribute heavily towards the material impact of the carriage. The chair had a materials impact of 98Kg CO_2e.

The second highest phase of life came from the manufacturing processes undertaken, resulting in 168Kg CO_2e (17% of the total life cycle impact). Again the large metal components made up the majority of the processing power. The rail (82Kg CO_2e) consumed the most power in bending the tube. The manufacturing of the Carriage (47Kg CO_2e) and the Chair (33Kg CO_2e) follows this.

The assembly of the product was the lowest impacting phase of life in terms of power consumption. The assembly cells produce 17Kg CO_2e (1.8% of total life). Supplier components entered the system at this stage of the process and the delivery packaging needed to be disposed of. This equated to 1Kg CO_2e per stairlift produced. The largest impact in assembly was the compressed air consumption (this was the compressed air that was consumed in the manufacturing phase of life too, but could only be included in the model at a single point) resulting in 16Kg CO_2e being released per product.

Transportation had a relatively small overall impact of 95Kg CO_2e (9% of total life). The sales visit however had a comparatively high impact (22kg CO_2e) due to the sole purpose of the visit being associated to a single product. It should also be considered that the salesman will not sell a product on every call so this impact could be under estimated.

Transportation of suppliers materials and components into Stannah represented 49Kg CO_2e in total. Considering the distances travelled and use of international shipping, international transport does not have a large impact, (22Kg CO_2e). This was thought to be because it is part of a large volume of freight being carried by ocean going ships. Transportation of components once in the UK had more of an impact (27 Kg CO_2e) especially when considering the shorter distances travelled.

Stannah's delivery of the finished product to the customer represented 11Kg CO_2e. Removing the product from the customer and returning it to the factory at end of life also had the same impact. A small onward footprint (2Kg CO_2e) would also be associated with sending the material off for recycling. It should be remembered, that the functional unit stated that this product was intended for the UK market, shipped directly from Andover to the customer. If the product were intended for the USA market, the rail (the heaviest item) would be sent via airfreight creating a far higher transportation impact. If air-freighting rails was within the functional unit, it was estimated the overall product footprint of the study would be doubled.

Packaging of the product equated to 25Kg CO_2e (2.5% of total life). The largest material and manufacturing impact was made up by the rail packaging (13Kg CO_2e), followed by the chair box (5Kg CO_2e) and then the carriage packing set (4Kg CO_2e). As with all material impacts, it was important to consider packaging with a whole life approach. The paper, cardboard and plastic packaging was recycled at the end life offsetting some of the initial material impacts. The impacts of the packaging associated with each stairlift module and the benefits of recycling it at end of life can be seen in Figure 4.8. The importance of a life cycle approach was seen when comparing the expanded polystyrene packaging of the Carriage and the cardboard packaging of the SL Chair. The cardboard packaging had a higher initial impact than the polystyrene, but was recycled unlike the polystyrene, which made it an overall lower impact choice.

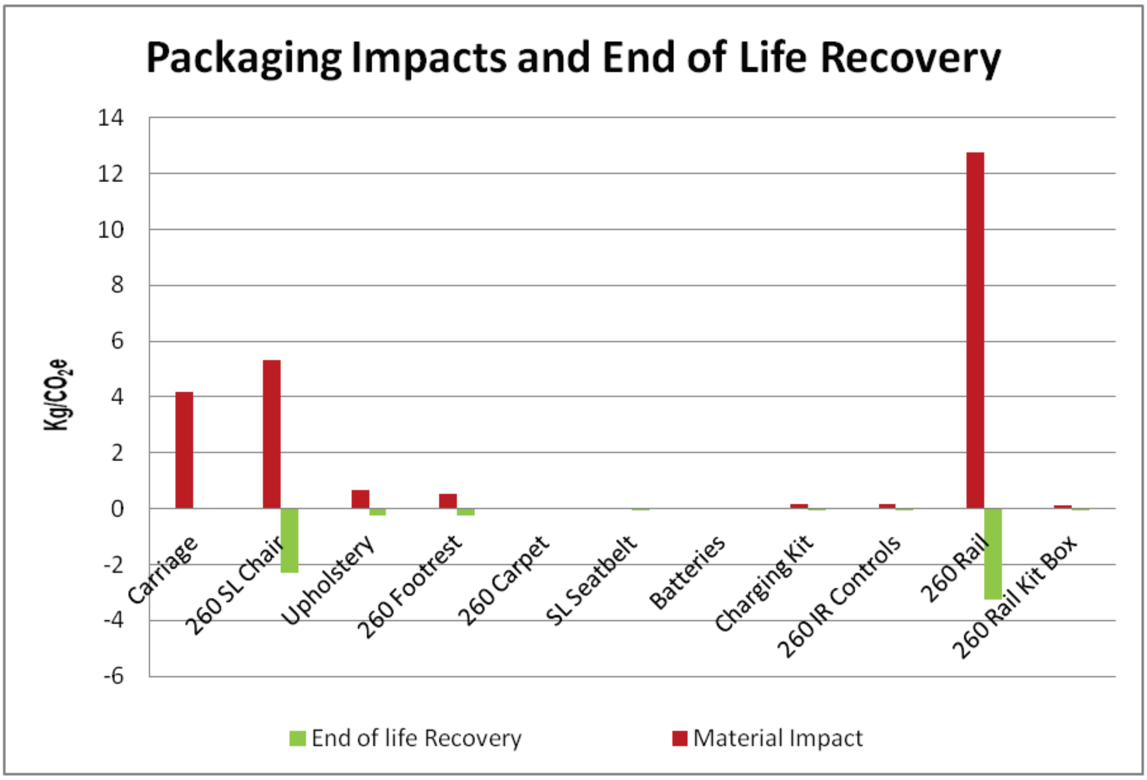


Figure 4.8 - Life cycle 260SL packaging impacts and end of life recovery

The use phase of life refers to the power consumed by the product over the four years it was in operation. This resulted in 119Kg CO_2e (12% of total life) being released, assuming that the house was powered by the average grid mix in the United Kingdom. The functional unit states that the product will be used for 14 journeys a day over a 4 year time period. This is a total of 20440 journeys over its lifecycle. With the whole life impact of the product being 632Kg CO_2e this equates to 31g CO_2e per journey.

If a service contract was taken out on the product or it was to break down requiring an engineer to attend, the use phase of life would increase with replacement components and the impact of an engineer travelling to site.

As the product was unsuitable for reuse in a second hand market due to its age, the only avoided burden came from the recovery of material through recycling. This resulted in a saving of 376Kg CO_2e (37% of lifecycle impact recovered at end of life), Figure 4.9.

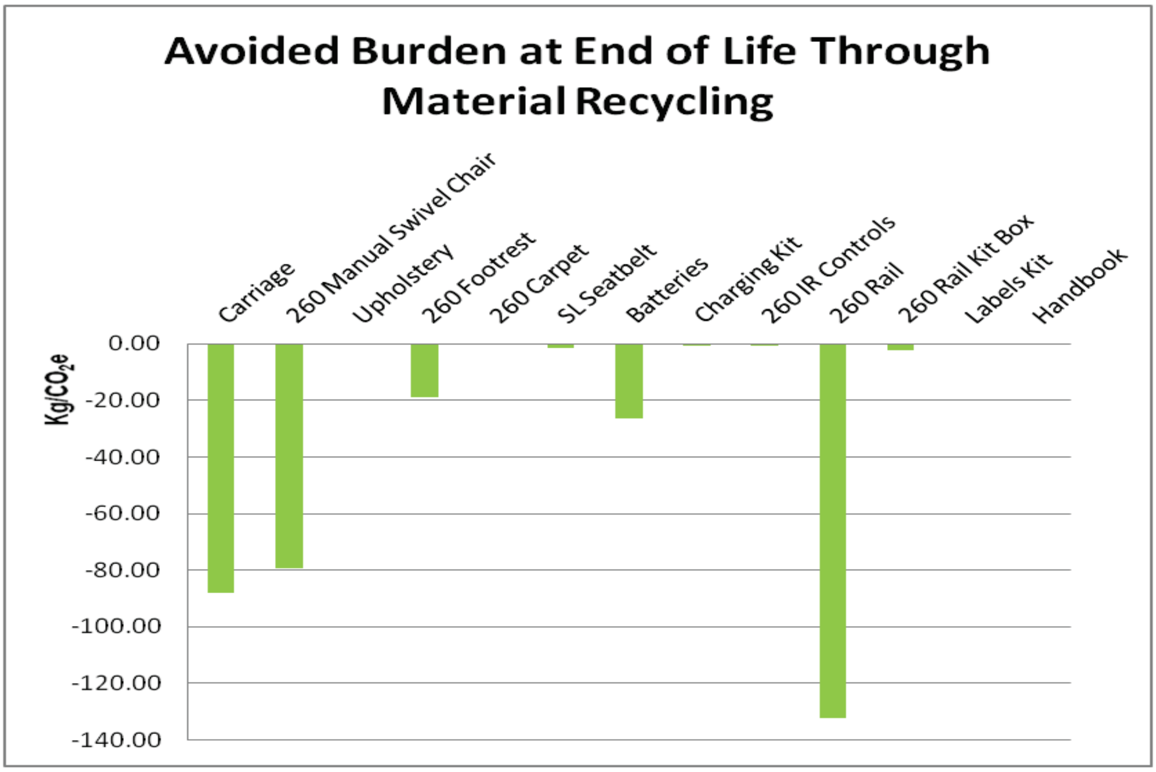


Figure 4.9 - The avoided burden resulting from end of life recycling

Figure 4.9 demonstrates how much impact can be avoided through recycling for each of the stairlift's modules. The rail had the highest material content and being steel, was easily recycled. As such, it had the greatest mass of material recovered at end of life (63% of material impact recovered). The chair and footrest were both highly recyclable both achieving 81% material impact recovery although there was clearly a greater mass of material to recover in the chair. The carriage was less recoverable only achieving 44% of material impact recovery through recycling.

The overall product footprint benefited greatly due to the end of life avoided burden from recycling. With materials being the highest impact there was great benefit in recycling at end of life. The benefit of recycling the products materials was subtracted from the impact of the raw material up front. In essence, the product had only borrowed the materials for the time of its life. Viewing the results in this light, Figure 4.10, gives a better representation of the impact of the materials in comparison to the other life cycle stages. This approach shifts manufacturing to the largest impacting stage of life.

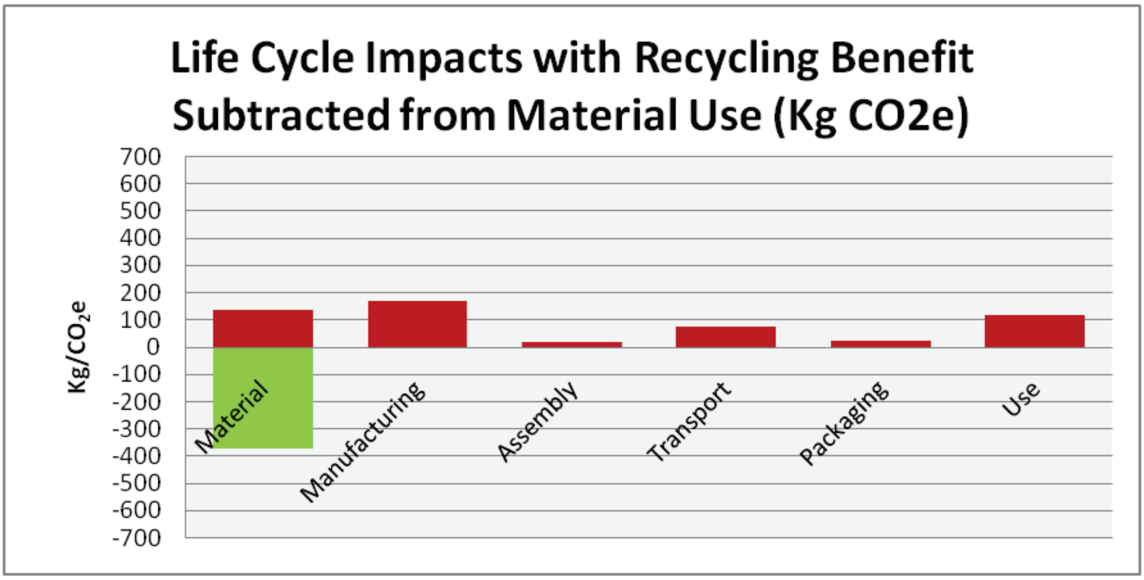


Figure 4.10 - 260SL Life impacts with end of life recycling imbedded

4.6.2 Results of the Life cycle assessment – by Stairlift Module

Looking at each stairlift module individually, it is possible to see which had the greatest whole life impact, including the end of life benefits of recycling, Figure 4.11. Whilst the rail had the biggest whole life impact, the carriage was close behind despite being less material intensive. This was because of the rails greater end of life recovery compared to the carriage.

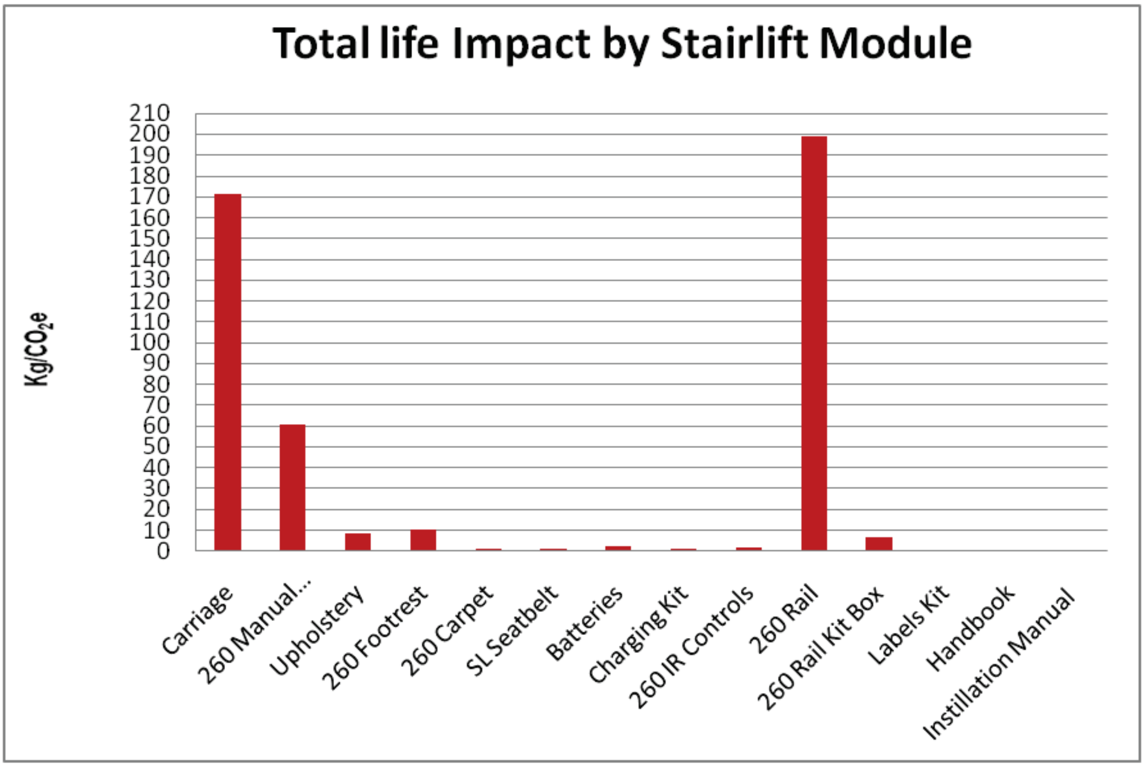


Figure 4.11 - Whole life impact by product stairlift module

Each stairlift module was also examined at a component level to gain more information on where the largest environmental impacts were occurring. For each stairlift module, components making up greater than 1% of the total CO_2e were highlighted. These components were then evaluated in more detail.

The 260 Carriage had 11 components with a CO_2e impact greater than 1% of the total carriage CO_2e impact, Figure 4.12. Of these, it was the motor that had the largest whole life impact due to it being one of few components with an impact resulting from the use of the product, (118Kg CO_2e). The component with the single highest material impact was the main control PCB, (43 Kg CO_2e). The skate had high materials (28 Kg CO_2e) and manufacturing (22 Kg CO_2e) impacts due to the casting process.

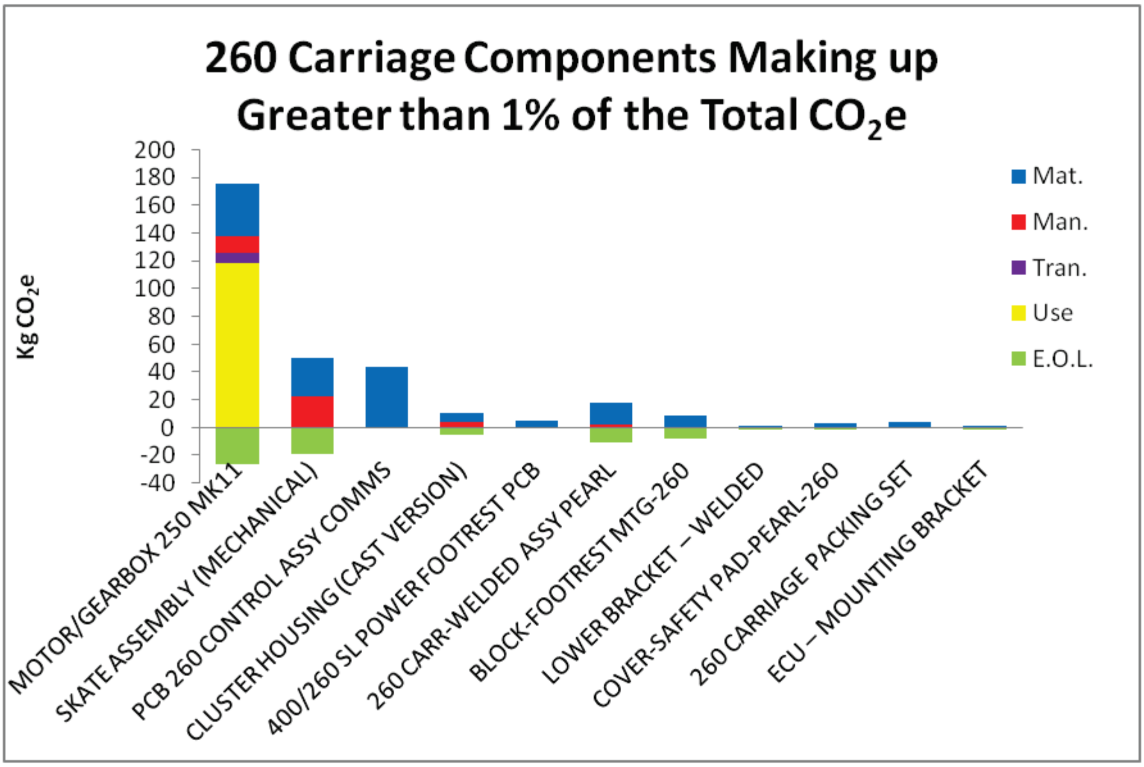


Figure 4.12 - 260 Carriage components making up greater than 1% of the total CO_2e

The SL Chair had 8 components with a CO_2e impact greater than 1% of the total chair CO_2e impact, Figure 4.13. There were a number of cast aluminium components leading to high material impacts, but good possibility to recycle. These included the chair back casting which had the largest overall impact (40 Kg CO_2e), the seat hinge (11 Kg CO_2e) and arms (10 Kg CO_2e). The Chassis was a welded steel assembly which also had a significant impact, (10 Kg CO_2e).

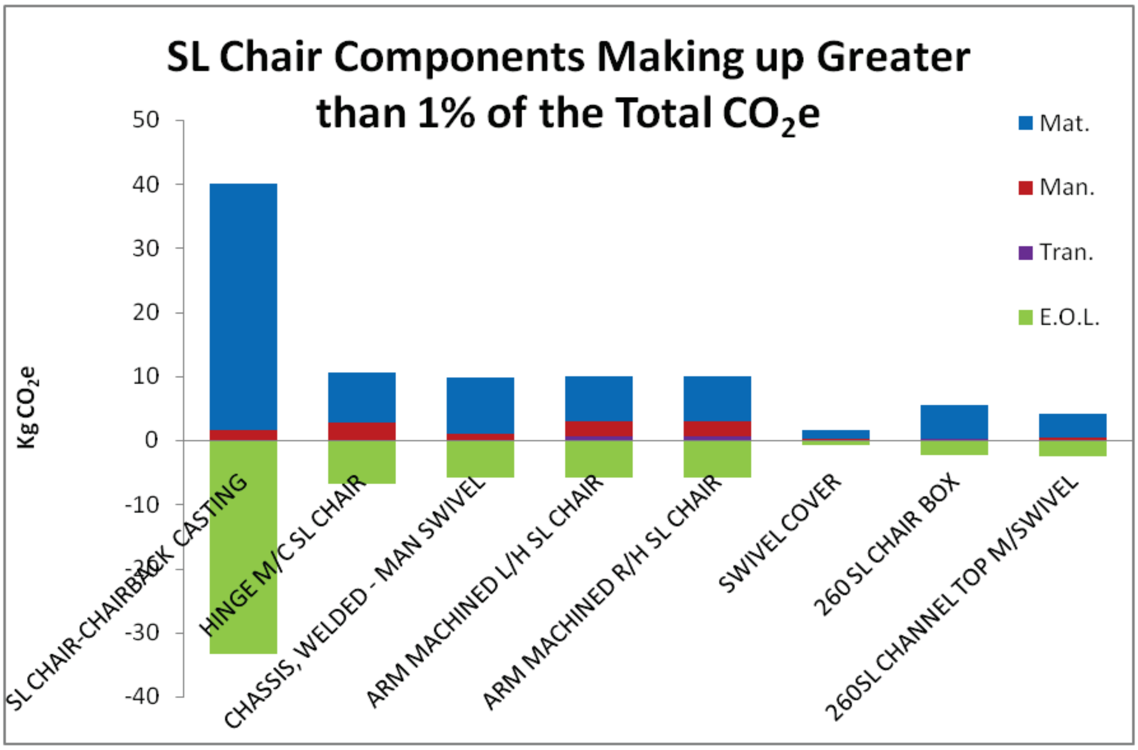


Figure 4.13 - SL chair components making up greater than 1% of the total CO_2e

The footrest was a small assembly with 4 components with a CO_2e impact greater than 1% of the total footrest CO_2e impact, Figure 4.14. Of these the major impact came from the aluminium casting (19Kg CO_2e) which made up the majority of the whole footrest module. With the casting being aluminium there was the possibility to recover 16Kg CO_2e worth of material impact through recycling.

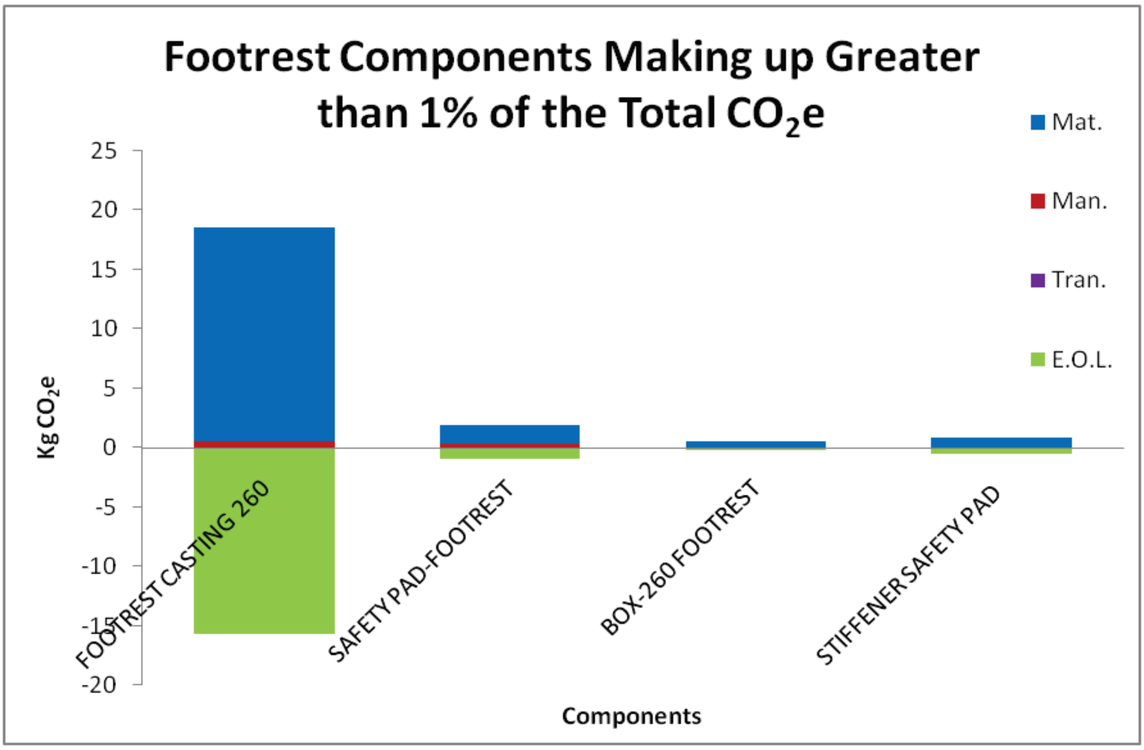


Figure 4.14 - Footrest components making up greater than 1% of the total CO_2e

The impacts of the kit box, Figure 4.15, were predominantly associated with the legs, (44kg CO_2e). These were welded steel assemblies that supported the rail on the staircase. The rail, Figure 4.16, another welded steel assembly, was the largest overall component of the stairlift and as such had the largest material impact, (180Kg CO_2e). The rail also produced the most waste in its manufacture, accounting for 11Kg of its total CO_2 impact. Both the rail and the legs were easily recycled, which reduced their whole life impact down to 23kg CO_2e for the legs and 98Kg CO_2e for the rail.

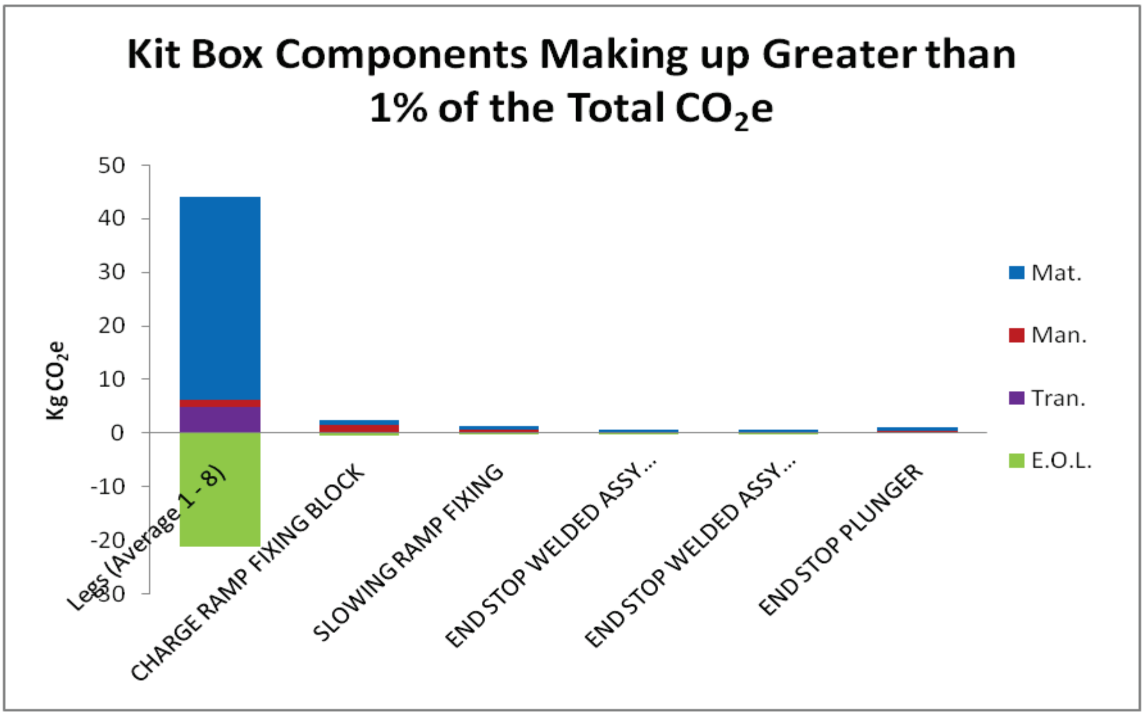


Figure 4.15 - Kit box components making up greater than 1% of the total CO_2e

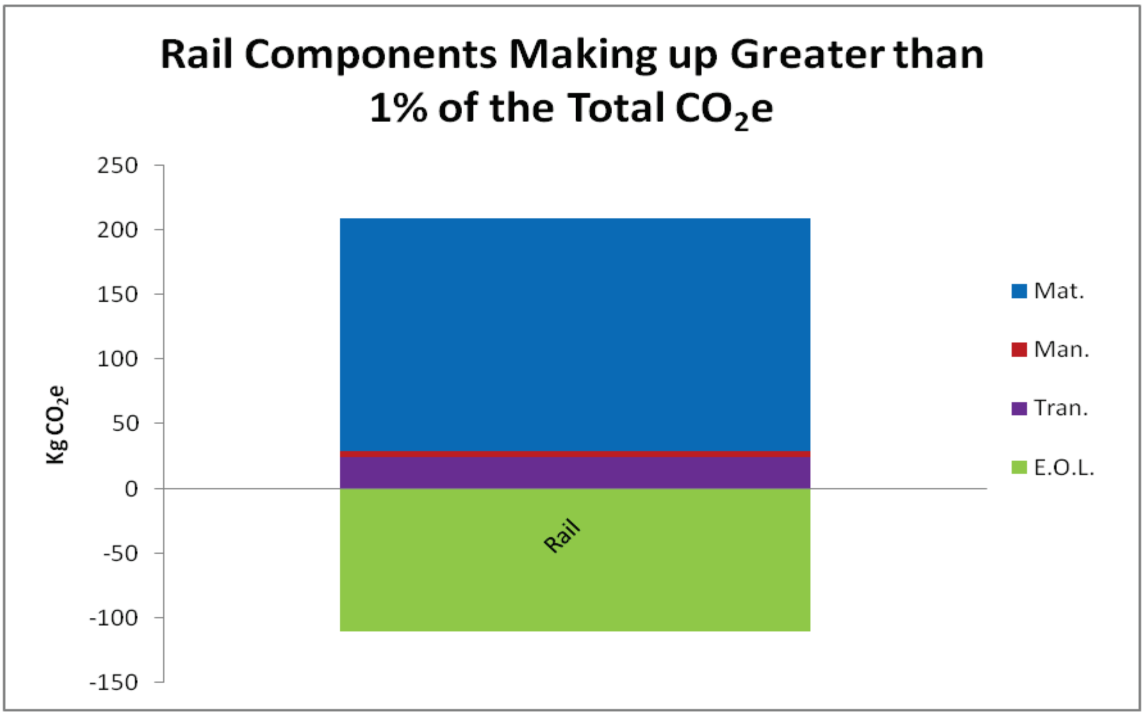


Figure 4.16 - Rail components making up greater than 1% of the total CO_2e

4.7 Chapter Conclusions

An LCA was conducted on the Stannah 260SL stairlift and the following observations were made:

- The most significant stages of life were the materials and end of life processing of stairlift components.
- If the recyclable material was recovered at end of life and subtracted from the materials impact, then the next most significant stage of life was manufacturing.
- The majority of the material and manufacturing impacts for each stairlifts module came from very few components.

Therefore, to reduce the overall impact of the 260SL, the materials and manufacturing impacts associated with the creation of its few high impact components should be targeted.

Despite the product being designed to last 20 years , at four years the stairlift is deemed no longer viable for reuse due to the warranty on the motor gearbox expiring. If this were to fail, it would be a costly and time-consuming repair for the business to replace. However, at four years components have only served 25% of their intended life. Therefore, remanufacturing the product to recover the materials and manufacturing energy might be a good way to reduce the impact of future product lives.

Chapter 5 – Remanufacturing Stannah's 260SL Stairlift

This chapter considers both CO_2e and cost to identify suitable components for remanufacture and estimate the benefit that remanufacture could bring to the product lifecycle. A case study was then conducted to verify the estimated savings and assess feasibility of remanufacturing the Stannah 260SL Stairlift.

Remanufacture was chosen as a potential end of life reprocessing technique, as it was the only one that allowed the product to be returned to a like-new condition, whilst maintaining as much of the embedded value in components as possible. This is important for Stannah, who are operating at the premium end of the market and so product quality is an important driver.

5.1 Case Study Methodology

In this study, the remanufacture of a Stannah 260SL stairlift followed the process stages shown in Figure 5.1 (produced by the author).

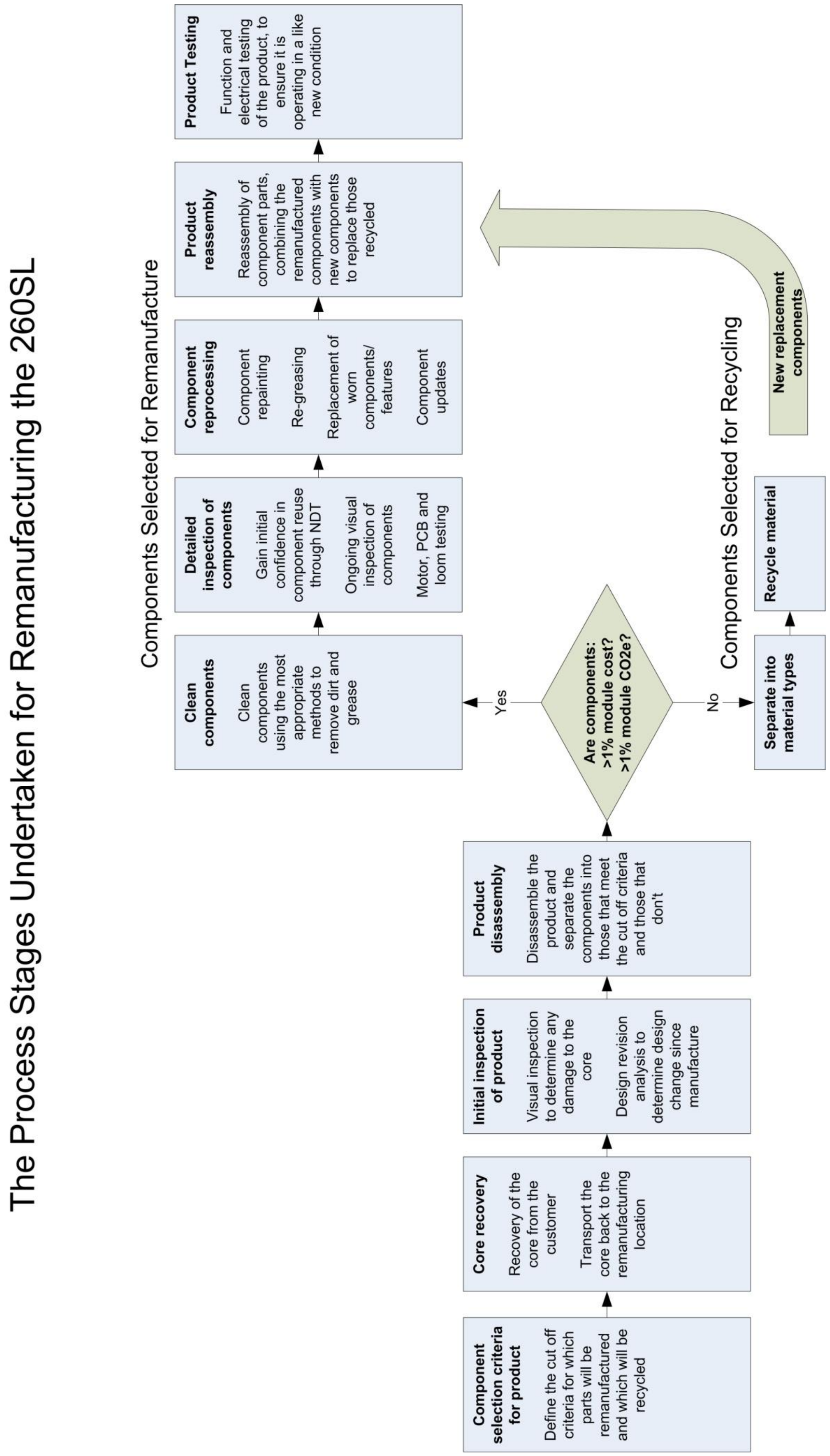


Figure 5.1 - Flow diagram of remanufacturing process stages

5.2 Selecting Critical Components for Remanufacture

Based on the LCA findings, only the high impact components in the 260SL were targeted for remanufacture. The product must also be commercially viable to remanufacture, so cost was also introduced as a selection criteria. This was to ensure that the components that have the highest value were also recovered. It is thought that only remanufacturing the critical components will lead to the majority of the benefit, with reduced cost and effort of only remanufacturing the selected few components.

5.2.1 Component Selection Methodology

An initial selection cut off criteria was set at >5% for each stairlift module. Unlike the LCA, there was no distinction made between material types as it did not matter what each component was made from, it was just the components with the highest impacts that needed highlighting. After investigation it was decided that this excluded too many components and greater recovery could be achieved if a lower cut off was used. For this reason a >1% cut off criteria was chosen.

5.2.1.1 Environmental analysis

When considering which components would be most beneficial for remanufacture in terms of environmental impact (CO_2e), the life cycle stages of materials, manufacturing and transporting components to the factory were used. These stages of life were deemed to be those that a remanufactured component would avoid, by displacing the need for new components. Based on this, components that made up greater than 5% and then 1% of each stairlift modules total impact were selected.

5.2.1.2 Cost analysis

Remanufacture has the potential to save material and processing energy (Steinhilper, 1998), but often at the expense of increased labour, (Charter, et al., 2007).

Based on this, only stairlift modules that have a greater material than labour cost were selected for remanufacture. Components from the selected modules were identified that made up greater than 5% and then 1% of each stairlift modules total cost.

5.2.1.3 Remanufacturing process suitability

Finally, with the product not currently being designed for remanufacture a decision was taken, based on the work by Charter, et al. (2007), Ijomah, et al. (2007) and Shu, et al. (1999) as to whether it was likely that each component could be economically brought back to a like-new condition. Plastic covers were an example of components identified on the grounds of

CO_2e/cost. However, after 4 years of use they would probably be damaged and not viable to reprocess. If the stairlift had been designed with remanufacture in mind, then these covers may have been made from a different material or painted so that their surface could be reprocessed back to a like-new condition. The rail was also discounted in its entirety as this is a bespoke item fabricated for each staircase. If this was a modular product made up of standard rail sections, then remanufacturing the individual rail sections could potentially become possible. This clearly demonstrates the benefit of developing products with remanufacture in mind at the design stage, so decisions are not made that will prevent the successful reprocessing of components at end of life.

5.2.2 Selected components by stairlift module

Figure 5.2 indicates the make up of material and labour cost in producing each of the major modules of the 260SL stairlift. In each of the stairlifts modules the material and manufacturing cost outweighs the labour involved in production. The savings in material and manufacturing processes recovered, could potentially absorb any increase in the labour cost due to the remanufacturing process. This being the case, there seems to be inherent value in end of life stairlift components for remanufacture.

From the major subassemblies, the carriage, chair and footrest were considered suitable for remanufacture, along with some components from the rail kit box such as the rail legs. The rail could not become a remanufactured product, as it was bespoke and designed and manufactured in each case for a staircase.

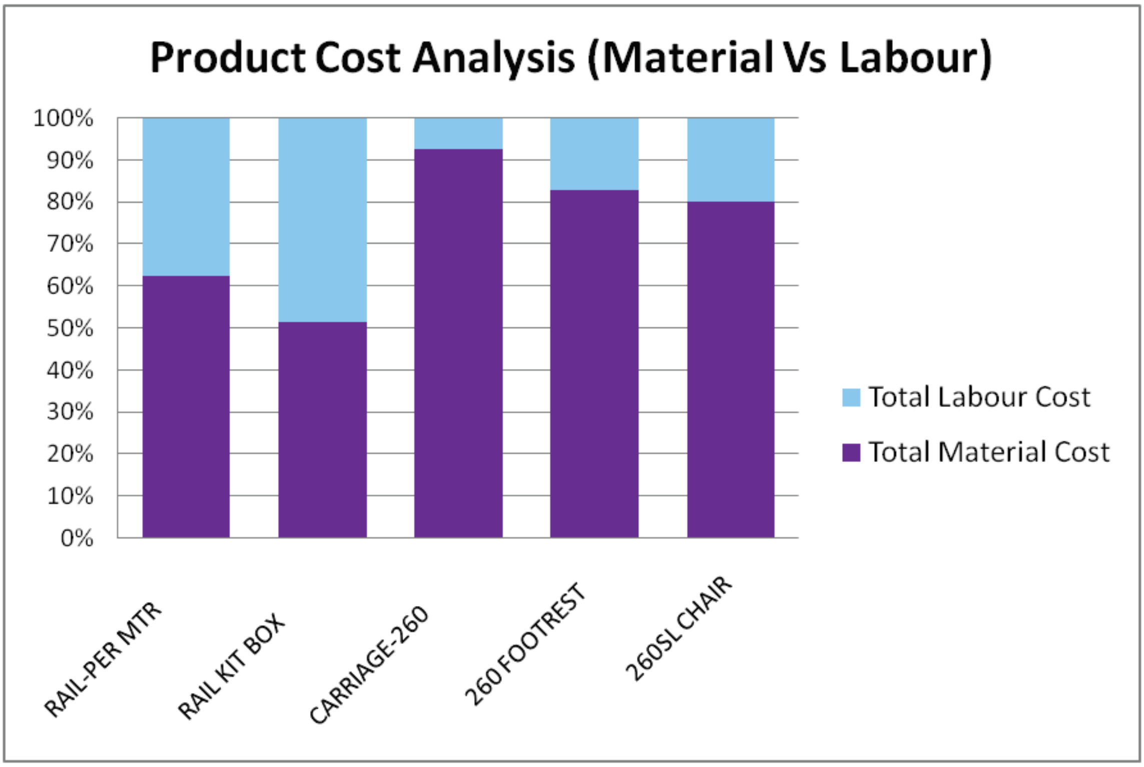


Figure 5.2 - The material Vs labour cost for major 260SL assemblies in 2012

An analysis of each stairlift module in turn, highlighted components where remanufacturing could be potentially beneficial based on the LCA results, component costs and physical examination of the product. These components were unlikely to have worn and had a high financial or environmental impact to the product.

5.2.2.1 260 Carriage

Based on the total manufacturing CO_2e impact (264 Kg/CO_2e) and cost (£472) of the 260 carriage, the component selection cut off values (1% and 5%) are listed in Table 5.1.

Cut off Criteria	Environmental Cut Off (Kg CO_2e)	Cost Cut Off (£)
1% of total	2.64	4.72
5% of total	13.2	23.62

Table 5.1 - Component selection cut off criteria for the 260 carriage

The components selected in Table 5.2 (selected on CO_2e) and Table 5.3 (selected on cost) are those that have been highlighted as above the cut off criteria. The components selected on environmental grounds were the drive unit and the large metal components that make up the carriage. The only components that were selected on CO_2e and not also selected under cost were the safety cover and the carriage packaging set. The components selected on the basis of cost include the looms and some welded assemblies which were purchased in from suppliers.

Environmentally Selected Components (Kg CO_2e)						
Component		Qty	Total	Suitable component	Cut off criteria	Comments
2604200102	**TOTAL 260 CARRIAGE**		**258.91**			
2504100	MOTOR/GEARBOX 250 MK11	1	56.97	✓	5%	
2504759	SKATE ASSEMBLY (MECHANICAL)	1	50.45	✓	5%	
260902700001	PCB 260 CONTROL ASSY COMMS	1	43.38	✓	5%	
2504892	CLUSTER HOUSING (CAST VERSION)	1	10.59	✓	5%	
4009117	400/260 SL POWER FOOTREST PCB	1	5.4	✓	1%	
2604208002	260 CARR-WELDED ASSY PEARL	1	17.74	✓	5%	
2504808	BLOCK-FOOTREST MTG-260	1	8.63	✓	5%	
2504803002	COVER-SAFETY PAD-PEARL-260	1	2.97	x	1%	Plastic Cover
641414	260 CARRIAGE PACKING SET	1	4.35	x	1%	Packaging

Table 5.2 - Components meeting environmental selection criteria in the 260 carriage

Cost Selected Components (£)						
Component		Qty	Cost each	Suitable component	Cut off criteria	Comments
2604200102	**TOTAL 260 CARRIAGE**		**£472.41**			
2504100	MOTOR/GEARBOX 250 MK11	1	£150.15	✓	5%	
2504759	SKATE ASSEMBLY (MECHANICAL)	1	£72.67	✓	5%	
260902700001	PCB 260 CONTROL ASSY COMMS	1	33.95	✓	5%	
2609031	260 SL CARR P/FOOT MOTOR+ LOOM	1	£22.71	✓	5%	
2504892	CLUSTER HOUSING (CAST VERSION)	1	£15.01	✓	1%	
4009117	400/260 SL POWER FOOTREST PCB	1	£13.78	✓	1%	
2504865021	LOWER BRACKET - WELDED	1	£12.74	✓	1%	
2609029	SL LOOM-CARRIGE TO CHAIR	1	£11.77	✓	1%	
2604208002	260 CARR-WELDED ASSY PEARL	1	£10.75	✓	1%	
2504808	BLOCK-FOOTREST MTG-260	1	£7.39	✓	1%	
2604250	HANDWINDING SPIGOT ASSY (HEX)	1	£5.30	✓	1%	

Table 5.3 - Components meeting cost selection criteria in the 260 Carriage

From Table 5.2 and Table 5.3, the components shown in Table 5.4 were targeted in the remanufacturing process for the 260 Carriage. The carriage packaging and plastic covers would likely have seen wear over the products life, making them unsuitable for remanufacture going forward.

260 Carriage Selected Components		
1	2504100	MOTOR/GEARBOX 250 MK11
2	2504759	SKATE ASSEMBLY (MECHANICAL)
3	260902700001	PCB 260 CONTROL ASSY COMMS
4	2609031	260 SL CARR P/FOOT MOTOR+ LOOM
5	2504892	CLUSTER HOUSING (CAST VERSION)
6	4009117	400/260 SL POWER FOOTREST PCB
7	2504865021	LOWER BRACKET - WELDED
8	2609029	SL LOOM-CARRIGE TO CHAIR
9	2604208002	260 CARR-WELDED ASSY PEARL
10	2504808	BLOCK-FOOTREST MTG-260
11	2604250	HANDWINDING SPIGOT ASSY (HEX)
12	2609007	LOOM 260 CLUSTER

Table 5.4 - Components selected for remanufacture from the 260 carriage

Figure 5.3 and Figure 5.4 show the proportion of the total CO_2e and cost that the selected components represent in the 260 Carriage. It can be seen that over 50% in both cases (CO_2e and £) can be recovered by selecting components that make up over 5% of the carriage total. Selecting components that are greater than 1% of the carriage total did not make a significant difference when looking at CO_2e; but did account for nearly 20% greater recovery when considering cost.

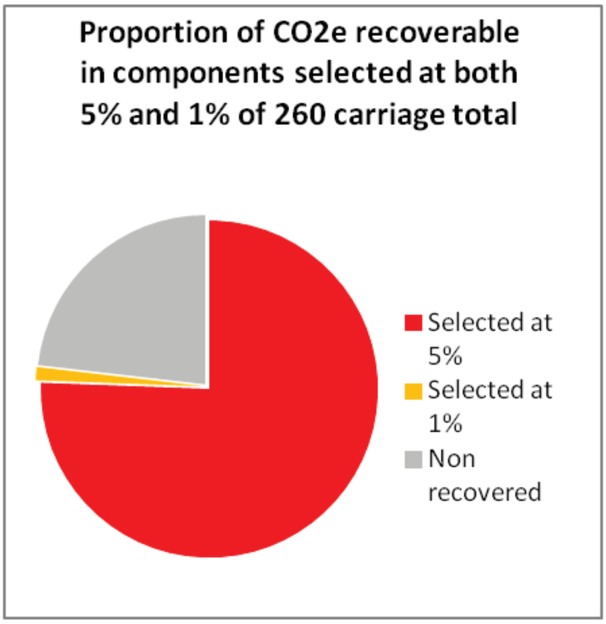


Figure 5.3 - Proportion of carriage CO_2e in selected components

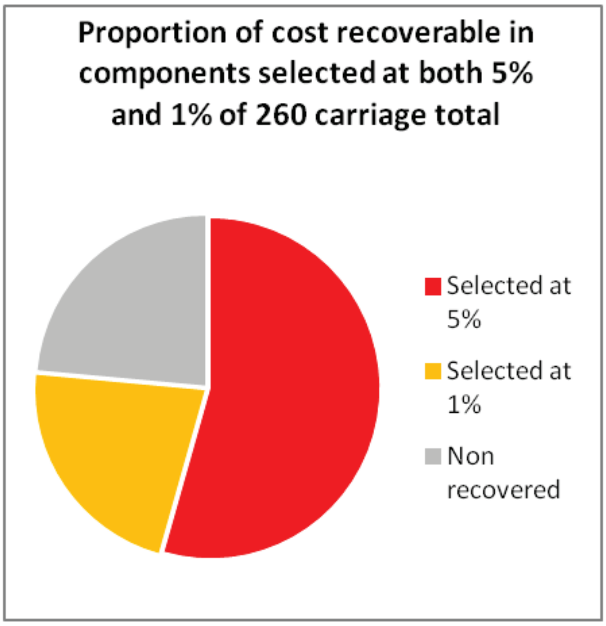


Figure 5.4 - Proportion of carriage cost in selected components

5.2.2.2 SL Chair

Based on the total manufacturing CO_2e impact (144 Kg/CO_2e) and cost (£229) of the SL chair, the component selection cut off values (1% and 5%) are listed in Table 5.5.

Cut off Criteria	Environmental Cut Off (Kg CO_2e)	Cost Cut Off (£)
1% of total	1.44	2.29
5% of total	7.20	11.44

Table 5.5 - Component selection cut off criteria for the SL Chair

The components selected in Table 5.6 (selected on CO_2e) and Table 5.7 (selected on cost) are those that were highlighted as above the cut off criteria. The components selected on environmental grounds are the various aluminium castings that make up the majority of the chair's structure and the steel seat base. The components also selected on being above the cost cut off criteria are the looms, control PCB and some purchased machined steel components and plastic mouldings.

Environmentally Selected Components (Kg CO_2e)						
Component		Qty	Total	Suitable component	Cut off criteria	Comments
2601054102	**TOTAL SL CHAIR**		**138.26**			
4004552	SL CHAIR-CHAIRBACK CASTING	1	40.02	✓	5%	
4004555	HINGE M/C SL CHAIR	1	10.59	✓	5%	
4004765002	CHASSIS, WELDED - MAN SWIVEL	1	9.87	✓	5%	
40045101	ARM MACHINED L/H SL CHAIR	1	9.98	✓	5%	
40045102	ARM MACHINED R/H SL CHAIR	1	9.98	✓	5%	
4004556002	SWIVEL COVER	1	1.61	x	1%	Plastic Cover
642052	260 SL CHAIR BOX	1	5.55	x	1%	Packaging
2604217	260SL CHANNEL TOP M/SWIVEL	1	4.19	✓	1%	

Table 5.6 - Components meeting environmental selection criteria in the SL Chair

Cost Selected Components (£)						
Component		Qty	Cost each	Suitable component	Cut off criteria	Comments
2601054102	260SL CHAIR L/H MANUAL SWIVEL		228.87			
4004552	SL CHAIR-CHAIRBACK CASTING	1	52.12	✓	5%	
2609139	260 SLCHAIR MANUAL SWIVEL LOOM	1	20.03	✓	5%	
4004555	HINGE M/C SL CHAIR	1	14.28	✓	5%	
4004765002	CHASSIS, WELDED - MAN SWIVEL	1	9.28	✓	1%	
40045101	ARM MACHINED L/H SL CHAIR	1	6.02	✓	1%	
40045102	ARM MACHINED R/H SL CHAIR	1	6.02	✓	1%	
4009110	400/260 SL CHAIR ARM PCB ASSY	1	4.3	✓	1%	
4004808004	SWIVEL BOSS	1	3.79	✓	1%	
4004796	ARM, EXTENSION, MOULDED	1	3.49	✓	1%	
4004923	ARM EXTENSION MOULDED	1	3.44	✓	1%	

Table 5.7 - Components meeting cost selection criteria in the SL Chair

From Table 5.6 and Table 5.7 the following components were targeted in the remanufacturing process for the SL Chair, Table 5.8. The packaging and plastic covers were deemed not suitable for remanufacture as they were likely to have sustained damage, which would not be reparable back to a like-new condition.

SL Chair Selected Components		
1	4004552.00	SL CHAIR-CHAIRBACK CASTING
2	2609139.00	260 SLCHAIR MANUAL SWIVEL LOOM
3	4004555.00	HINGE M/C SL CHAIR
4	4004765002.00	CHASSIS, WELDED - MAN SWIVEL
5	40045101.00	ARM MACHINED L/H SL CHAIR
6	40045102.00	ARM MACHINED R/H SL CHAIR
7	4009110.00	400/260 SL CHAIR ARM PCB ASSY
8	4004808004.00	SWIVEL BOSS
9	4004796.00	ARM, EXTENSION, MOULDED
10	4004923.00	ARM EXTENSION MOULDED
11	2604217.00	260SL CHANNEL TOP M/SWIVEL

Table 5.8 - Components selected for remanufacture from the SL Chair

Figure 5.5 and Figure 5.6 show the proportion of the total CO_2e and cost that the selected components represent in the SL Chair. It can be seen that selecting components with greater than 5% of the subassemblies CO_2e accounts for nearly 80% of the environmental impact. Another 4% was included by components making up greater than 1% of the total CO_2e impact. When selecting components by their financial, value 38% is recoverable at a 5% cut off criteria. Including the components that account for greater than 1% allowed a further 16% of the cost to be recovered.

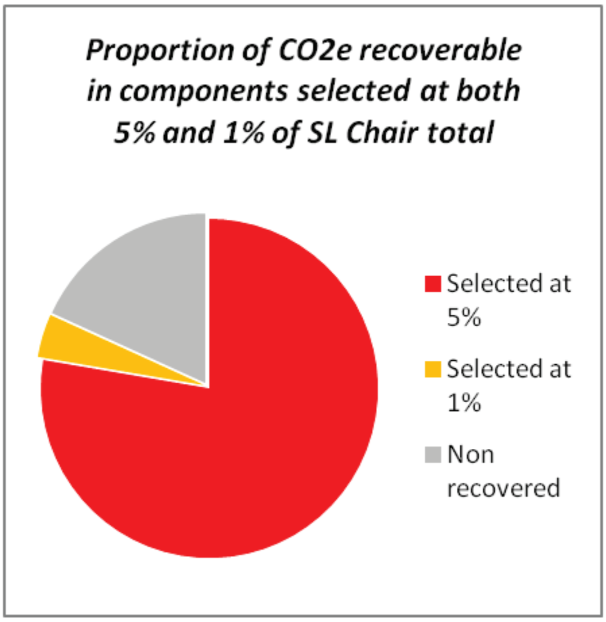


Figure 5.5 - Proportion of SL chair CO_2e in selected components

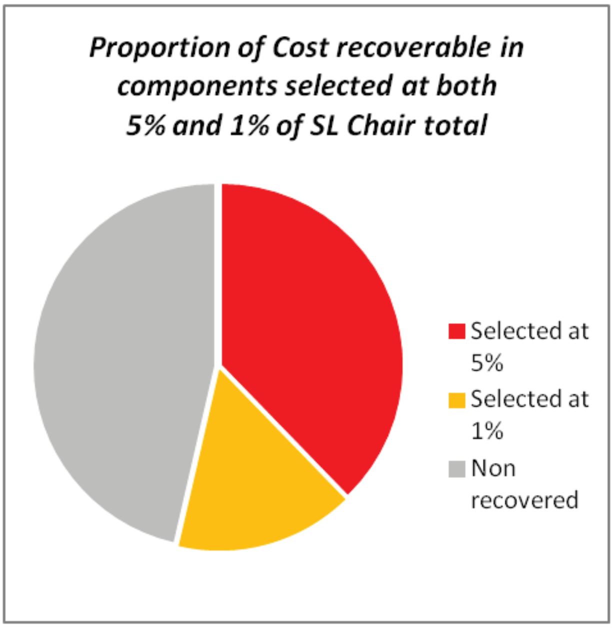


Figure 5.6 - Proportion of SL chair cost in selected components

5.2.2.3 260 Footrest

Based on the total CO_2e impact (29 Kg/CO_2e) and cost (£20) of the 260 footrest, the component selection cut off values (1% and 5%) are listed in Table 5.9.

Cut off Criteria	Environmental Cut Off (Kg CO_2e)	Cost Cut Off (£)
1% of total	0.29	0.20
5% of total	1.45	0.99

Table 5.9 - Component selection cut off criteria for the 260 Footrest

The components highlighted as above the environmental cut off criteria, Table 5.10, were also all included in the cost selection criteria Table 5.11, for the footrest. The footrest loom and switches were also included within the cost criteria along with some plastic components.

Environmentally Selected Components (Kg CO_2e)						
Component		Qty	Total	Suitable component	Cut off criteria	Comments
2604105102	**TOTAL FOOTREST**		**28.16**			
2504807	FOOTREST CASTING 260	1	18.527	✓	5%	
2504804002	SAFETY PAD-FOOTREST	1	1.877	x	5%	Plastic Cover
641433	BOX-260 FOOTREST	1	0.57	x	1%	Packaging
2504935	STIFFENER SAFETY PAD	1	0.85	✓	1%	

Table 5.10 - Components meeting environmental selection criteria in the 260 Footrest

Cost Selected Components (£)						
Component		Qty	Cost each	Suitable component	Cut off criteria	Comments
2604105102	**260 FOOTREST ASSY LH PEARL**		**£19.82**			
2504807	FOOTREST CASTING 260	1	£10.83	✓	5%	
2609160	260 FOOTREST LOOM L/H (CEN)	1	£2.25	✓	5%	
2504804002	SAFETY PAD-FOOTREST-PEARL-260	1	£1.92	x	5%	Plastic Cover
2604096102	SAFETY PAD EXT LONG LH PEARL	1	£0.57	x	1%	Plastic Cover
641433	BOX-260 FOOTREST	1	£0.50	x	1%	Packaging
2504935	STIFFENER SAFETY PAD	1	£0.35	✓	1%	
908504	SWITCH 1427 NC SAIA BURGESS	4	£0.26	x	1%	Safety Switch
3004607	FOOTREST WEBBING	2	£0.23	✓	1%	

Table 5.11 - Components meeting cost selection criteria in the 260 Footrest

From Table 5.10 and Table 5.11 the following components were targeted in the remanufacturing process for the 260 Footrest, Table 5.12. The packaging and external plastics would likely have irreparable surface damage so were also excluded. The safety switches were also excluded from remanufacture because of their importance to safety.

260 Footrest Selected Components		
1	2504807.00	FOOTREST CASTING 260
2	2609160.00	260 FOOTREST LOOM L/H (CEN)
3	2504935	STIFFENER SAFETY PAD
4	3004607	FOOTREST WEBBING

Table 5.12 - Components selected for remanufacture from the 260 Footrest

Figure 5.7 and Figure 5.8 show the proportion of the CO_2e and cost that is recoverable with the selected components in the 260 Footrest. It can be seen that 89% of the footrests total CO_2e impacts was captured at a 5% cut off criteria. By including the 1% cut off criteria, a further 6% of the CO_2e impact was also included. 80% of the cost was captured selecting all the components with greater than 5% and another 9% was captured using the 1% cost cut off criteria.

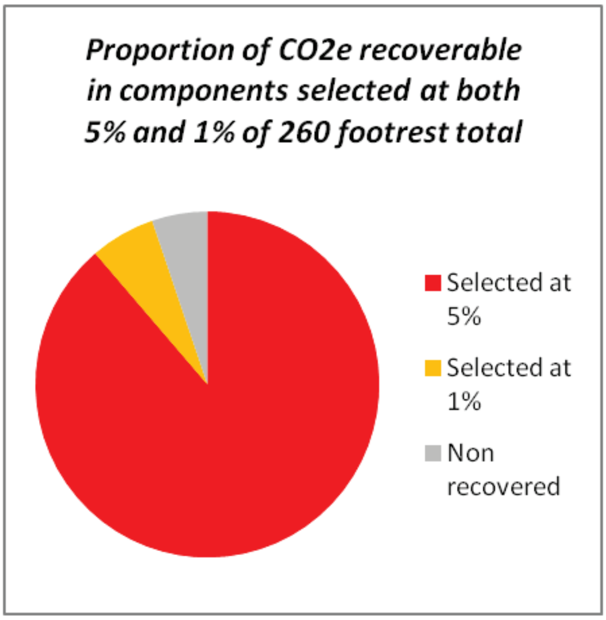


Figure 5.7 - Proportion of footrest CO_2e in selected components

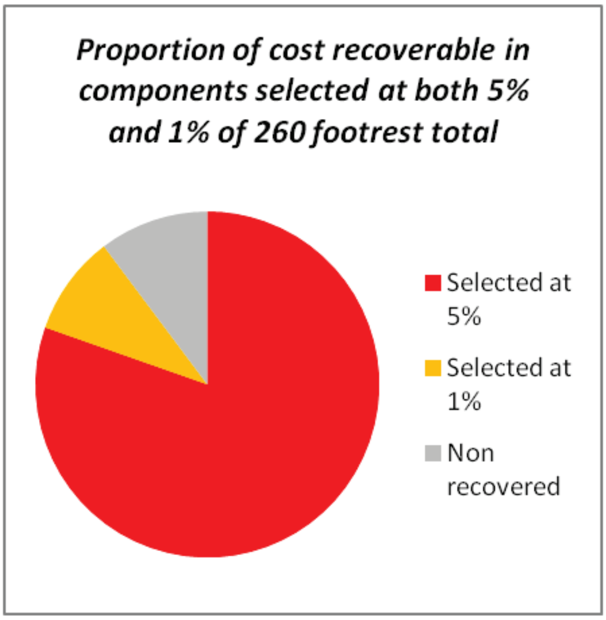


Figure 5.8 - Proportion of footrest cost in selected components

5.2.2.4 Rail Kit Box

Based on the total CO_2e impact (53 Kg/CO_2e) and cost (£44) of the rail kit box, the component selection cut off values (1% and 5%) are listed in Table 5.13.

Cut off Criteria	Environmental Cut Off (Kg CO_2e)	Cost Cut Off (£)
1% of total	0.53	0.44
5% of total	2.63	2.22

Table 5.13 - Component selection cut off criteria for the rail kit box

The rail legs make up the majority of the kit box and were selected under both environmental impact, Table 5.14, and cost, Table 5.15, along with other smaller components that make up the rail furniture.

Environmentally Selected Components (Kg CO_2e)						
Component		**Qty**	**Total**	**Suitable component**	**Cut off criteria**	**Comments**
2503001002	**TOTAL KITBOX**		**52.66**			
	LEGS (AVERAGE 1-8)	8	44.09	✓	5%	
2503608	CHARGE RAMP FIXING BLOCK	2	2.354	x	1%	Disposed of with rail
2503553	SLOWING RAMP FIXING	2	1.217	x	1%	Disposed of with rail
2503606102	END STOP WELDED ASSY PEARL LH	1	0.58	x	1%	Disposed of with rail
2503606202	END STOP WELDED ASSY PEARL RH	1	0.58	x	1%	Disposed of with rail
2503580004	END STOP PLUNGER	2	1.084	x	1%	Disposed of with rail

Table 5.14 - Components meeting environmental selection criteria in the 260 Rail Kit Box

Cost Selected Components (£)							
Component		Qty	Cost each	Suitable component	Cut off criteria	Comments
2503001002	**RAIL KIT BOX PRICE / PEARL**		**44.39**			
	LEGS (AVERAGE 1-8)	8	4.1	✓	5%	
2503553	SLOWING RAMP FIXING	1	£1.81	x	1%	Disposed of with rail
502226P	TOUCH-UP STK PEARL-260 RAIL	1	£1.50	x	1%	Disposed of with rail
2503608	CHARGE RAMP FIXING BLOCK	2	£0.79	x	1%	Disposed of with rail
2503581	SLOWING RAMP	1	£0.56	x	1%	Disposed of with rail

Table 5.15 - Components meeting cost selection criteria in the 260 Rail Kit Box

From Table 5.14 and Table 5.15 the following components were targeted for remanufacture from the rail kit box, Table 5.16. All components except the rail legs were excluded as they would be disposed of with the rail and not easily recoverable for remanufacture.

Rail Kit Box Selected Components		
1		LEGS (AVERAGE 1-8)

Table 5.16 - Components selected for remanufacture from the Rail kit box

Figure 5.9 and Figure 5.10 show the proportion of the cost and CO_2e that is recoverable with the selected components in the Rail Kit box. From the rail kit box only the rail legs were recoverable for remanufacture. These still account for nearly 80% of the CO_2e impact and 74% of the total financial cost of the kit box.

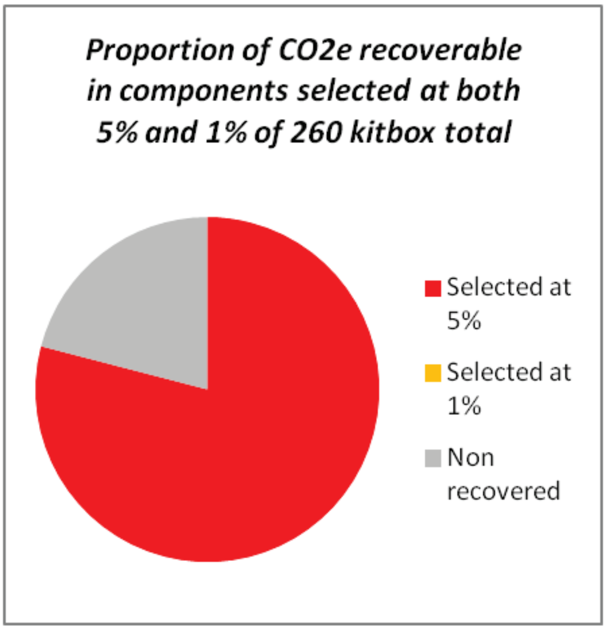


Figure 5.9 - Proportion of kit box CO_2e in selected components

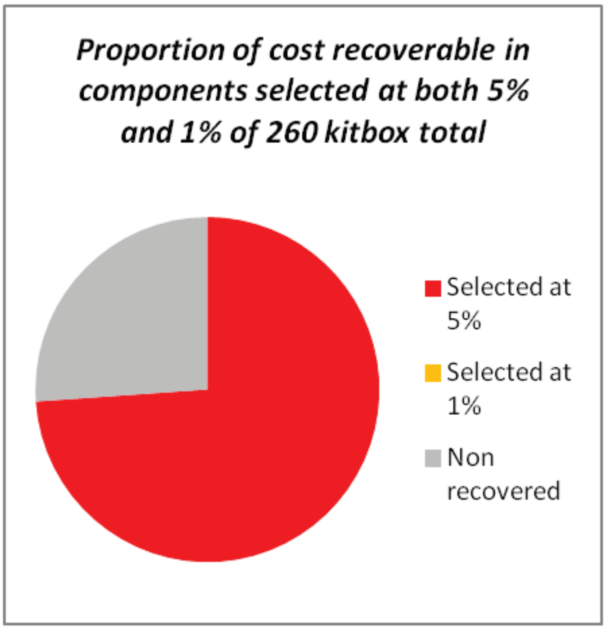


Figure 5.10 - Proportion of kit box cost in selected components

5.3 Estimated Benefit of Remanufacturing the 260SL Stairlift

In many cases the components that carry the highest value were also those that have the highest environmental impacts. Creating a remanufactured range of products targeting remanufacture of these critical components would have the greatest impact environmentally and financially for the business.

The quoted figures of an 85% energy saving (Steinhilper, 1998), a doubling of labour time (Charter, et al., 2007) and an 85% manufacturing cost saving (Ijomah, et al., 2007), were used by the author and developed into the following equations, Figure 5.11.

$$\text{Cost saving} = \text{Existing total cost} - \left(\left(\begin{matrix}\text{Recovered}\\ \text{component}\\ \text{cost}\end{matrix} \times 0.15\right) + \left(\begin{matrix}\text{Replacement}\\ \text{component}\\ \text{cost}\end{matrix}\right) + \left(\begin{matrix}\text{Total}\\ \text{labour}\\ \text{cost}\end{matrix} \times 2\right)\right)$$

$$CO_2e\ \text{Saving} = \text{Existing total CO2e} - \left(\begin{matrix}Recovered\\ material\\ CO2e\end{matrix} + \left(\begin{matrix}recovered\\ manufacturing\\ CO2e\end{matrix} \times 0.15\right) + \left(\begin{matrix}replacement\\ component\\ CO2e\end{matrix}\right)\right)$$

Figure 5.11 - Estimate remanufacturing cost and CO_2e savings equations, (by the author)

In the equation for cost saving, components for remanufacture have only 15% of their manufacturing cost retained for reprocessing back to a like-new condition. Components that were not selected for remanufacture have been replaced with new and their associated cost added into the equation. The existing labour cost has been doubled to allow for product disassembly, reprocessing of components and finally reassembly. Finally, the cost of the remanufactured product is subtracted from the cost of a new product to equate the potential saving.

In the equation for CO_2e saving, 100% material recovery was applied for remanufactured components. This is because all the material will be recovered for these components and there will be no need to replace this. 15% of the manufacturing impact has been maintained to allow for component reprocessing impacts. Components not selected for remanufacture have been replaced with new and their impact added into the equation. Finally, the reduced impact of the remanufactured product is subtracted from that of a new product to equate the potential savings.

Taking the selected components for each stairlift module, cost and CO_2e savings were estimated using the derived equations, Table 5.17.

Stairlift Module		£	Kg CO_2e
260 Carriage	Existing material	£415	162
	Existing labour	£57	
	Existing Total	**£472**	**162**
	Recovered material	£54.22	5.93
	New parts	£53.52	43.93
	Labour x2	£114	
	New Total	**£221.74**	**49.86**
	Total Carriage Saving	**£250.26**	**112.14**
SL Chair	Existing material	£183.57	57
	Existing labour	£45.30	
	Existing Total	**£228.87**	**57**
	Recovered material	£18.67	1.57
	New parts	£59.09	31.95
	Labour x2	£90.6	
	New Total	**£168.36**	**33.52**
	Total SL Chair Saving	**£60.51**	**23.04**
260 Footrest	Existing material	£18.69	9
	Existing labour	£3.81	
	Existing Total	**£22.50**	**9**
	Recovered material	£2.05	0.09
	New parts	£6.25	5.76
	Labour x2	£7.62	
	New Total	**£15.92**	**5.85**
	Total 260 Footrest Saving	**6.58**	**3.15**
260 Kit box	Existing material	£44.40	24
	Existing labour	£9.62	
	Existing Total	**£54.02**	**24**
	Recovered material	£4.92	0.20
	New parts	£11.60	6.43
	Labour x2	£19.32	
	New Total	**£35.84**	**6.63**
	Total Rail Kit Box Saving	**£18.18**	**17.79**
TOTAL	**Total Calculated Saving**	**£335.53**	**156.12**

Table 5.17 - Estimated potential environmental and cost savings through remanufacture

The existing total cost of the 260SL stairlift modules considered for remanufacture is £777. A saving of £336 equates to 43% of the original cost. The total CO_2e impact of a new product is 252 Kg CO_2e. A 165 Kg CO_2e saving represents 62% of the original impact. In both the cost and CO_2e, the majority of the saving were made up from the carriage and chair.

It should be noted that the calculated savings relate to the material and manufacturing stages of life alone. There will likely be other life cycle impacts, such as transporting components back to suppliers for remanufacture and impacts and costs associated with recovering of the core. These among others, will reduce the savings associated with a remanufactured product. Savings however, were still expected to be significant, compared with the production of a new product.

5.4 Case Study to Remanufacture the 260SL Stairlift

For each of the stairlift's modules, components were highlighted as possible candidates for remanufacture due to their value and/or environmental impacts. The estimated benefit of doing this was calculated and the 260SL looks to be a commercially and environmentally viable product for end of life remanufacture.

The practicality of product disassembly and component remanufacture was also assessed. A practical case study was used to test the feasibility, and verify the cost and environmental savings estimated for remanufacturing a stairlift as well as identify any issues with remanufacturing Stannah's 260SL stairlift.

5.4.1 Core Recovery

Stannah's installation and maintenance division offer a product removal service when the stairlift is no longer required. If the product is suitable for reuse then the customer may be offered a buyback option to encourage them to return the product to Stannah. The decision to reuse or scrap the product is based on the product age. Once 4 years is reached, the product is scrapped due to the lack of remaining time on the warranty of the motor gearbox, which would expire during the one year warranty offered with a refurbished product. Once the product is destined for scrap, there is a charge to the customer for product removal.

Stannah originally manufactured the test case stairlift in 2009, Figure 5.12. Since its first sale the product spent 4 years in service at a private residence and was removed by a Stannah engineer when it was no longer required, Table 5.18. Due to its age, this product would not be reused by Stannah and as such, would have ordinarily been scrapped after removal.

Recovered Product Information

a) **b)** **c)**

Figure 5.12 - Scrap 260 carriage (a), SL chair (b) and 260 footrest (c)

Model:	LH 260SL Sofia Manual.
Product serial No and manufacturing date:	Carriage – U26009154245 (Week 15 2009). Chair – C26009143315 (Week 14 2009). Footrest – F26009154518 (Week 15 2009).
Date of original purchase: Date of removal:	30/03/2009 13/05/2013
Product age (total time in use)	5 Years (4 Years).
Service history:	Annually serviced with no call out for breakdown or repair.

Table 5.18 - Detailed product Information record

To improve this stage, there needs to be better communication to the customer that Stannah will remove unwanted products even after 4 years of life. With the product no longer going to scrap, a buyback should also be offered for these older units to further encourage returning the product to Stannah. Once the product is back in the business, a system needs to be established to return the cores back to the manufacturing division of the Stannah Group for remanufacturing.

5.4.2 Initial Inspection

5.4.2.1 Visual inspection

Visually the product appeared to be in reasonable working order. The plastics were dirty and/or scratched along with some of the metal covers. The upholstery on the chair was worn in places and the footrest carpet was very worn and dirty. The engineer's notes that accompany the product stated that:

"The footrest motor was broken whilst removing the product."

The footrest motor, which was intended for remanufacture, had sustained damage at some point in the removal of the product or transportation back to Stannah. At this point the product had no packaging so a method of protecting it, such as a reusable transit crate, was required to ensure that the core was not damaged in transit and the level of remanufacture was kept to a minimum. This agrees with the work of Shu, et al. (1999). There should also be training provided to engineers tasked with removing products, to ensure they look after the core as a resource re-entering the business and not as scrap exiting the business.

At the point of initial inspection it would have been helpful to understand how heavily the product had been used. If the product kept a record of its use, this could be downloaded to give an indication of component wear. This would be particularly useful for assessing the likely condition of the motor.

With components being disassembled, reprocessed and reassembled potentially multiple times into different products, a method of recording the history of these components is also needed. This should track as a minimum their age, but preferably also the reprocessing undertaken so that when a component exceeds its tested life it is removed from the remanufacturing system and sent for recycling. Charter, et al. (2007) also noted this need and suggested that this could be achieved through date stamps or automatic identification and data capture (AIDC) technology such as RFID tags or barcodes on the components.

5.4.2.2 Stairlift design revision

It was necessary to identify any design changes that had taken place to the design of Stannah's 260SL stairlift since the manufacture of the case study product in week 14/15 of 2009. If they were not, at reassembly they would not marry up with new components on the production line.

Considering only the components that were selected for remanufacture, Stannah's Engineering Change Note (ECN), concession record and component drawings were consulted to identify changes. This process was made very difficult as there were no master records of changes made to the product. This resulted in a paperwork exercise to consult every component drawing for any changes that had been implemented since the date of manufacture. A product lifecycle management (PLM) system detailing the history of all components would have automated this process and identified any changes far more efficiently.

The changes that had taken place to the 260 carriage components, Table 5.19, SL chair components, Table 5.20, and 260 footrest components, Table 5.21, are listed below. Due to the significance of the changes and the resource that would be required to bring back to current revision, these components were not remanufactured. Removing these components from the study meant that, at product reassembly, they would be replaced with new components reducing the overall savings.

260 Carriage components no longer suitable for remanufacture			
Part No.	**Component**	**Date**	**Change details**
2604208002	260 CARR-WELDED ASSY PEARL	10/12/2010	Hole pattern changed for hand winding assembly.
		05/08/2012	Features for ISO switch and hand winding handle. Rocker switch pocket and hole enlarged.
		10/12/2010	Loom routing slot repositioned. Lifting handle feature added.
		07/01/2011	Lifting strap moved down 2mm, stop plate slot length reduced.
		29/06/2012	2 countersunk holes added. 2 recesses merged. Compatibility changes for S2 chair. Alternative loom route added.
		02/08/2012	Access for p/swivel PCB.
2504808	BLOCK-FOOTREST MTG-260	2012	Footrest casting and Block-Footrest combined into one part.
2609007	LOOM 260 CLUSTER	08/02/2012	Changed items 1-6 & 8-12 from 16/0.2 stranded to 126/0.07 stranded.
		03/05/2012	Reduced PVC sleeve by 90mm and added a cable tie.
2504865021	LOWER BRACKET - WELDED		Hole 2.1mm wider and 5mm deeper so larger switch cone fits within.
2604250	HANDWINDING SPIGOT ASSY (HEX)	2014	Dimensional changes.

Table 5.19 - 260 Carriage component design changes

SL Chair components no longer suitable for remanufacture			
Part No.	**Component**	**Date**	**Change details**
4004808004	SWIVEL BOSS	19/05/2009	2 holes diameter 5.1, CSK 1.0 x 45 degrees added.
2604217	260SL CHANNEL TOP M/SWIVEL	19/05/2009	4 holes added dia 4.0.

Table 5.20 - SL Chair component design changes

Footrest components no longer suitable for remanufacture			
Part No.	**Component**	**Date**	**Change details**
2504807	FOOTREST CASTING 260	27/11/2009	Switch mounting bosses removed and additional tapered holes for switch mounting added.
		27/11/2012	Footrest casting and Block-Footrest combined into one part.
2609160	260 FOOTREST LOOM L/H (CEN)		More switches added to the footrest assembly resulting in loom needing more connectors.
2504935	STIFFENER SAFETY PAD	18/09/2010	Dimensional changes.
3004607	FOOTREST WEBBING	18/09/2010	No Change, but permanently fixed to stiffener safety pad which has altered.

Table 5.21 - 260 Footrest component design changes

If these design revisions had not taken place, then all of these components would have still been suitable for remanufacture, highlighting the importance of design control in remanufactured products. It should be noted however, that the number of product changes seen here are higher than would ordinarily be expected over a 4 year period. The 260SL had a major update in order to meet the additional requirements of a new stairlift specific standard (British Standards, 2008) in late 2009. It was because of this update that many of the components were changed, excluding them from the study.

With no consideration currently being given to the future remanufacturability of components by Stannah, this had resulted in a lack of design control in the components intended for remanufacture. In total, 12 of the 28 selected components including the entire footrest module were eliminated from the study because of design changes. Figure 5.13 and Figure 5.14 demonstrate the proportion of the selected components these make up.

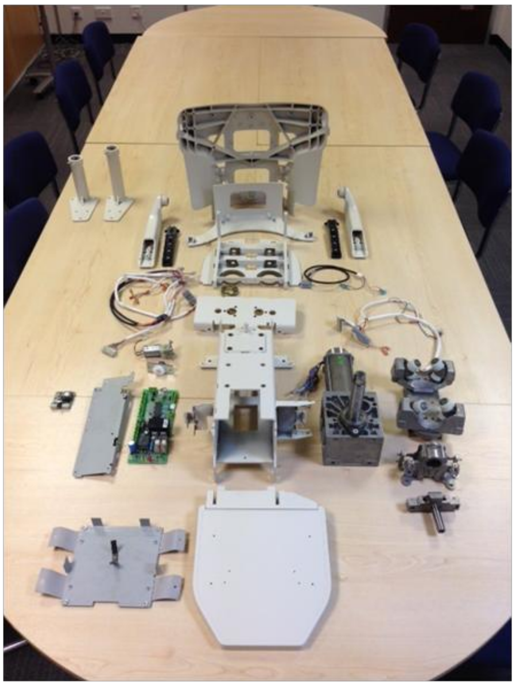


Figure 5.13 - Components initially selected for remanufacture

Figure 5.14 - Components of current revision not excluded from remanufacture

A reduction in design change to selected components could be achieved, for example, by establishing a blacklist of parts that cannot be changed without a higher level of sign off. Any product change would ideally then take place to the surrounding non remanufactured components. To an extent this is already happening to the cast components due to the high tooling cost of modifying these components. As such, the majority of the castings had not changed and remained within the study.

Designing with a modular philosophy would also help to prevent components from being excluded due to design changes, as critical constraints would remain the same enabling old and new components to be reused together.

5.4.3 Product Disassembly

The 260 carriage, SL chair, 260 Footrest and Kit box were each disassembled using a high torque air tool on a flat workbench. For each module, the time taken, total number and types of fixings were recorded, along with issues encountered, Table 5.22 - Table 5.25.

260 Carriage Disassembly	
Time to remove (min)	26:45
No. fixings removed	125
No. fixing types removed	15
Issues encountered in disassembly	
- Spade connectors and cable ties made removing looms difficult without damage. - PCB clips and cable ties hard to remove without damaging PCB. - Many different sized fixings and some in restricted locations. - Some hidden fixings that required over disassembly in order to access. - Circlips were fiddly to remove. - A bearing puller was required to remove the pinion which took a long time. - Dirty and greasy components needed to be removed.	

Table 5.22 - 260 Carriage disassembly

SL Chair Disassembly	
Time to remove (min)	11:10
No. fixings removed	51
No. fixing types removed	9
Issues encountered in disassembly	
- Dirty and greasy components needed to be removed. - Removing looms was be difficult with tight loom routing. - Many different sized fixings and some in restricted locations. - Some hidden fixings that required over disassembly in order to access. - Seatbelt hard to remove from arm and had to be cut free. - Sticky back Velcro left foam residue on the surface when peeled off. - Removing the seat base required a flexible adapter to access fixings.	

Table 5.23 - SL Chair disassembly

260 Footrest Disassembly	
Time to remove (min)	1:20
No. fixings removed	10
No. fixing types removed	2
Issues encountered in disassembly	
- Spade connectors made removing loom difficult without damage. - Rivets used to permanently attach components.	

Table 5.24 - 260 Footrest disassembly

Rail Kit Box Disassembly	
Time to remove (min)	0
No. fixings removed	0
No. fixing types removed	0
Issues encountered in disassembly	
- The legs required no further disassembly once they had been removed from the rail.	

Table 5.25 - Rail Kit Box disassembly

There were no real obstacles to overcome in disassembly. The high torque air tool removed all fixings with ease and was not hindered by substances such as Loctite threadlocker. Many of the components selected for remanufacture made up the major structural elements of each stairlift module. Consequently total product disassembly was required to extract them from the core. This process could have been made easier if there was further optimisation of fixing methods to reduce the number of fixing types and ensure they were easily accessible. As can be seen in Figure 5.15 and Figure 5.16 there were also some hidden fixings that slowed the process of disassembly.

Figure 5.15 - Hidden fixings on Cluster Housing

Figure 5.16 - Hidden fixing behind seatbelt strap

One of the most complex disassembly tasks was removing the looms from the product, most of which were intended for remanufacture so could not be cut free. Loom routing was tight, Figure 5.17, meaning switches had to be removed and in one instance tight spade connectors caused damage to the loom during disassembly, Figure 5.18. Cable ties were also extensively used to secure looms and the process of cutting these free posed a risk of damaging the loom.

Figure 5.17 - Tight and complex loom routing

Figure 5.18 - Broken cable from removing spade connector

Whilst permanent fixing methods were not extensively used, rivets were found in a few locations. If both components are found to be of a current revision, there is the possibility that they could be reused together without separation. If design change happens to one component however, then both would have to be excluded from future remanufacture due to them being inseparable.

To optimise the disassembly process and speed up component recovery, a disassembly line should be established with jigs to securely hold the product in place. Having multiple tools available, each with its own fixing type, would have also improved the efficiency of the disassembly process.

As total product disassembly was required to remove the target components, it was thought that additional components could be selected for remanufacture. These components would require no more than a visual inspection, but if they were current design revision and in good condition why shouldn't they also be recovered? It was decided that to maintain the clarity of the study and to determine the impact of remanufacturing, only the selected components would go forward.

5.4.4 Clean and Initial Inspection of Components

The internal components that were not painted required cleaning to remove dirt, grease and light corrosion which had gathered over the product life. An industrial jig washer, Figure 5.19, was used, which is designed to remove dirt and grease associated with welding processes from jigs. This is a fully automated process for cleaning and drying components. The chemical cleaner used by the jig washer is Pro-Spray 5400. This spray wash and degreaser has minor health and safety concerns and is not regarded as a danger to the environment.

Dry ice blasting, Figure 5.20, was also tested as a cleaning process and proved effective at removing dirt and grease from the components but was a slow and labour intensive process.

Figure 5.19 - Industrial jig washer

Figure 5.20 - Dry ice blasting

Some components did however, require additional cleaning due to their form trapping dirt, Figure 5.21 and Figure 5.22. If the product had been designed with cleaning components post use in mind, then some of the component forms could have been optimised to remove the need for additional cleaning. The work by Shu, et al. (1999) identified that smoothing of recesses and removal of small radii corners in areas prone to gathering dirt would help reduce the cleaning required . This is another example of how the design of a component can be optimised, if it is known that the component will be remanufactured early on, whilst the product is still in its design phase.

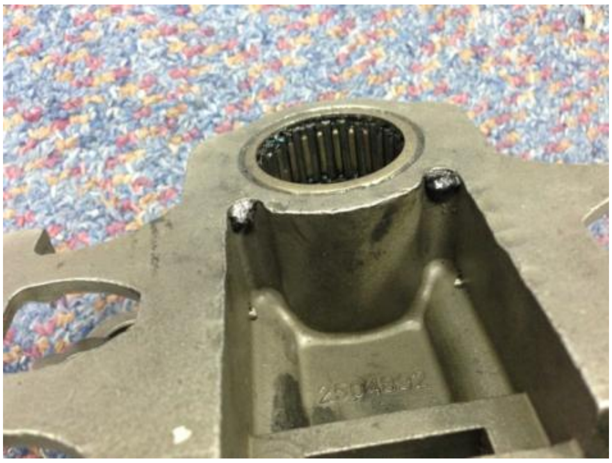


Figure 5.21 - Cluster housing gathers grease and dirt

Figure 5.22 - Motor gearbox gathers grease and dirt

After cleaning, some of the selected components showed signs of wear or damage. The Footrest Motor, Figure 5.23, had its shaft broken during removal from the property, preventing its remanufacture. The Swivel Boss, Figure 5.24, had some grooving around its circumference but this was light and not deemed to affect its performance going forward. A number of components including the footrest block, Figure 5.25, showed signs of paint damage that would require repainting.

Static looms should not degrade and visually appeared to be in good condition. Looms that articulate in operation degrade over the product's life. There was damage found on the exterior of the Cluster loom, Figure 5.26. This did not affect the functionality of the loom but the future durability of this cable was reduced. For this reason, it was not remanufactured.

The 260 carriage PCB was visually in good condition, but the software revision was out of date.

Figure 5.23 - Broken Footrest Motor

Figure 5.24 - Swivel boss wear

Figure 5.25 - Paint damage

Figure 5.26 - Cracked outer cable on a loom

The study required total removal of the epoxy powder coat to allow non destructive testing (NDT) to take place in the detailed inspection phase of the study. There were several methods explored for removing epoxy powder coat paint from metal components, Table 5.26:

	Method	Labour Intensity	Comments
Grit blasting	Painted surface is hit with a stream of grit propelled by compressed air.	Intensive	Slow and can damage component features such as threads.
Plastic pellet blasting	Painted surface is hit with a stream of plastic pellets propelled by compressed air.	Intensive	Slow process but softer than grit blasting, reducing component damage.
Fluidised bed	Parts are placed in a cage that is submerged in a fluidised bed of heated sand. A combination of heat and abrasion removes the paint. Post process washing is required.	Medium	Thin sections of metal can become warped. Parts require thoroughly washing.
Acid dipping	Parts are submerged in acid which dissolves the paint. Post process washing is required.	Medium	Environmental concerns over the hydrochloric acid used.
Pyrolysis oven	Parts are baked in a an oven causing the paint to expand and crack. Post process washing is required.	Medium	Thin sections of metal can become warped. Even after washing recoating paint can be affected.

Table 5.26 - Epoxy paint removal techniques

Environmentally, the best method of removing paint will depend on the impact categories being studied. Processes involving heat typically require high gas usage, so would not be an attractive option for global warming potential studies such as this one. To successfully remove all the paint without risking damage to the component, acid dipping was the most suitable method for all components, Figure 5.27. The use of hydrochloric acid presents significant danger to human and environmental health so the sustainability of this choice needs serious consideration if it were to be used as a production process. This process also presented the biggest overall cost to remanufacturing the effected components, making up on average 89% of the total component rework cost.

Figure 5.27 - Acid dipping to remove paint

If NDT components were not needed, the surfaces of the painted components could have been assessed against the paint standard which sets the acceptable levels of defect, damage, surface texture, colour and paint thickness. The quality of finish required is dictated by the visibility of the area to the customer:

A. This classification signifies a high quality surface exposed to close customer scrutiny and affecting the overall appearance of the product.
B. This classification is used on less conspicuous surfaces and/or surfaces that are normally hidden when the product is in everyday use.
C. No special consideration to film weight, colour, texture spots and inclusions will be applied. All Surfaces that are not identified as A or B Surfaces are considered Class C.

Where components fail the paint standard, over painting components may have been possible to cover cosmetic damage without prior paint removal. This would prevent this costly and environmentally hazardous process stage needing to be performed.

After cleaning and initial inspection, the following components were deemed to be damaged/worn beyond remanufacture and were removed from the study, Table 5.27. The components that were ruled out due to design change were also inspected to understand if they would have been suitable for remanufacture if they had been current revision, with none of them exhibiting significant signs of wear.

The footrest motor was damaged accidentally when the product was removed so in this instance it cannot be reused, but in the future should not be ruled out. The loom on the other had fatigued in life due to its articulation. This suggested that in its current design it would not be a suitable component for remanufacture.

Part Number	Part Name	Reason for exclusion
2609031	260 SL CARR P/FOOT MOTOR+ LOOM	Broken motor shaft.
2609007	LOOM 260 CLUSTER	Cable outer worn and cracked.

Table 5.27 - Parts excluded due to damage

5.4.5 Detailed Component Inspection

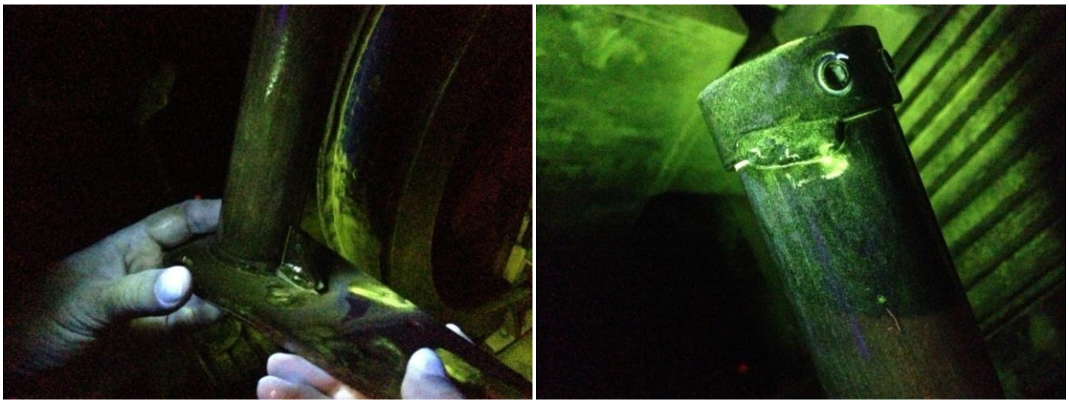
Products are life-tested for 10 years in product development (motors tested for 20 years), so a 4 year old product should not show significant signs of wear or fatigue. If however, the product was older or components had served several lives already in different products, then they would need to be inspected to determine if they were still safe to reuse.

Detailed inspection was undertaken to assess each of the components for the signs of wear or fatigue. The parts that were already excluded from the study due to design changes were also tested to ensure they had not fatigued and would be suitable for remanufacture if they had been current revision.

Non-destructive testing (NDT) was carried out on all parts that may have fatigued to ensure they were still safe to be remanufactured. A number of methods were used to assess components based on the level of inspection thought to be required. X-ray and ultrasound can identify component failure right the way through a material but were time consuming and expensive processes to conduct. Most fatigue related failure of components would start on the surface and penetrate through the material, (Mr Jay Noah (Inidam Ltd), 2014, personal communication). For this reason, faster and more cost effective methods were used that only inspect the surface of the component. Magnetic Particle Inspection (MPI) was used on ferrous materials. Dye Penetrant Inspection (DPI) was used non-ferrous materials.

To gain confidence in component remanufacture, testing was initially conducted on 100% of the surface area, for all castings and steel assemblies. All welds were also assessed looking for failure, Figure 5.28. Components such as the footrest casting and seat hinge that may have seen heavy load bearing were also X-rayed to look for any material flaws.

Once confidence had been established in a component's suitability for remanufacture and its life expectancy verified, an ongoing inspection classification could be used. Most components should only require a visual inspection, but electrical components would still require a greater level of testing as a visual inspection would be unlikely to identify loom or PCB failures.



a) **b)**

Figure 5.28 - Rail leg surface area (a) and welds (b) assessed for fatigue

Components were classified based on their load bearing function and likelihood of damage occurring in life. Component classifications are listed in Table 5.28:

Classification	**Inspection required**	**Test method**
0	No further inspection	n/a
1	Visual inspection	Eye
2	Surface analysis	Magnetic particle inspection Dye penetrant inspection
3	Material analysis	X- Ray
4	Electrical inspection	Electrical test equipment

Table 5.28 - Component testing classifications

Table 5.29 - Table 5.32 identifies the testing required (to gain initial confidence and ongoing requirement) for each component by stairlift module.

260 Carriage Component Inspection				
Part No	**Component**	**Confidence Classification**	**Ongoing Classification**	**Areas Requiring Specific Inspection**
2504100	MOTOR/GEARBOX 250 MK11	4 & 1	4 & 1	Electrical test Component wear
2504759	SKATE ASSEMBLY (MECH)	2	1	
260902700001	PCB 260 CONTROL ASSY COMMS	4	4	Electrical test
2609031	260 SL CARR P/FOOT MOTOR+ LOOM	4	4	Electrical test
2504892	CLUSTER HOUSING (CAST VERSION)	2	1	Fixing points Play in joints
4009117	400/260 SL POWER FOOTREST PCB	4	4	Electrical test
2504865021	LOWER BRACKET - WELDED	2	1	Welded joint
2609029	SL LOOM-CARRIGE TO CHAIR	1	4	Electrical test
2604208002	260 CARR-WELDED ASSY PEARL	2	1	Welds Fixing points
2504808	BLOCK-FOOTREST MTG-260	2	1	Fixing points
2604250	HANDWINDING SPIGOT ASSY	1	1	
2609007	LOOM 260 CLUSTER	1	4	Electrical test
2604238	ECU – MOUNTING BRACKET	0	1	

Table 5.29 - 260 Carriage components testing requirements

SL Chair Component Inspection				
Part No	**Component**	**Confidence Classification**	**Ongoing Classification**	**Areas Requiring Specific Inspection**
4004552	SL CHAIR-CHAIRBACK CASTING	2	1	Fixing points
2609139	260 SLCHAIR MANUAL SWIVEL LOOM	4	4	Electrical test
4004555	HINGE M/C SL CHAIR	3	1	Fixing points
4004765002	CHASSIS, WELDED - MAN SWIVEL	2	1	Welds Fixing points
40045101	ARM MACHINED L/H SL CHAIR	2	1	
40045102	ARM MACHINED R/H SL CHAIR	2	1	
4009110	400/260 SL CHAIR ARM PCB ASSY	4	4	Electrical test
4004808004	SWIVEL BOSS	1	1	Circumference
4004796	ARM, EXTENSION, MOULDED	1	1	
4004923	ARM EXTENSION MOULDED	1	1	
2604217	260SL CHANNEL TOP M/SWIVEL	2	1	

Table 5.30 - SL Chair components testing requirements

260 Footrest Component Inspection				
Part No	**Component**	**Confidence Classification**	**Ongoing Classification**	**Areas Requiring Specific Inspection**
2504807	FOOTREST CASTING 260	3	1	Around fixing points
2609160	260 FOOTREST LOOM L/H (CEN)	1	4	Electrical test
2504935	STIFFENER SAFETY PAD	1	1	
3004607	FOOTREST WEBBING	0	1	

Table 5.31 - 260 Footrest components testing requirements

Kit Box Component Inspection				
Part No	**Component**	**Confidence Classification**	**Ongoing Classification**	**Areas Requiring Specific Inspection**
	LEGS (AVERAGE 1-8)	2	1	Welding Collar Base plate welding

Table 5.32 - Kit box components testing requirements

The results of the non-destructive testing identified fatigue on the carriage chassis with a 4mm crack in one weld, Figure 5.29. This feature provides a mechanical stop for the skate. A 2mm crack was identified in one of the seat chassis welds. A crack 10mm in length was also found in one of the bend radii of the same component, Figure 5.30. These failures were assessed by Stannah's Engineering department and were deemed not to be safety critical or acting in the plane of strength, so would not prevent the reuse of these components.

Figure 5.29 - Fatigue identified on the carriage chassis

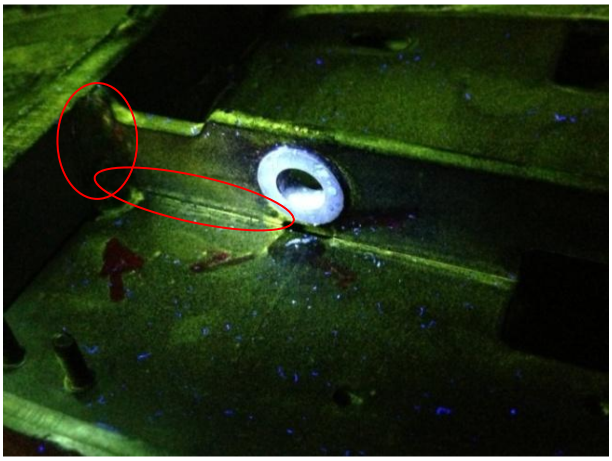


Figure 5.30 - Fatigue identified on the seat chassis

No signs of fatigue were witnessed in any of the castings based on their surface analysis. The footrest, Figure 5.31, and seat hinge, Figure 5.32, were also X-rayed as they had the potential to have taken excessive load in life. These both came back clear with no signs of material failure or defect.

Figure 5.31 - 260 Footrest X-ray inspection

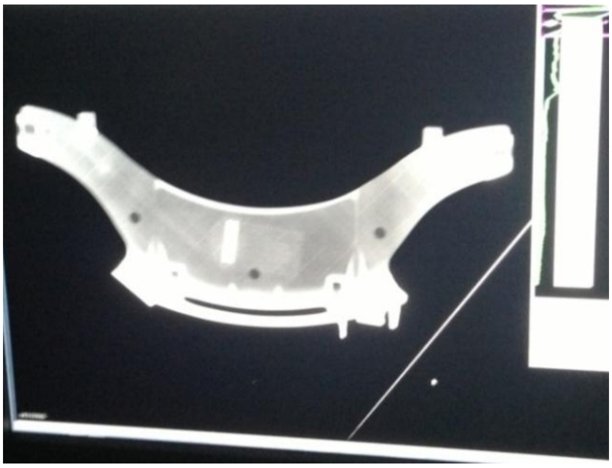


Figure 5.32 - SL chair seat hinge X-ray inspection

This testing was arguably flawed because, despite the product having seen 4 years worth of life, it was not known what level of use, load or angle of staircase the stairlift had been subjected to. To achieve the required level of confidence that all components would be safe for reuse will require further testing. A controlled test should subject batches of components to the maximum load capacity of the product and be tested for the maximum period of time that products would be accepted back for remanufacture. If no failures were found using NDT, then all components received back for remanufacturing should be safe for reuse.

The electrical components within the stairlift were tested to ensure they were still in good working order. The motor was tested using a dyno rig, Figure 5.33, to assess its electrical characteristics compared to a new motor.

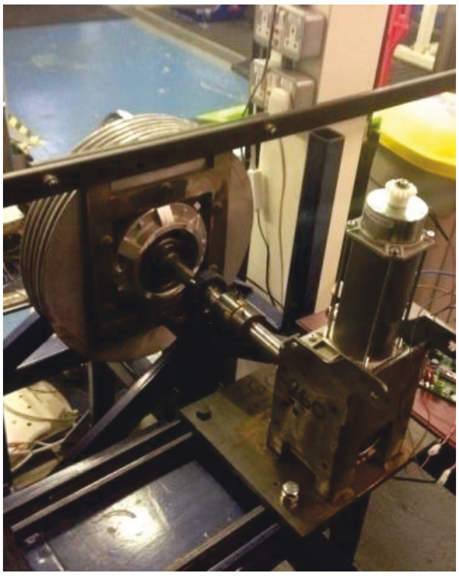


Figure 5.33 - Motor dyno test rig

The motor dyno test simulated a varying load being applied to the motor. The current was recorded to assess the performance and condition of the motor. Comparing load and current, Figure 5.34, and Load verses RPM, Figure 5.35, it was found that the motor was performing very closely to a new motor and at no point outside the excepted tolerance of a new unit.

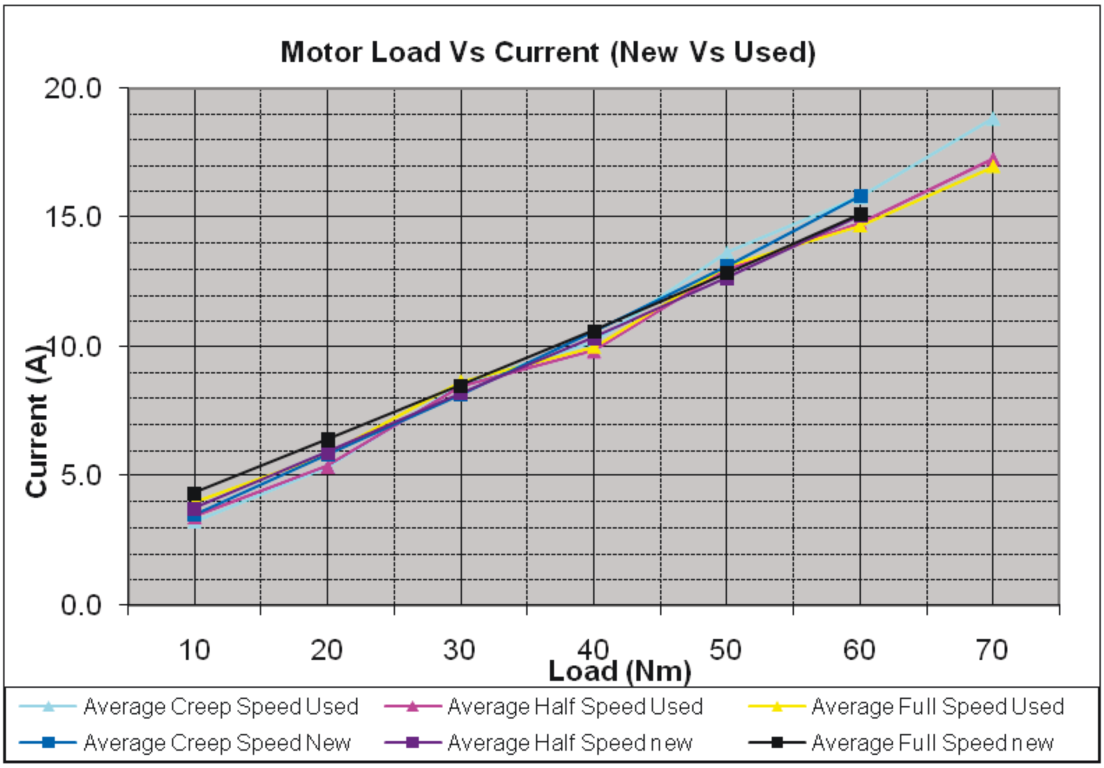


Figure 5.34 - Motor load Vs Current (New Vs Used)

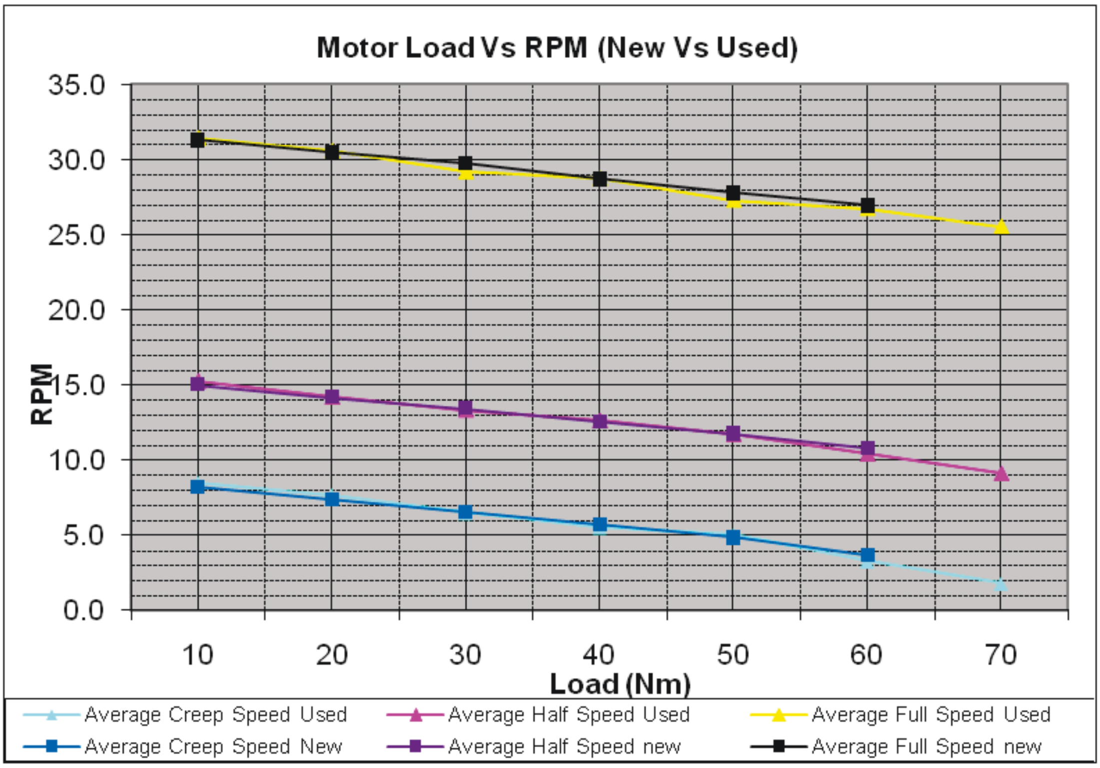


Figure 5.35 - Motor load Vs RPM (New Vs Used)

Following the dyno test, the motor was sent back to the original manufacturer for disassembly and inspection for signs of wear and fatigue. The carbon brushes were worn down by 1.4 mm one side and 2.4 mm the other, Figure 5.36. This slight difference in wear follows from a minimal incorrect adjustment to neutral at manufacture. The Collector, Figure 5.37, had normal traces from the carbon brushes but no sign of significant wear.

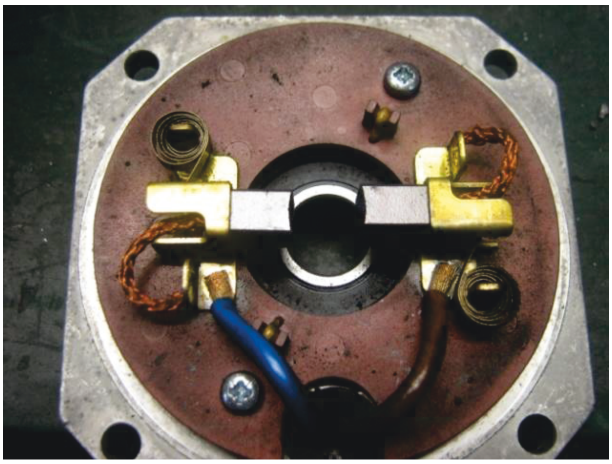


Figure 5.36 - Motor carbon brush wear

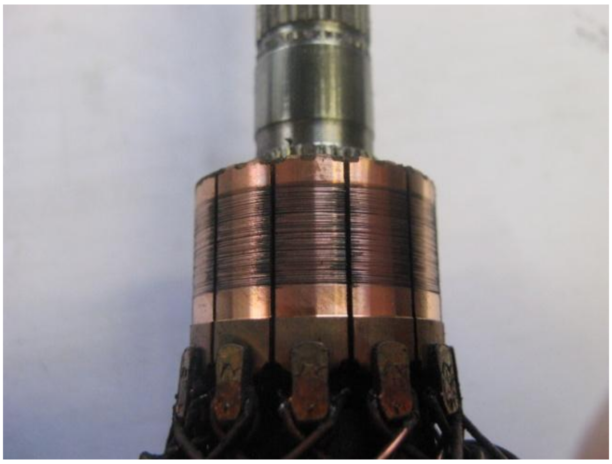


Figure 5.37 - Motor collector wear

The Gear stages in the gearbox show little sign of wear and were all in excellent condition, Figure 5.38

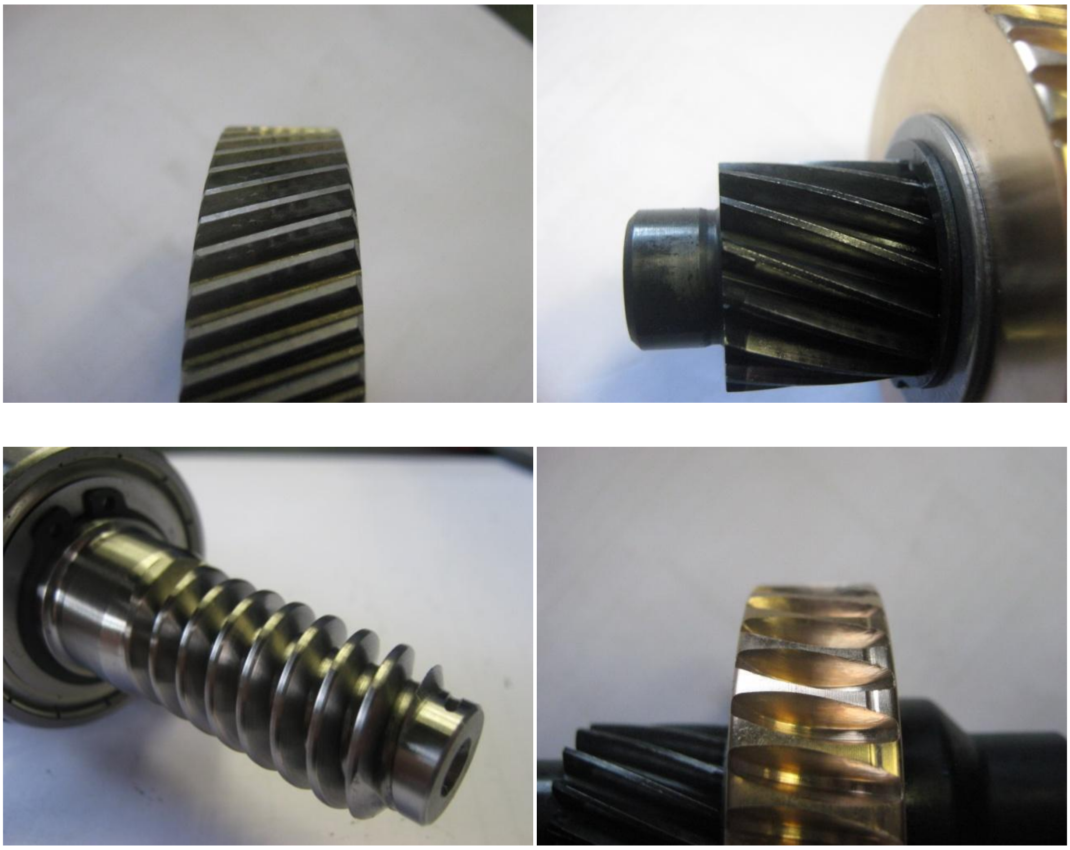


Figure 5.38 - Motor gearbox wear

The wear to the radial seal seat, Figure 5.39, was minimal and showed little sign of being worn in. The Gearbox oil, Figure 5.40, was also in very good condition and showed little sign of wear within the gearbox.

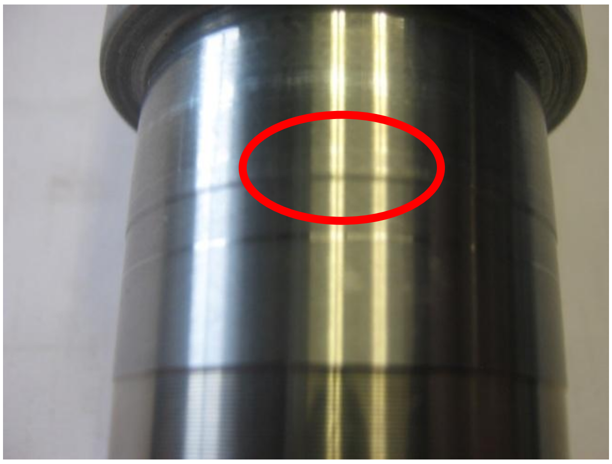


Figure 5.39 - Motor radial seal seats wear

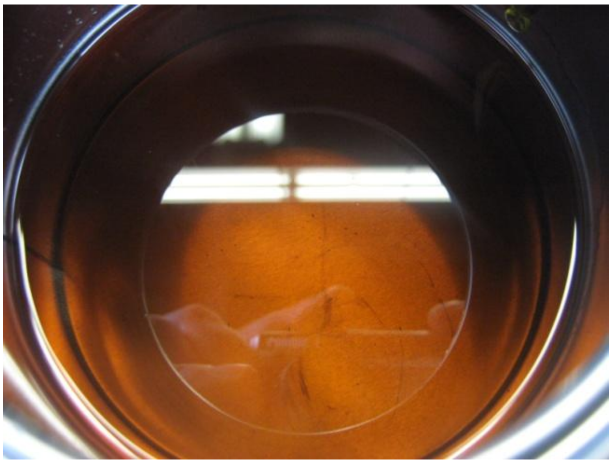


Figure 5.40 - Motor gearbox oil wear

The motor brake demonstrated a fault that was present in motors of its age, an issue rectified in later models. The serrated hole in the centre of the brake disc, Figure 5.41, slowly strips the teeth off the plastic, until the point it fails to grip the motor shaft and the brake ceases to operate. The rest of the brake unit, Figure 5.42, was still in good condition, although it was not known at what point the brake disc failed and so how much life the brake had actually seen.

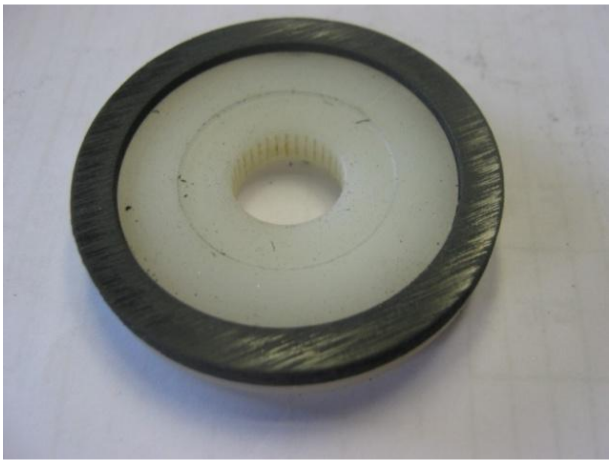


Figure 5.41 - Failed motor brake disc

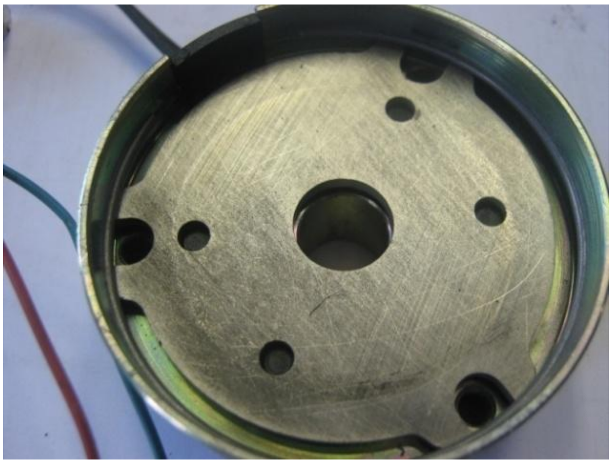


Figure 5.42 - Motor break wear

In general, other than the fault with the brake, it was felt after four year's worth of use the motor was in very good condition, only showing minimal signs of wear.

The update to the motor brake is a good example of how even if components are blacklisted to prevent change, updates may be required to correct issues such as reliability. Updates such as these would need to be managed as part of the remanufacturing process. The key requirement of the update though, is that it does not impact on surrounding components and can be retro fitted to the existing design ensuring future compatibility.

The 260 control PCB and footrest PCB s were both tested to ensure they were not faulty or damaged during life or the disassembly process. The original manufacturer tested each PCB using their end of line test equipment. The bed of nails tested the circuit was fully working as expected and that there was no damage/errors to the board or software, Figure 5.43. The functional test checked the PCB by physically asking it to perform tasks as it would in use, such as operating a motor, Figure 5.44.

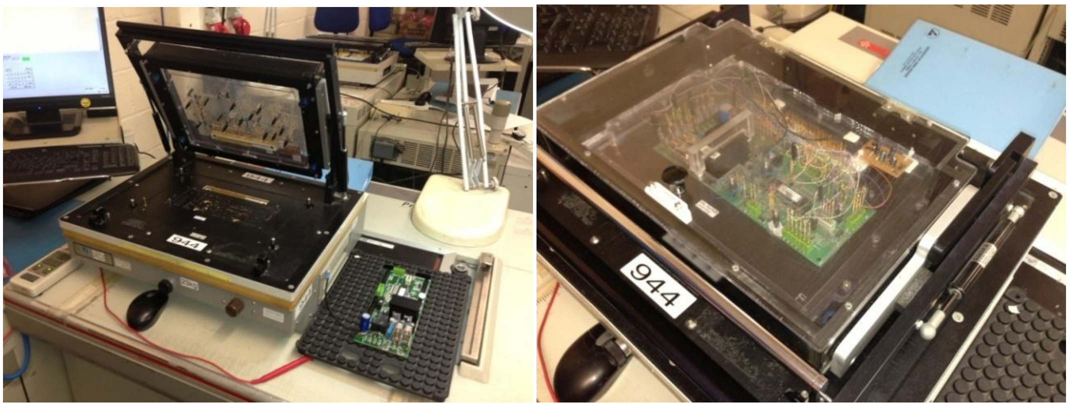


Figure 5.43 - Bed of nails PCB test equipment

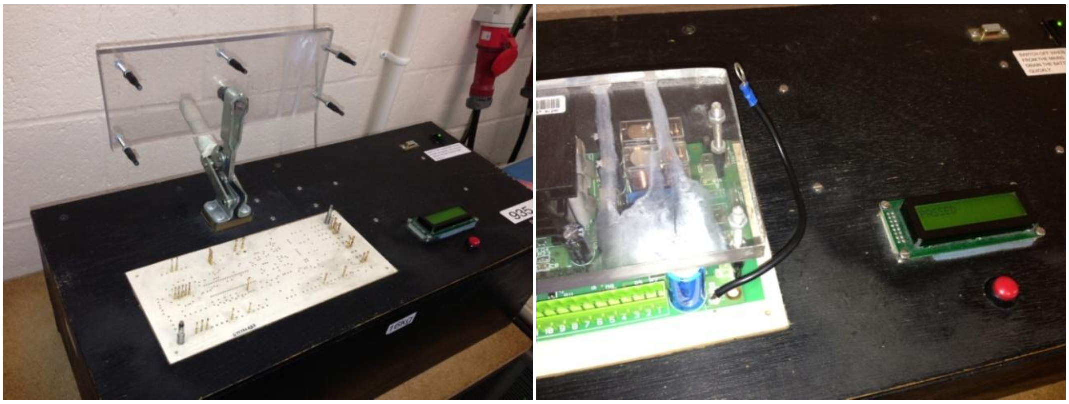


Figure 5.44 - Functional PCB test equipment

In testing, the 260 control PCB was not operating within the same specification as a brand new board. This was because some components wear in before stabilising in use. This was an expected characteristic and would not affect the ongoing operation of the product. Both PCBs were deemed to have passed the bed of nails and the functional testing, but a software update would be required on the 260 control PCB.

Looms were inspected and on one occasion signs of fatigue were identified ruling this loom out from further reprocessing. The looms represent costly components that are vulnerable to wear, and are a good example of components that might benefit from being over specified to ensure durability. Shu, et al. (1999) suggests that an additional cost associated with design for remanufacture can be offset against multiple product lives. Likewise, any increased upfront cost to improve durability may be offset against the increased number in acceptable condition for reuse. A side benefit of increasing the durability of vulnerable components such as looms is that a reduction in reliability issues in first and future lives should also follow.

The detailed inspection stage of the remanufacturing process raised the question of whether basing the reuse guidelines for products on age was the correct measure. A product that had seen 4 years life with a large user, on a steep staircase would likely be in a worse condition than a product of 8 years that had seen an easy life. If better recording of product use was possible, such as miles travelled, user weight and staircase angle this would give a better indication of the product's overall condition. With most users not weighing the maximum 135kg load capacity, this might also increase the number of cores returned and suitable for remanufacture.

Taking this concept one stage further, each component could be given a specific reuse cut off criteria determined by its function. An example of this would be the reuse of the motor would be determined by the miles travelled and load, whereas a casting might be better determined by age and load. This is an area for further investigation and moves the reuse criteria closer to the approach of Xerox (2005), which determined a 'signature' for each component. Continued reuse of the component was permitted provided the component remained within tolerance of the original 'signature', which was not determined by age.

5.4.6 Reprocessing Components Back to a Like-new Condition

It was decided that no component updates would be carried out to retrofit design changes. The majority of the remaining components did not require a vast amount of reprocessing to bring them back to a like-new condition. The most common reprocessing activity was repainting components to give them a clean, new, aesthetic appearance.

5.4.6.1 Skate Assembly (Mechanical)

The skate is an integral part of the stairlift carriage, used to secure the product to the rail and ensure the product remained level on the staircase. It was disassembled using a high torque air gun, Figure 5.45, regreased and then reassembled to the correct torque level. Shims were used to ensure there was no more the 1mm of movement between the component parts. If the skate components had worn, the shims could be replaced to bring the assembly back within tolerance.

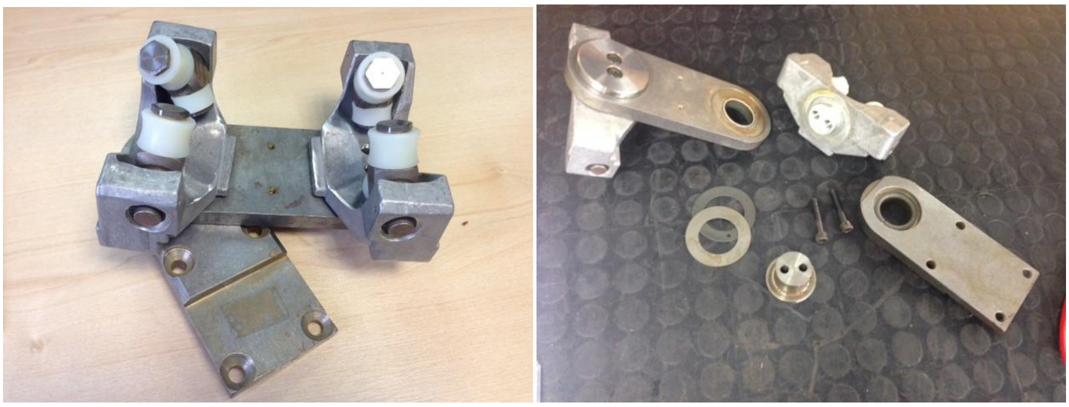


Figure 5.45 - Skate disassembly for cleaning and regreasing

The rollers on the skate assembly had worn in use and required replacing. Since the date of manufacture there had also been a design change to the yokes which hold the rollers. These therefore required replacing as well with the simple removal of a circlip, Figure 5.46. If the yokes had been current revision, then only the rollers would have required replacing and the yokes also reused, Figure 5.47.

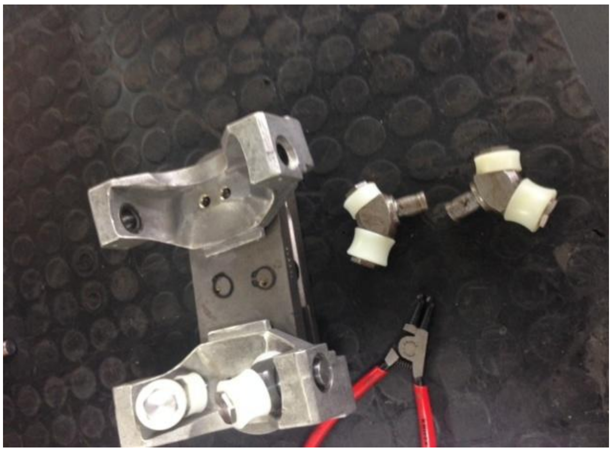


Figure 5.46 - Roller yoke replacement

Figure 5.47 - Roller only replacement

5.4.6.2 Cluster Housing

A bearing was pressed into the cluster housing which allowed the motor shaft to rotate cleanly. The condition of the bearing was assessed and not deemed to have worn significantly. The cluster had passed through the jig washer, thoroughly cleaning the bearing. Therefore it was decided it should be regreased and reused.

The bearing was pressed into the casting from one side as shown in Figure 5.48. There was no access to the bearing from the other side to remove this again, which would have proved problematic had the bearing needed replacing.

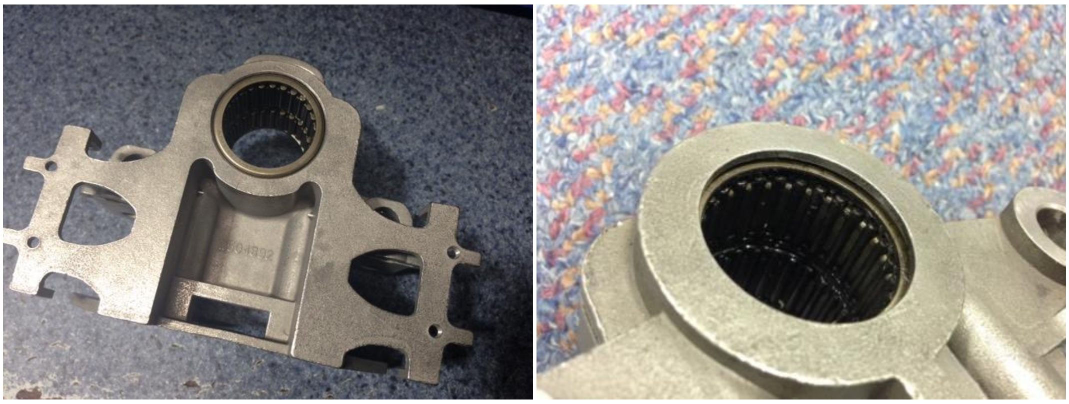


Figure 5.48 - Bearing pressed into cluster housing

5.4.6.3 Motor Gearbox

The motor gearbox took the most reprocessing of any of the selected components for remanufacture, but it is also the most valuable component so had the highest worth in recovering and reprocessing. The remanufacturing was conducted by the original manufacturer and with the detailed inspection revealing its good condition, much of the motor and gearbox was reused, only replacing the worn components:

- Brushes, end plate and loom.
- 0,3kg of synthetic Oil.
- Roller bearing on 1^{st} and 2^{nd} gear stages.
- Joint ring (x3).
- Sealing cap (x2).
- Notched ring.

The brushes were worn and required replacement, but as they were permanently fixed to the end plate and loom, everything had to be replaced. Redesigning the method of attaching the brushes to the board would enable easy replacement and greater recovery at remanufacture.

In addition to this reprocessing work, there was also the need to correct the brake failure. This was possible, but required an extensive rebuild. The solution to the motor brake failure corrected, back in late 2009, was to change the serrated hole in the brake disk to a square hole, Figure 5.49, increasing strength. The motor rotor also required changing to match the change to square geometry. This change resulted in further components requiring replacement as part of the motor remanufacture:

- Whole brake assembly.
- Whole motor rotor.
- Insulating band.
- Anchor body of the motor.

(a) **(b)**

Figure 5.49 - Old serrated hole brake disc (a) and new square hole brake disc (b)

In total the reprocessing of the motor gearbox took 180 minutes but it was felt that the majority of this time was in updating the break failure. If simply inspecting and replacing the worn components the reprocessing time was estimated at around 30 minutes.

5.4.6.4 PCB Software Update

The software on the 260 control PCB required updating to the next revision, correcting some minor software glitches that had been identified since 2009. All the software on the PCB was recorded to a removable microprocessor. The old microprocessor was lifted out of its socket with a flat head screwdriver, Figure 5.50. The replacement microprocessor was then reinserted in its place.

Whilst a simple process, care had to be taken not to bend or break the pins when reinserting the microprocessor back into the PCB. To reprogramme the microprocessor without removing it would be a better solution, but a connection point would be needed to plug the board in and upload the new software. This again is an example of how the product could be redesigned to improve its remanufacturability. Care was also taken not to subject the board to electro-static discharge. To prevent this an earthing strap was worn when handling the PCBs.

Figure 5.50 - Replacing the PCB microprocessor

Coatings and finishes

The painted components that were stripped, required repainting. To repaint the components they were passed back through the factory paint plant to recoat them in the same way any new component would be.

First bungs were fitted to any features such as threads where paint should be avoided, Figure 5.51. The components were then washed to remove any dirt or oils on the surface which would affect the adhesion of the paint, Figure 5.52. Components were negatively charged and their surface sprayed with positively charged powder paint, which sticks, Figure 5.53. Finally, the paint was cured in an oven at 200 degrees Celsius, Figure 5.54.

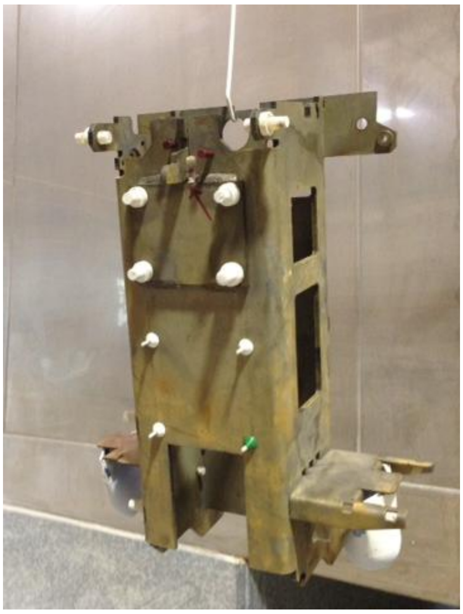


Figure 5.51 - Components bunged

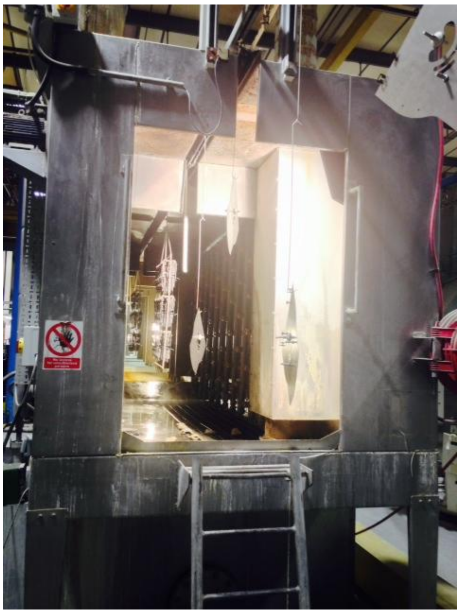


Figure 5.52 - Pre paint wash

Figure 5.53 - Powdered paint applied

Figure 5.54 - Paint cured in oven

5.4.7 Product Reassembly

After going through the remanufacturing cycle, parts were excluded for various reasons at each stage. The components that were deemed acceptable and reprocessed back to a like-new condition, are listed in Table 5.33 (carriage), Table 5.34 (chair) and Table 5.35 (kit box).

Components remanufactured from the 260 Carriage		
1	2504100	MOTOR/GEARBOX 250 MK11
2	2504759	SKATE ASSEMBLY (MECHANICAL)
3	260902700001	PCB 260 CONTROL ASSY COMMS
5	2504892	CLUSTER HOUSING (CAST VERSION)
6	4009117	400/260 SL POWER FOOTREST PCB
7	2609029	SL LOOM-CARRIGE TO CHAIR

Table 5.33 - Carriage components suitable for remanufacture

Components remanufactured from the SL Chair		
1	4004552.00	SL CHAIR-CHAIRBACK CASTING
2	2609139.00	260 SLCHAIR MANUAL SWIVEL LOOM
3	4004555.00	HINGE M/C SL CHAIR
4	4004765002.00	CHASSIS, WELDED - MAN SWIVEL
5	40045101.00	ARM MACHINED L/H SL CHAIR
6	40045102.00	ARM MACHINED R/H SL CHAIR
7	4009110.00	400/260 SL CHAIR ARM PCB ASSY
8	4004796.00	ARM, EXTENSION, MOULDED
9	4004923.00	ARM EXTENSION MOULDED

Table 5.34 - SL Chair components suitable for remanufacture

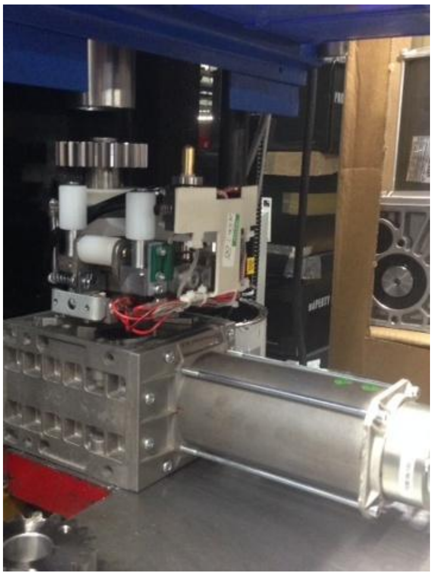
Components remanufactured from the Rail Kit Box		
1		LEGS (AVERAGE 1-8)

Table 5.35 - Kit box carriage components suitable for remanufacture

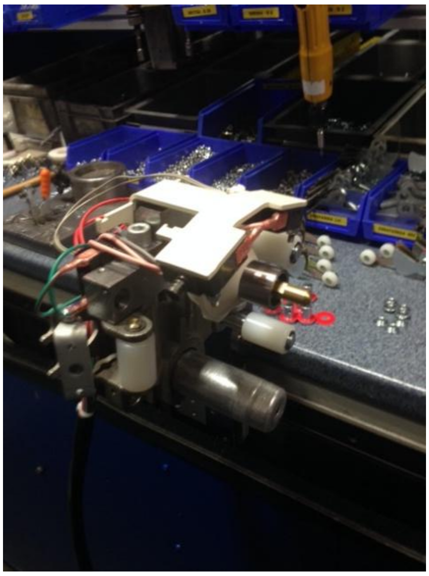
To reassemble the remanufactured components back into a product Stannah's existing production line was used. This ensured that the products were rebuilt using the same process and to the same standard as a new product. Components that were removed from the study were replaced with new from the line.

5.4.7.1 260 Carriage Reassembly

The carriage reassembly process, Figure 5.55, ran smoothly down the production line with both new and old components combining to rebuild a 260 carriage with no problems encountered.

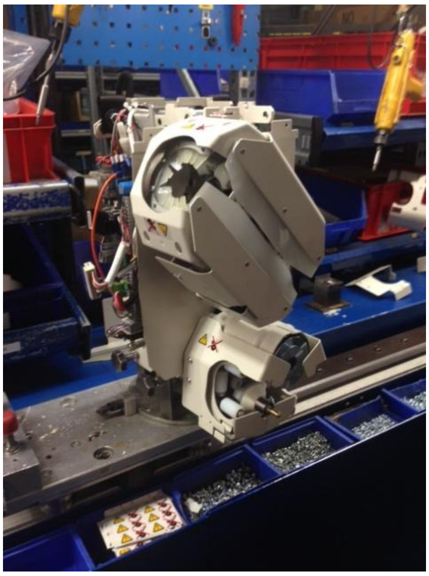


a)



b)

c)



d)

Figure 5.55 - 260 carriage reassembly

a) Rebuilding the drive mechanism.

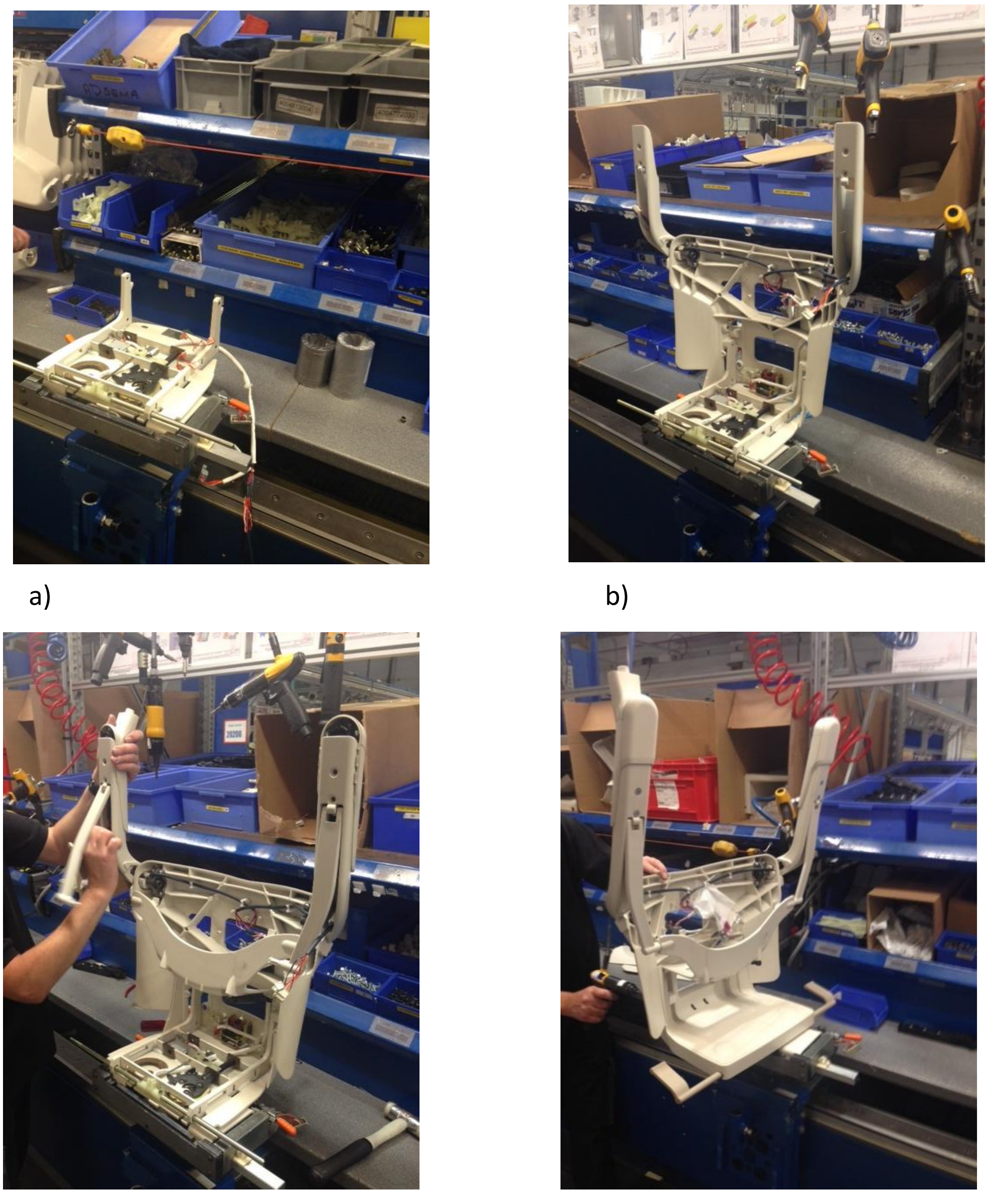
b) Mounting the drive mechanism on to the motor gearbox.

c) Assembling the drive mechanism and skate to the carriage chassis.

d) Safety covers being assembled around the carriage.

5.4.7.2 SL Chair Reassembly

The SL chair reassembly process, Figure 5.56, also ran smoothly in the main with remanufactured parts going back together in combination with new components on the line.



a) b)

c) d)

Figure 5.56 - SL chair reassembly

a) Seat base and swivel mechanism assembly.

b) Seat back casting and arms assembled to seat base.

c) Seat hinge added and arm controls connected.

d) Covers assembled around the chair.

One threaded hole in the SL seatback casting was damaged, Figure 5.57, and was not detected in the reprocessing of this component. This feature required re-tapping before assembly could continue as the hole was not accepting the bolt. This demonstrated the need for reassembly lines to have the ability to quickly resolve minor reprocessing issues that have been missed. E.g. re-tapping a cross threaded hole or adding a small amount of touch up paint to a component. Alternatively, components would be rejected for reworking, requiring any assembly that had already taken place to be disassembled again.

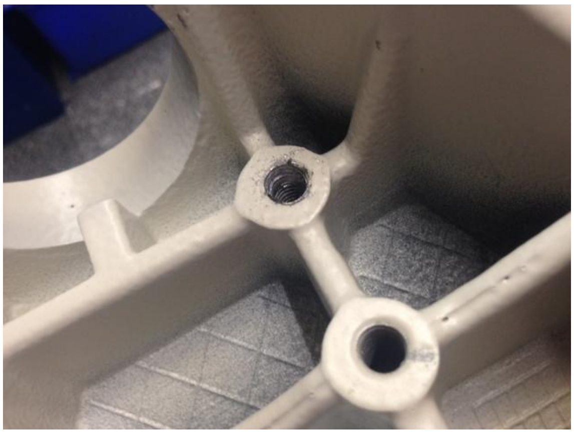


Figure 5.57 - Damage thread on the SL chair back casting

5.4.8 Testing

Testing was carried out on both the carriage and chair to ensure that they were both operating at the standard expected of new product.

5.4.8.1 260 Carriage testing

The 260 carriage was tested at several stages throughout its remanufacture. The first test stage, Figure 5.58, ensured that the over speed governor (a safety feature) was operating correctly. This test was passed.

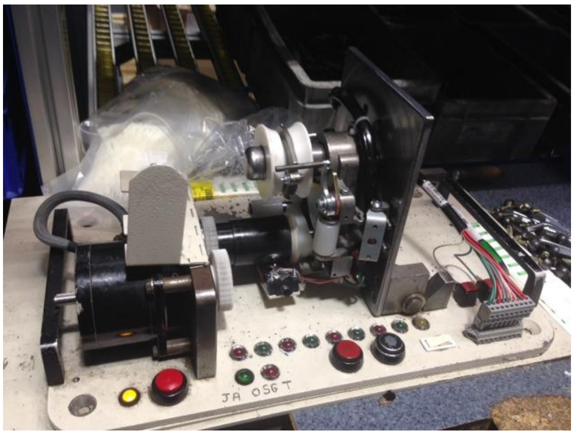


Figure 5.58 - Carriage over speed governor test

The carriage safety pad switches were then tested, Figure 5.59, to ensure that they were all operating correctly. This test was passed. Finally a load was applied to the top of the carriage and a full operation test carried out on a test rail, Figure 5.60. This test failed due to an update that had taken place on the 260 control PBC which was not picked up in the bed of nails test previously conducted. This was because the test only checked key functions such as motor operation and not every operation, such as sounding the alarm which was not present on the board. After the control PCB was replaced with a new board the test was passed. This demonstrates the importance of fully, rather than partially checking the functionality of components. This kind of disruption would slow the reassembly process, significantly reducing efficiency of the line.

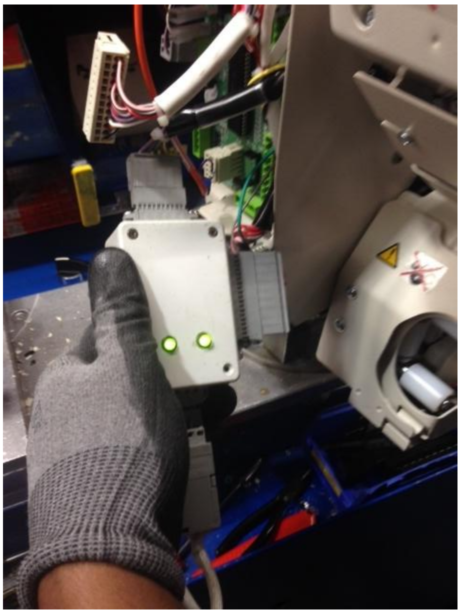


Figure 5.59 - Carriage switch tests

Figure 5.60 - Carriage full operational test

5.4.8.2 Testing the SL Chair

The SL chair was only tested at the end of the production line and ensured all the controls and safety switches were operational, Figure 5.61. This test was passed.

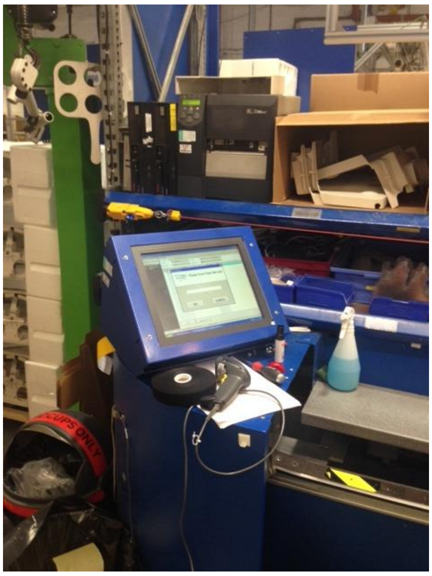


Figure 5.61 - SL chair operational test

5.5 Results from Remanufacturing Stannah's 260SL Stairlift

Once the remanufacture of the Stannah 260SL stairlift was concluded, the benefits of remanufacture were assessed. The list of 28 component parts initially identified for remanufacture was reduced down to 17 due to component damage, design change and component suitability. The overall success of remanufacturing the 260SL stairlift was assessed against two factors:

1. The CO_2e of the remanufacture product compared to that of a new product.
2. The cost of the remanufacture product compared to that of a new product.

5.5.1 Remanufacturing CO_2e Savings

Figure 5.62 maps out the remanufacturing process undertaken in the case study and highlights the points where CO_2e was released in addition to that associated with the production of a new product, which has already been studied in the LCA.

Along the top of the diagram are the remanufacturing stages, starting with the collection of the core at one end, through to retesting the remanufactured product at the other. With the product already being returned to Stannah as part of the standard lifecycle, the first impact associated with remanufacture was the disassembly process, which used compressed air.

The orange boxes group components with like reprocessing activities. The processes undertaken for each group in order to bring them back to a like-new condition are listed in each column. Each process step indicates the impacts associated with it, such as transportation or electricity.

After the components were reprocessed, the replacement components were added back in and the product was reassembled and finally tested. These were all stages that replicate standard production so there were no further additional impacts associated with remanufacture.

Figure 5.62 - CO2e remanufacturing process flow

The life cycle impacts of a new 260SL Stairlift were established in the LCA phase of this research, chapter 6. The impact of making a stairlift with remanufactured components has been considered and CO_2e savings established, both looking at the product lifecycle and by individual stairlift module.

Remanufacturing the stairlift has not drastically changed the profile of the stairlift's lifecycle as can be seen in Figure 5.63. What did occur however, is a reduction in the life cycle stages with the largest impacts, materials (reduced by 32%) and manufacturing (reduced by 29%). Overall, the life cycle impact was reduced from 632 Kg CO_2e to 552 Kg CO_2e. This was a 13% overall reduction.

It should be remembered that the biggest impacting component on a 260SL stairlift was the curved rail (materials 180Kg CO_2e, manufacturing 4Kg CO_2e and disposal -110Kg CO_2e) , which it was not possible to currently remanufacture so no reduction could be achieved.

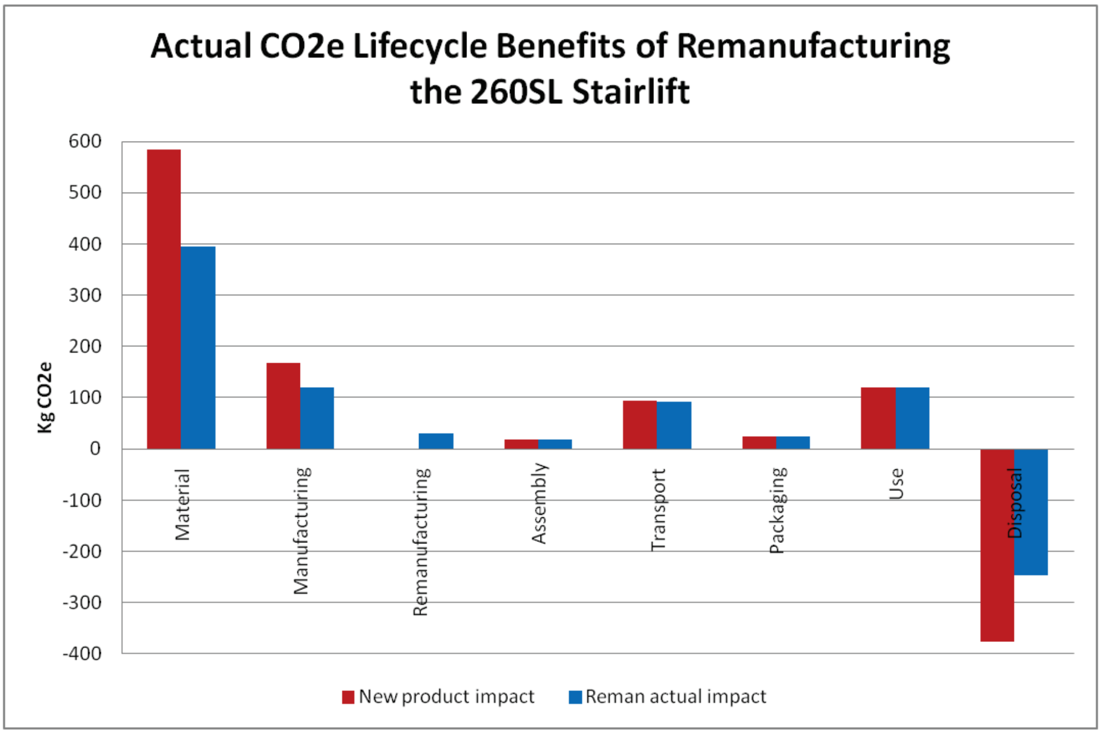


Figure 5.63 - Remanufactured 260SL Lifecycle assessment

The life cycle stage "remanufacture" was added to the product lifecycle. This covers all the impacts associated with disassembly and bringing the selected components back up to like-new condition. The largest of the impacts in this section were down to the replacement of components in the motor gearbox and skate assembly.

Assembly impacts remained the same as those for a new product. No matter whether components are new, or remanufactured, they still require the same method of being assembled into a product.

Transport impacts were reduced slightly due to the fact that suppliers no longer needed to deliver component parts that were being remanufactured. Some components such as the motor gearbox however, needed to be sent back to the supplier to be remanufactured. This slightly reduced the transport savings.

With packaging being disposed of at installation, it was not recovered for this study and so was replaced with new. As such, there was no saving achieved. Similarly there was no reduction in the use impacts of the product as no matter whether the components were remanufactured or not, they consume the same power and/or consumables in use.

As some components were reused in their current form and not recycled, there was less of a disposal benefit. The disposal benefit dropped from -376 Kg CO_2e to -246 Kg CO_2e, but this was more than offset by the benefits of remanufacturing components rather than recycling them.

Looking at each of the stairlift modules in turn it was possible to see which of the selected components contribute most towards the savings and what overall impact this had on the modules. The rail which had the highest impact could not be remanufactured and the 260 footrest could not be remanufactured either due to the level of design change. As such, no savings were achieved for either of these modules.

Remanufacturing the carriage, Figure 5.64, saved a total of 39 Kg CO_2e representing a reduction of 23%. The Skate assembly was the most beneficial component remanufactured saving 18Kg CO_2e (58% of its original materials and manufacture). If the motor had not required the break failure update then its impact could have been nearly halved again from 22Kg CO_2e down to 13 Kg CO_2e.

The cluster housing, power footrest PBC and Loom only required cleaning so had very low remanufacturing impacts.

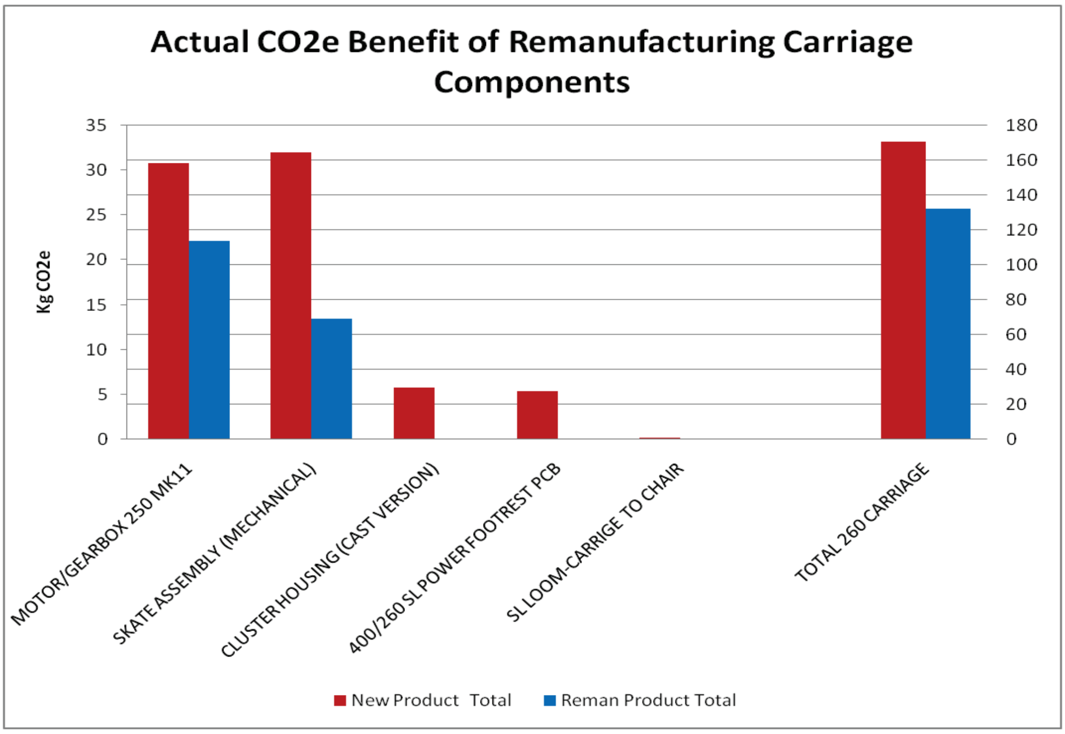


Figure 5.64 - Carriage remanufacturing CO_2e results

The SL chair achieved an overall reduction of 22 Kg CO_2e, representing a 38% reduction on manufacturing a new chair, Figure 5.65. All the cast components benefited greatly from being remanufactured. The chair back casting reduced by 6Kg CO_2e (88%), the chair hinge reduced by 3 Kg CO_2e (89%) and the arms both reducing by 4 Kg CO_2e (90%). There were a number of components that did not require any reprocessing and so could be reused achieving a total component saving.

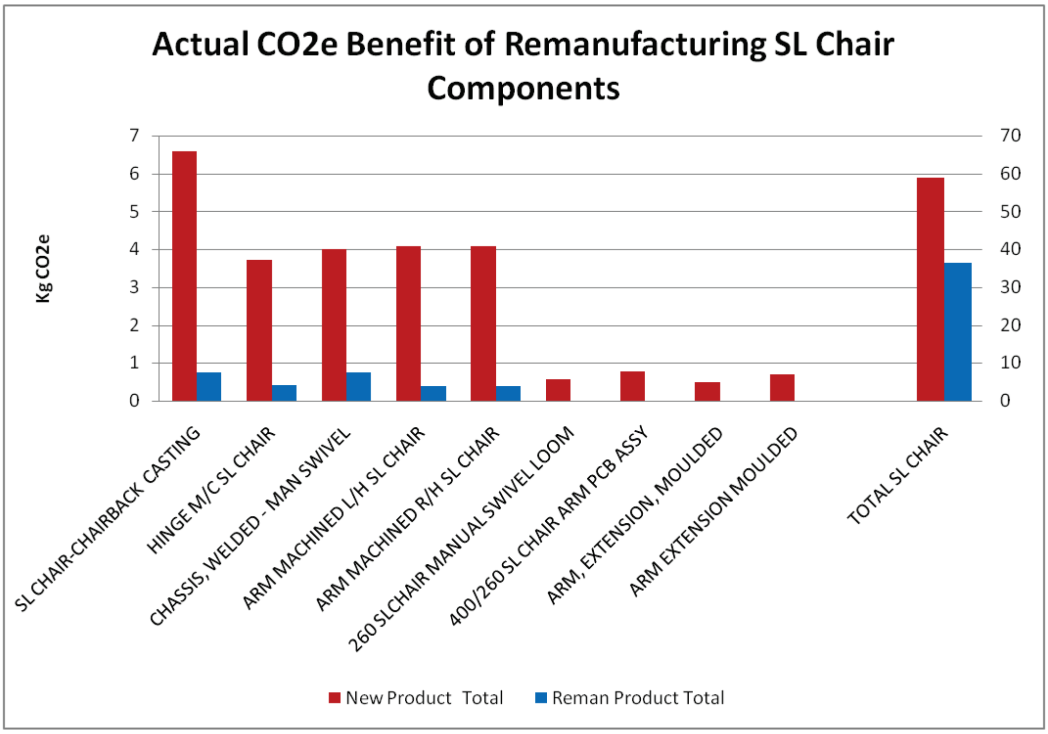


Figure 5.65 - SL chair remanufacturing CO_2e results

Remanufacturing the eight legs in the kit box resulted in a total of 19 Kg CO_2e (64%) being saved, Figure 5.66. Looking at the legs in isolation from the rest of the kit box, each leg reduced by 2.3 Kg CO_2e (82%).

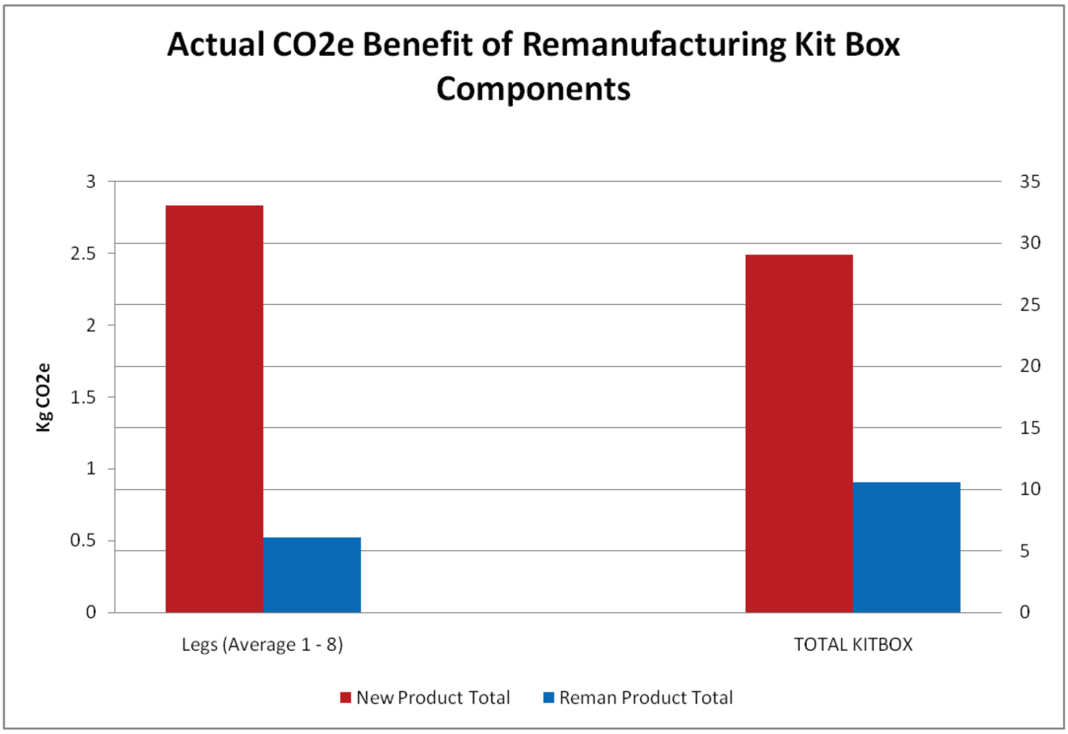


Figure 5.66 - Kit box remanufacturing CO_2e results

5.5.2 Remanufacturing Cost savings

Figure 5.67 maps out the remanufacturing process undertaken in the case study and where cost was incurred to bring the core back to a like-new condition. The remanufacturing process stages flow across the top of the diagram and the orange boxes group components that underwent like reprocessing activities. The first instance when cost could have been incurred is offering a financial incentive to the customer for returning the product. In the case study this was not the case, as the product would ordinarily have been removed for scrap. Going forward, higher core recovery might however, be possible if a financial incentive was given. Once the core was recovered, there was the cost of labour to disassemble the product and sort components.

The reprocessing activities shown for each group of components highlight where cost was incurred in addition to the production of a new product. This included transportation, labour and energy costs at various points. After the components had been reprocessed, the replacement components were added back in, the product was reassembled and finally tested. These are all stages that replicate standard production so there was no further additional costs associated with remanufacture.

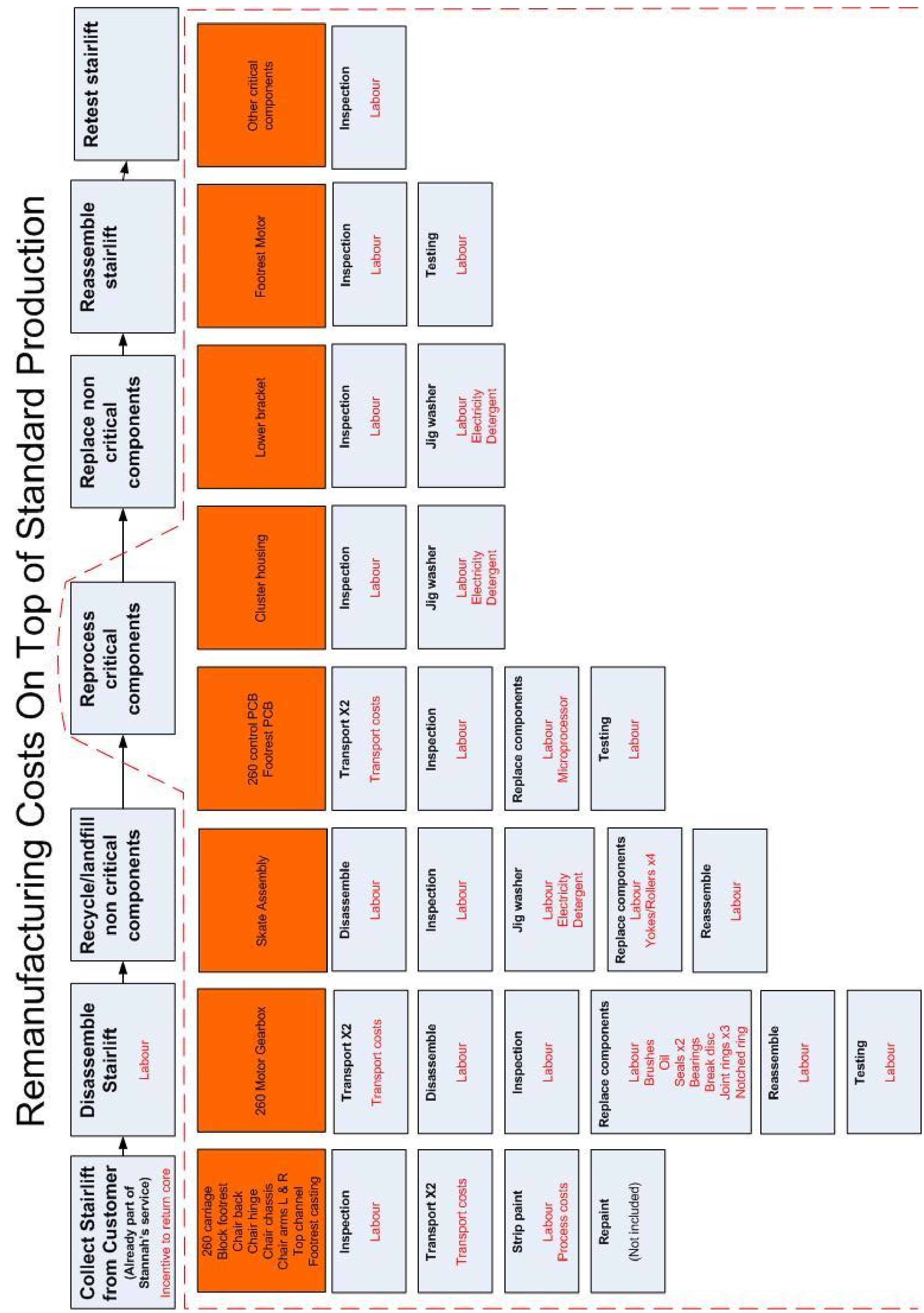


Figure 5.67 - Cost remanufacturing process flow

Overall, from remanufacturing the carriage, chair and rail legs a saving of £259 was achieved, representing a 34% saving compared with manufacturing a new product. The 260 Footrest could not be remanufactured, due to the level of design change that had taken place.

Looking at each stairlift module in turn it was possible to evaluate the cost benefit of remanufacturing against manufacturing with new components.

Overall remanufacturing the selected components in the 260 carriage, Figure 5.68, reduced the production cost from £472 to £324. A saving of £148, representing a 31% reduction in cost. The majority of this saving was down to the motor gearbox despite the major update it required to correct the break fault. Some components such as the cluster housing and looms did not require any more than a clean and inspection in order to bring them back to a like-new condition making them very cost effective to remanufacture.

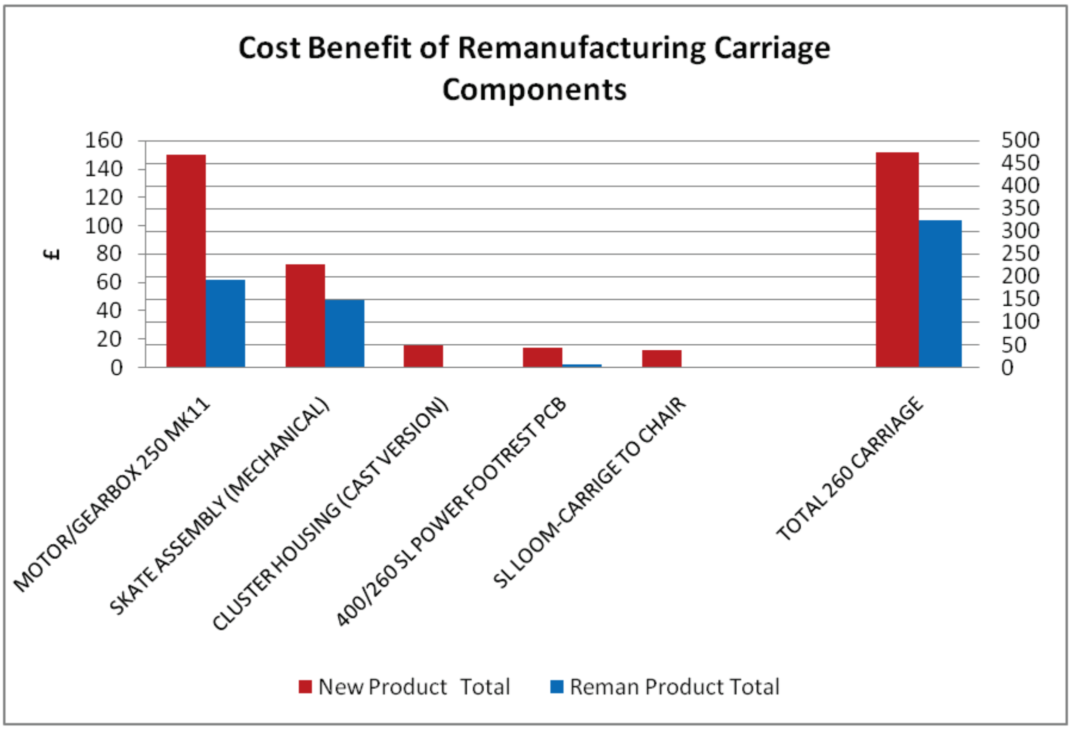


Figure 5.68 - Carriage remanufacturing cost results

The selected components remanufactured in the SL Chair, resulted in the production cost reducing from £229 to £129. The £100 reduction in production cost represents a saving of 44%. The largest saving came from remanufacturing the chair back saving £45 (87%). Stripping paint from the chair back cost £6, nearly 90% of the rework cost for this component.

Components such as the chair loom and arm extensions did not require any reprocessing as the only associated cost was inspection prior to being reused.

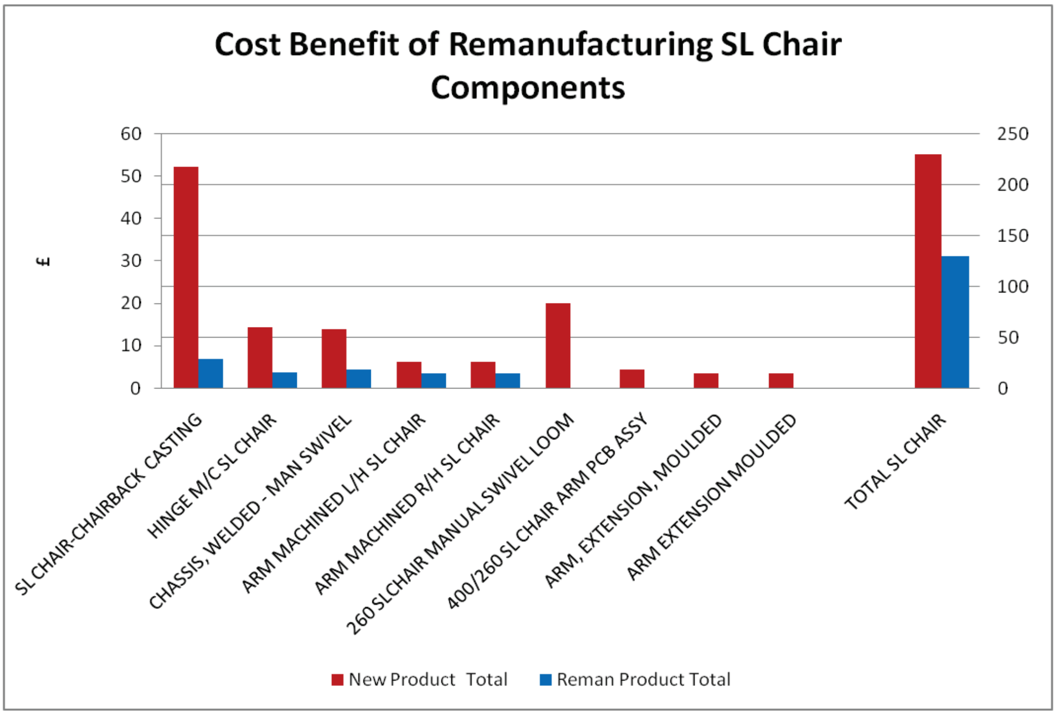


Figure 5.69 - SL Chair remanufacturing cost results

The sole savings for the kit box, Figure 5.70, were from the remanufacture of rail legs. Remanufacturing each leg saved £1.45 (27%). Based on eight legs, overall this saves £12 (26%) of the £44, total kit box value. The largest cost associated with remanufacturing the legs was stripping off the epoxy paint. This cost £3.60 per leg (90% of the rework cost) seriously reducing the recoverable value.

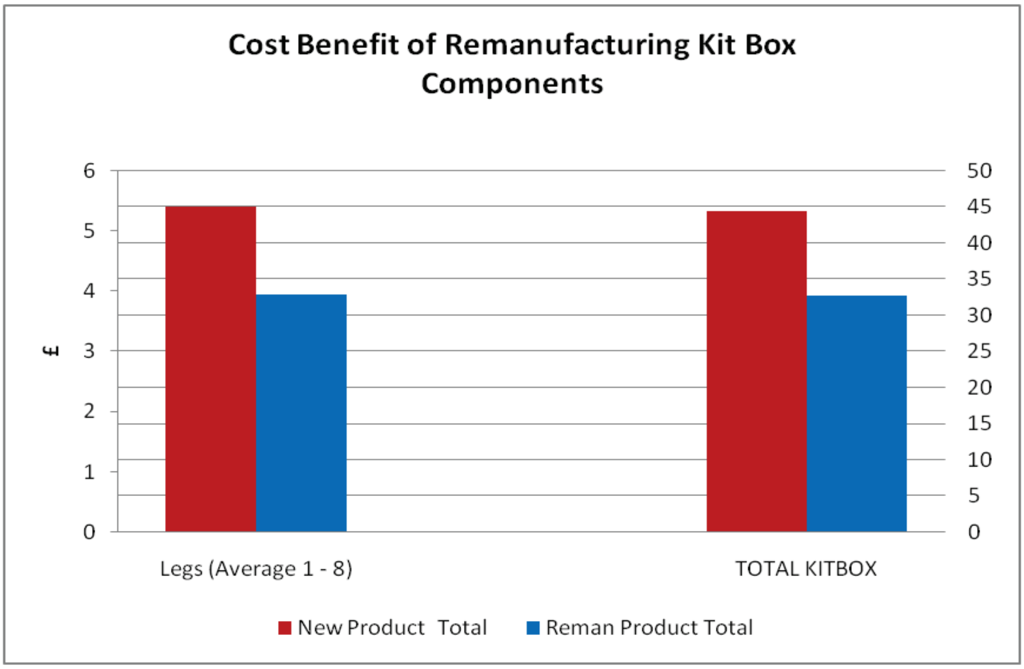


Figure 5.70 - Kit box remanufacturing cost results

5.6 Chapter conclusions

- The 260SL was an easy product to remanufacture, with attractive savings in both CO_2e and cost.
- Of the 28 components highlighted only 17 were eventually remanufactured into a like-new product.
- Design change since the manufacture of the product, was the biggest factor preventing the remanufacture of components, removing 10 of them from the study, including the entire footrest module.
- Disassembly was slowed by the variety of fixings used in the stairlift. Total disassembly was also required in order to remove the selected components.
- Cleaning could have been simplified if the product had smoother surfaces reducing areas for dirt and grease to gather.
- If the durability of looms was increased then there is greater chance of them being in an acceptable condition for remanufacture.
- Of the reprocessing costs, stripping epoxy paint off components was the most costly on average making up 89% of the total component rework cost.
- Of the reprocessing CO_2e impacts, remanufacturing the motor gearbox had the largest associated impact down to the large update that was required.

Therefore, remanufacturing selected high impact components from the 260SL stairlift presented a significant opportunity to reduce the whole life impacts of the product. The remanufacturing process could have been improved however, if the selected components were designed with remanufacturing in mind. Similarly, the components that were not selected for remanufacture, could have been optimised to enable reduced life cycle impacts if it had been known that they would be recycled at of end of life. By designing components for either recycling or remanufacture, end of life processing can be optimised.

Chapter 6 – Design for End of Life Optimisation

This chapter considers how the data gathered in the life cycle assessment and remanufacturing case study can be used to develop more sustainable products going forward, in particular focusing on optimising them for end of life. To achieve this, a model for end of life optimisation was developed by the author.

6.1 The End of Life Optimisation (EOLO) Methodology

The EOLO design model developed by the author, aimed to highlight the best end of life reprocessing option for each component based on either environmental impact or cost. Components were either assigned:

1. Design for remanufacture, looking to optimise the design of these components for each stage of the remanufacturing process. This will focus the designer on aspects such as the ease of reprocessing the component back to a like-new condition.
2. Design for recycling, accepting that the component will only be used once and then its material recycled. Components should be optimised to minimise their impact as far as possible and enable easy end of life recycling.

After being assigned for remanufacture or recycling, each group of components were then assessed for how suited they were for the chosen end of life reprocessing. Finally, recommendations were made to further optimise the design.

6.1.1 EOLO component selection

The efficiency of only remanufacturing the high worth components was seen in the remanufacturing case study, chapter 5. The results of this work were carried forward and the selection of high value components from the product formed the first stage of the EOLO model. Figure 6.1 sets out a model for splitting components into those that should be designed for remanufacture and those that should be designed for recycling.

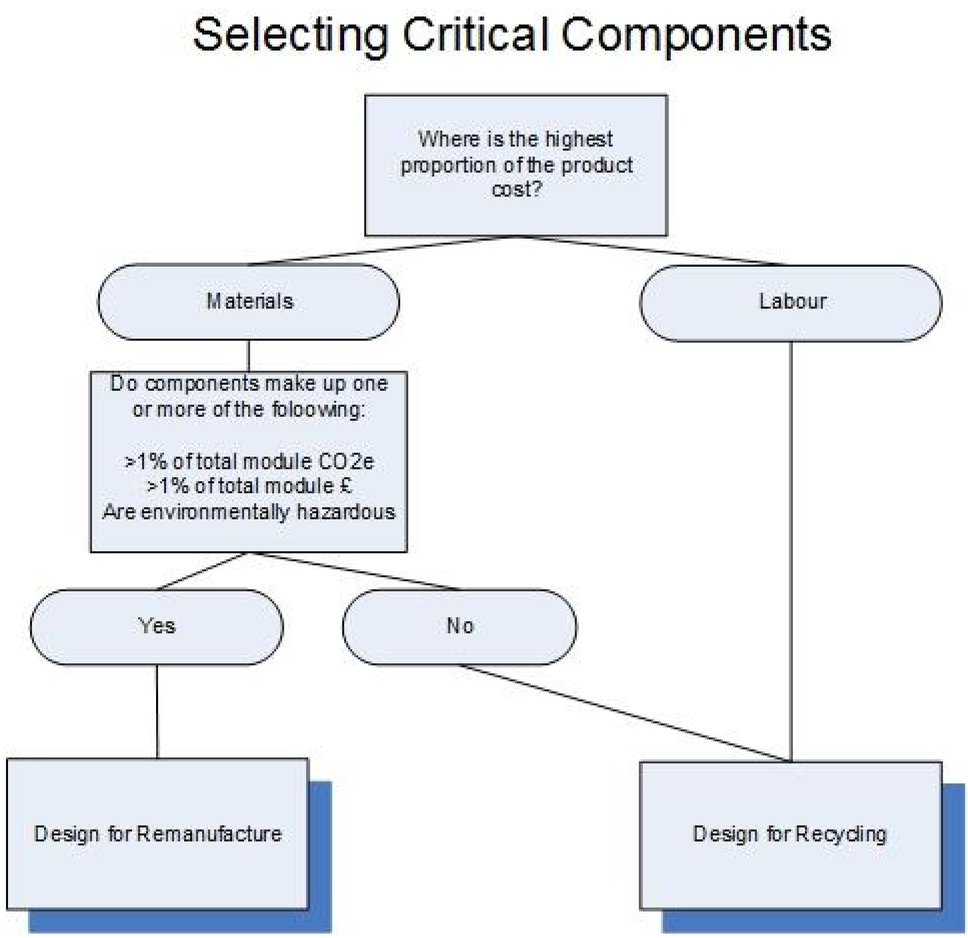


Figure 6.1 - Component selection decision tree

The first assessment in the decision tree looked at the split of labour to material cost within a product or product module. Products/modules that had a high labour cost and little material to recover would be less suitable for remanufacture. These should therefore be designed for recycling, minimising their impacts over each phase of life.

Products that indicate that remanufacture might be suitable due to their high material content, go on to the second assessment stage to select the critical components from the product. Initially when the design is fluid and accurate environmental and cost data is not available, components can be chosen on their perceived impact. As the design matures this selection should be refined, only selecting components that make up greater than 1% of the total product/module cost or CO_2e impact. It was thought that the cut-off criteria of >1% selected an appropriate number of components in the stairlift case study, so this was again chosen for both CO_2e and cost. The concept of selecting components based on a percentage of the product total is intended to make the process applicable for both large/small and cheap/expensive products. If the product being assessed was entirely different to Stannah's

260SL stairlift, then different percentages may need to be chosen but this could be determined in use.

Finally, a third selection criteria was also included to pick up any components not greater than the 1% cut-off but known to be environmentally hazardous and so should be remanufactured if at all possible.

The components selected as critical go on to be optimised for remanufacture. The components not deemed to be critical are diverted back to be designed for recycling, minimising their lifecycle impacts.

6.1.2 EOLO Component Assessment Matrices

Many of the individual reprocessing stages for remanufacture require the same product characteristics, for example durability; and the same can be said for recycling.

To simplify and speed up assessing components, for both design for remanufacture and design for recycling, groups of components were scored against component characteristics, rather than the reprocessing stages themselves. The output of the model was based on matrices, which considered which of the product design properties were important for each process stage. The relevant characteristic scores were then used in combination with one another to indicate how suitable each component was for each stage of the remanufacturing or recycling process.

Some product characteristics were important to multiple process stages. The focus was therefore placed on improving the more significant product characteristics. This introduced weighting to the model. An example of this was improvements made to “ease of identification” which resulted in an improvement to five process stages, whereas an improvement made to “ease of verification” only improved two process stages. It was hoped that that this would incentivize the designer to improve the more critical product characteristics first.

In both groups (those for remanufacture and those for recycling), components were assessed against a scoring matrix containing the product characteristics. These range from worst practice (-2 score) through to best practice (+2 score) for each product characteristics.

6.1.2.1 Remanufacturing product characteristics matrix

For components to be remanufactured the important product characteristics for each reprocessing stage were indicated in the remanufacturing process matrix, Table 6.1.

	(1) Ease of Identification	(2) Ease of Verification	(3) Ease of Access	(4) Ease of Separation/ Securing	(5) Ease of Upgrade	(6) Physical Attributes	(7) Wear Resistance
Inspection	*	*	*				
Cleaning			*			*	*
Disassembly	*		*	*		*	*
Storage	*					*	
Reprocessing	*		*	*	*	*	*
Reassembly	*			*	*	*	*
Testing		*	*				

Table 6.1 - Remanufacturing process matrix

Key for remanufacturing process matrix:

1. **Ease of identification** is important for many of the remanufacturing process stages. If components are not easily identifiable then this will slow, if not hinder, the remanufacturing process. An example would be an attempt to inspect components when it was not obvious which components or which features are to be inspected.

2. **Ease of verification** is important at the beginning and again at the end of the remanufacturing process. Initial verification takes place during inspection to ascertain component wear or damage. Finally the product is tested to ensure it is operating to the same standard as that of a new product. By simplifying the verification process it becomes instantly visible whether components are viable for continued use or they need replacing.

3. **Ease of access** is again important for many reprocessing stages. An example would be gaining visual access to internal components to inspect their condition. Access after product disassembly is also required to bring the component back to a like-new condition. In this case it may be the component's own features, such as undercuts that prevent access for cleaning and reprocessing.

4. **Ease of separation/securing** is most important during disassembly and then reassembling the product after reprocessing. The most important requirement is that components are not permanently fixed together, making disassembly impossible. These stages can also be optimised, for example by reducing the number and types of fixings used. The amount of component reprocessing required can also be affected by ease of separation, as any component damage sustained will need repairing.

5. **Ease of upgrade** simplifies the reprocessing and reassembly processes. If components are designed to be upgraded then the functionality of a module can be improved without compromising its ability to be reassembled back into a product containing both new and old product modules.

6. **Physical attributes** of the components will determine how easily they can be handled, the space that will be required for storage etc. The shape and surface texture of components will also determine aspects such as the cleaning and reprocessing that is required.

7. **Wear resistance** is important for components intended to last several lives as damage, wear and durability will affect how many times the component can withstand being used and reprocessed.

With only the 1% of components with the highest impact being selected for remanufacture, this category contained the fewest number of components, but those that had the highest impact. For this reason, components intended for remanufacture were scored on an individual component basis. Each component was scored against the seven product characteristics for remanufacture, Table 6.1. Scoring was based on value judgements made by the designer, of where the design currently sat on the design for remanufacture scoring matrix, which was a -2 to +2 scale, Table 6.2. The negative score is designed to hurt the product score for design decisions that will hinder remanufacture/recycling. When positive decisions are made the design is rewarded with a positive score.

	Ease of Identification	Ease of Verification	Ease of Access	Ease of Separation/ Securing	Ease of Upgrade	Physical Attributes	Wear Resistance
-2	Components are indistinguishable from one another, but will require exact reassembly	Component testing/inspection locations are not easily located	Access to inspect components is restricted Features exist that will obstruct reprocessing, such as undercuts	Components are permanently fixed together Fixings unprotected form the environment in locations susceptible to corrosion	Location of fixing points not defined No Standardisation between components or product modules	Materials chosen that will prohibit reprocessing, e.g. cleaning: -Melting points -Chemical resistance Special care must be taken to avoid component damage, e.g. from static	Components wear due to friction in use Component has unnecessary/none durable coatings that may wear or flake Components may sustain damage whilst being disassembled
-1	Components are not easily distinguishable from one another Component design revisions not easily distinguishable from one another	Inspection points are obstructed or not within line of sight	Fixings are not easily accessible	Snap fit design prevents easy component separation Components easily tangle such as cables and springs Fixing locations will weaken with multiple uses, E.g. self tapping screws	No platform or modular design approach used	Many different types of material in used Light colours used that will show up dirt Coarse surface textures used that will gather dirt	High gloss and very smooth coatings used that will be difficult to restore

+1	Components are clearly identified, especially those that look similar. E.g. dot matrix identification	Areas requiring specific testing are highlighted Acceptable wear tolerance marked on components and sacrificial futures indicate current condition Component history recorded to track age and reprocessing undertaken	Covers over inspection points are designed to be easily removable	Reduced the number of components requiring disassembly Fixings are easily located with no hidden fixings Fixings have been optimised -Total number of -Number of different -Thread Lengths Deeper threaded holes provided, giving a longer fixing a fresh thread. E.g. for critical fixing points	Aesthetics easy to update using external covers	Forms avoided that will collect dirt: -Sharp groves -Recesses -Small radii corners Component forms stack enabling easy storage Components are easy to handle: -Size -Weight -Shape -Centre of mass	Unnecessary surface coatings removed Areas susceptible to wear designed with sleeves/inserts to allow replacement
+2	Components can be easily grouped into those that require similar reprocessing	Sensors monitor and record product use and condition Product indicates optimal point for remanufacture	Component not obstructed in any way	The number of axis and path lengths are minimised Gravity is utilised to aid disassembly Smart materials are used to facilitate active disassembly Ease of component alignment optimised	Plug and play module connectivity	Form designed for repetitive remanufacture, e.g. re-machining surfaces Materials chosen for repetitive remanufacture	Components over engineered for multiple uses Wearing components within product modules designed to have comparable life expectancies

Table 6.2 - Design for remanufacture scoring matrix

6.1.2.2 Recycling product characteristics matrix

For the components intended to be recycled at end of life, the important product characteristics for each reprocessing stage are indicated in the recycling process matrix, Table 6.3. It can be seen there were fewer critical characteristics for recycling than remanufacture.

	(1) Material Selection	(2) Manufacturing Attributes	(3) Ease of Identification	(4) Ease of Separation
Manufacture	*	*		
Disassembly	*			*
Disposal	*		*	

Table 6.3 - Recycling process matrix

Key for recycling process matrix:

1. **Material selection** is important as if non-recyclable materials are chosen, this will prevent recycling at disposal. The number of different materials and the specific materials selected will also affect the economic value for recyclers, determining the attractiveness of the waste stream.

2. **Manufacturing attributes** are important in the upfront stages of creating the component. The component can be dematerialised and manufacturing stages minimised to reduce the embodied energy of the component, minimising what needs to be disposed of.

3. **Ease of identification** is important for recycling. By labelling different materials, they can be easily segregated, maintaining the quality and purity of recycling streams.

4. **Ease of separation** is important to maximise the capability and profitability of recycling. Permanently bonding components or specifying laminated composites make separation back to raw materials very difficult if not impossible for recycling.

The components selected for recycling have the least impact but make up the greatest number of components. For this reason, components intended for recycling at end of life were scored as a collective. This group of components was assessed against the design for recycling scoring matrix, Table 6.4. Scoring was again based on value judgements made by the designer, of where the design currently sat on the -2 to +2 scale.

	Material Selection	Manufacturing Attributes	Ease of Identification	Ease of Separation
-2	Non recyclable materials used Hazardous materials used Composite and laminated materials used	Production processes result in toxic or hazardous wastes being generated	Material identification codes not used on plastics	Components are permanently fixed together Fixings unprotected from the environment in locations susceptible to corrosion
-1	Material not easily recycled CO_2e intensive materials chosen Materials with high embodied energy chosen	Components are manufactured geographically distant from use		Snap fit design prevents easy component separation Components easily tangle such as cables and springs The use of inserts in components made from an alternative material
+1	Minimal material types have been chosen Materials chosen that are as ubiquitous and abundant as possible Recycled material is used in production Material remains as close as possible to the feedstock, minimising the use of additives, inks, paints and pigments	Production waste, such as material off cuts, are minimised The number of production steps have been limited	All large components marked with material type	Fixings are easily located with no hidden fixings Fixings have been optimised -Total number of -Number of different -Thread Lengths
+2	Material has positive economic value for recyclers Material density is minimised to that required by the function of the component	Reduce material content through introduction of structural features	All components marked with material type Materials with different densities used to automate segregation into different material types	The number of different axis and path lengths are minimised for fixings Gravity is utilised to aid disassembly Smart materials are used to facilitate active disassembly

Table 6.4 - Design for recycling scoring matrix

6.1.3 EOLO Model output

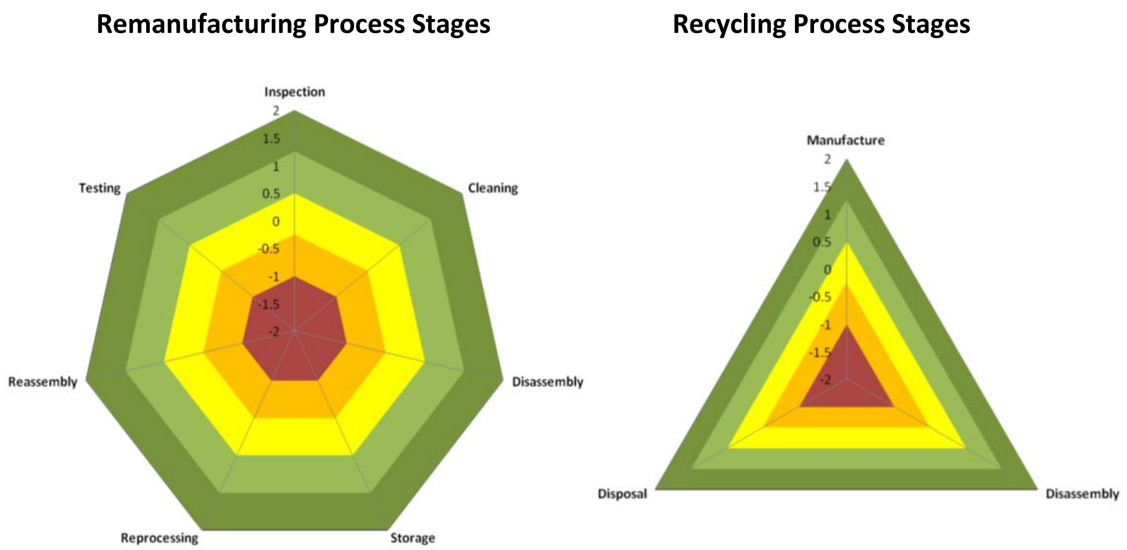
The model was built in Microsoft Excel so that when each component was scored against each product characteristic, the results automatically populate the rest of the model and display the results in a graphical form for easy analysis.

The output of the model was delivered in layers to allow designers to see increasing levels of detail. Initially an overview was provided to show how remaunfacturable/recyclable the product is as a whole, based on the individual reprocessing stages. The next layer looked at each process stage in turn, to indicate which of the important product characteristics were weakest. Finally, the component level data was scrutinised to indicate which components require the most attention and further development.

As designers become more experienced in design for remanufacture and recycling they may choose to miss out the initial component evaluation and move directly to scoring the process stages for each group of components.

6.1.3.1 Whole end of life process overview

The whole end of life process overview provides the designer with an initial picture of how optimised the components are for each stage of remanufacture or recycling. The data is presented on a colour coded radar chart. Examples of which can be seen in Figure 6.2.



a) b)

Figure 6.2 - EOLO process overview radars for remanufacturing (a) and recycling (b)

The centre of the remanufacturing process overview radar is red, which represents worst practice. If any of the stages are indicated as red they are likely to hinder remanufacturing. The green outer ring represents best practice and should be the target for all process stages.

The recycling process overview radar used the same colour coded principles for best and worst practice. Any stages indicated as red hinder the recycling of components, making them more likely to be destined for landfill. The green outer ring demonstrates that components can be easily and profitably recycled.

6.1.3.2 Process stage by product characteristic

The results are next indicated in a greater level of detail for both groups of components. Each process stage is graphically represented with the relevant product characteristics as indicated by the remanufacturing/recycling process matrices. An example of which can be seen in Figure 6.3.

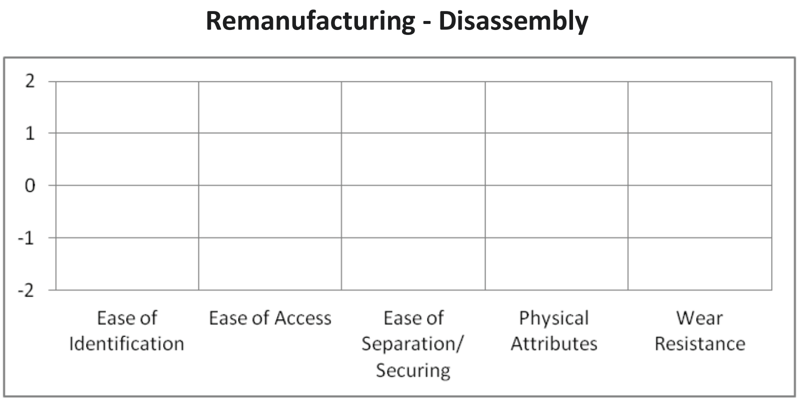


Figure 6.3 - Example EOLO process stage graph (Remanufacturing-disassembly)

The current profile for each process is shown in turn again ranging from a -2 worst practice to +2 best practice. This allows the designer to identify which product characteristic need to be improved upon, in order to improve upon the overall process stage score.

6.1.3.3 Product characteristic by component

Finally, by revisiting the component scoring, the results can be viewed by individual component. This allows the designer to identify if there is any one component that is negatively impacting the average product characteristic score or if any components have low overall component scores. Future design work can then be focused on making improvements to these components.

This is only possible for the design for remanufacture components which are individually scored. The remainder of the product which is designed for recycling is assessed as a whole and, as such, component level analysis is not possible.

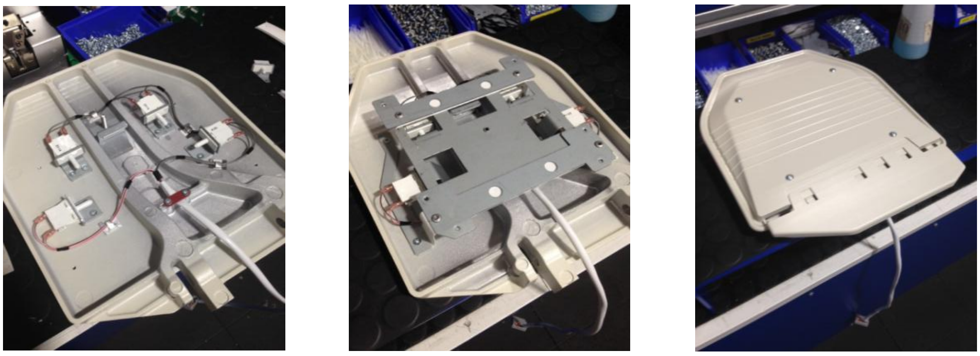
6.1.4 Design optimisation

Once the designer has assessed the product's components for either remanufacture or recycling, they can look to improve the design. To guide the designer in making improvements, they can revisit the relevant scoring matrix. For example, if the current score is deemed to be a -1 then looking at the requirements to meet the +1 score will give the designer guidance on how to improve weak product characteristics.

6.2 Testing the EOLO model: Stannah's 260 footrest

To test the EOLO model, Stannah's 260 stairlift footrest was used as a worked example showing each stage of the model. This demonstrated how the model can be used to both initially assess products and to direct component design improvements.

The 260 Footrest consisted of 32 components mostly comprising of a mixture of castings, fabricated steel parts and plastic injection mouldings, Figure 6.4.



a) b) c)

Figure 6.4 - 260 Footrest components

a) Switches and looms assembled onto the footrest casting.

b) Safely pad activator mechanism added to the assembly.

c) Plastic injection moulded cover added to the assembly.

6.2.1 260 footrest component selection

Looking at the components in the 260 footrest, several components were selected for remanufacture using the component selection decision tree, Figure 6.1. From the 32 components, those selected for remanufacture based on being greater than 1% of the total CO_2e, cost or deemed significant are listed in Table 6.5.

Component Name	CO_2e	Cost	Env. Signif.
FOOTREST CASTING 260	✓	✓	
BLOCK-FOOTREST MTG-260	✓	✓	
STIFFENER SAFETY PAD	✓	✓	
260 FOOTREST LOOM L/H (CEN)		✓	
SAFETY PAD EXT LONG LH PEARL		✓	
SAFETY PAD-FOOTREST-PEARL-260	✓	✓	
FOOTREST WEBBING		✓	

Table 6.5 - Components selected for remanufacture from the 260 footrest

The remaining 25 components from the 260 footrest were optimised for recycling at end of life.

6.2.2 260 footrest component assessment

The individual components highlighted for remanufacture, were scored against the identified product characteristics important for each remanufacturing stage, Table 6.6. This demonstrates how the current characteristics of components are scored on the -2 to +2 ratings set out in the design for remanufacture scoring matrix, Table 6.6.

	Ease of Identification	Ease of Verification	Ease of Access	Ease of Separation/ Securing	Ease of Upgrade	Physical Attributes	Wear Resistance
FOOTREST CASTING 260	1	-1	1	-1	-2	1	1
BLOCK-FOOTREST MTG-260	1	-1	2	-1	-2	1	-2
STIFFENER SAFETY PAD	1	-1	1	-2	-2	1	1
260 FOOTREST LOOM L/H (CEN)	1	-1	-1	-1	-2	1	-2
SAFETY PAD EXT LONG LH PEARL	1	-1	1	1	-1	-1	-1
SAFETY PAD-FOOTREST-PEARL-260	1	-1	2	2	-1	-1	-1
FOOTREST WEBBING	1	-1	1	-2	-2	1	1

Table 6.6 - Individual scoring for the components intended for remanufacture

The remainder of the 260 footrest's components were assessed as a group against the product characteristics important for recycling, Table 6.7. These were assessed against the design for recycling scoring matrix, Table 6.7.

	Material Selection	Manufacturing Attributes	Ease of Identification	Ease of Separation
REMAINDER OF COMPONENTS	1	2	1	-1

Table 6.7 - Collective scoring for the components intended for recycling

6.2.3 260 footrest model output

After scoring each component against the desirable product characteristics for remanufacture and recycling, the top level results for the EOLO model, are shown in Figure 6.5 and Figure 6.6

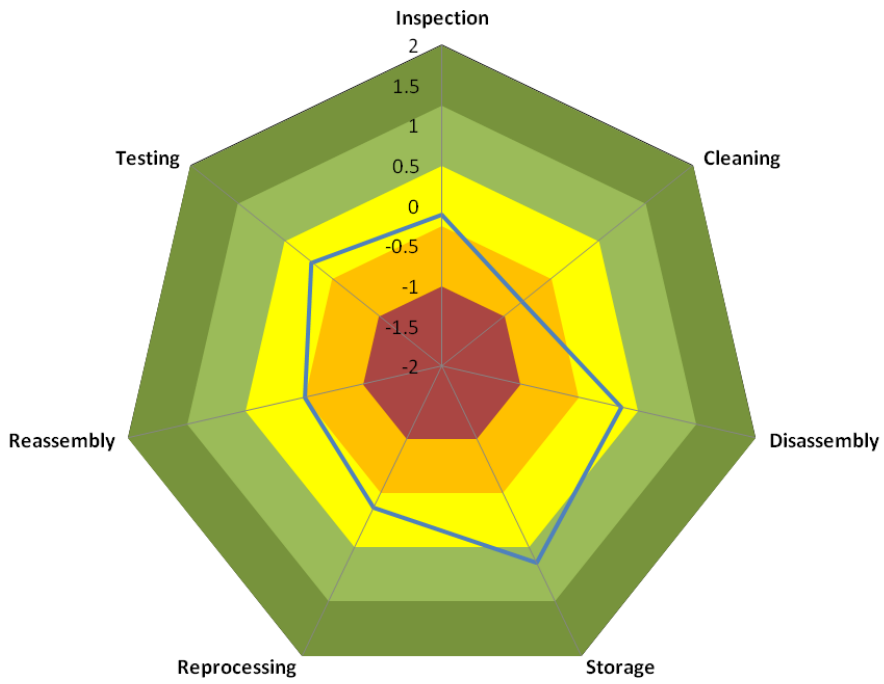


Figure 6.5 - Remanufacturing process overview radar

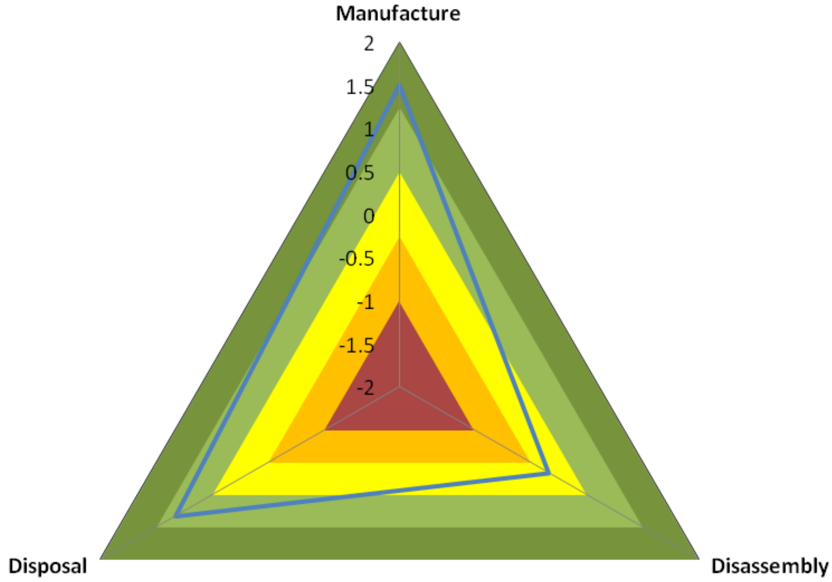


Figure 6.6 - Recycling process overview radar

Figure 6.5 gives an initial view of how remanufacturable the selected components from the 260 footrest were by process stage. This suggests that the cleaning, followed by the reassembly process needs improving the most, in order to improve the overall remanufacturability of the product. The remainder of the components intended to be recycled indicate that their disassembly prior to recycling will be the weakest process stage, Figure 6.6.

With the cleaning and reassembly highlighted as the weakest stages for remanufacture, Figure 6.7 shows more detail and highlights that whilst none of the scores were high, it was the product characteristic of 'wear resistance' that needed improving the most in order to improve the cleaning process stage.

Figure 6.7 - Cleaning product characteristics for remanufacture

Assessing the reassembly process stage in Figure 6.8, it was the product characteristic of ‘upgradeability’ that needed the most work in order to improve.

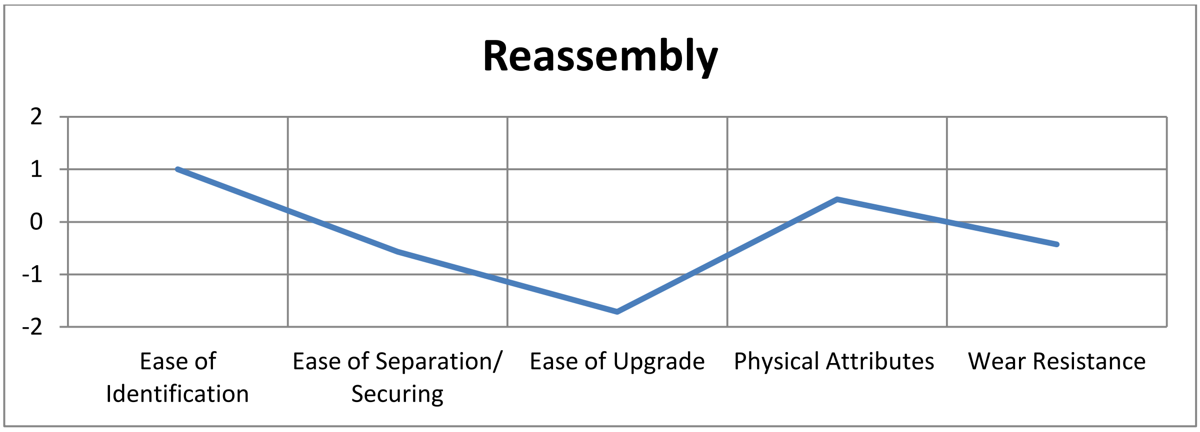


Figure 6.8 - Reassembly product characteristics for remanufacture

An analysis of the components intended for recycling, showed that it was ‘component disassembly’ that was the weakest process stage. Looking at the process stage in Figure 6.9, it was the ‘ease of separation’ product characteristic that was the lowest, and this is where improvements need to be made.

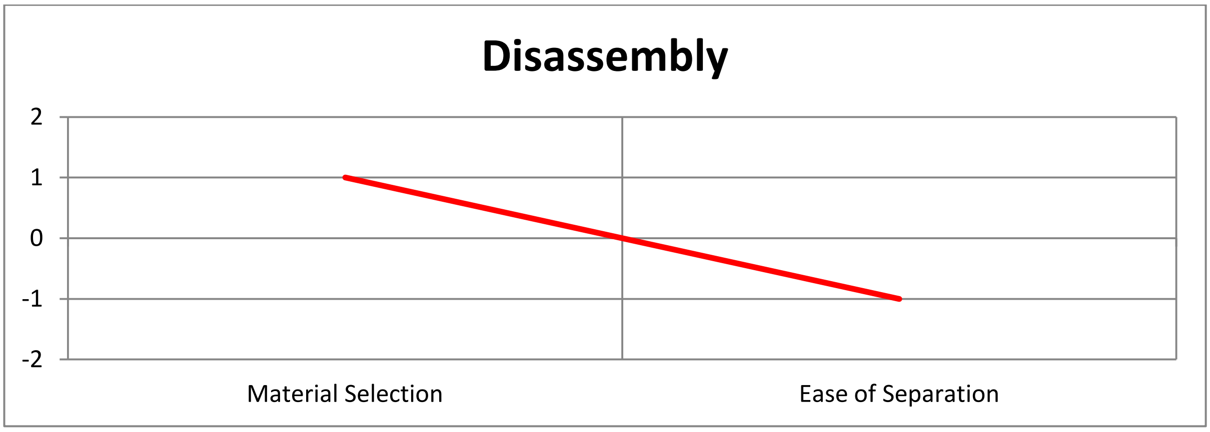


Figure 6.9 - Disassembly product characteristics for recycling

Re-examining the original component scoring table for remanufacture, Table 6.6, it can be clearly seen that ease of upgrade was not considered for any of the selected components.

Wear resistance was worst on the Block Footrest, which had a localised friction point, that resulted in component wear. The Footrest Loom articulated with the operation of the footrest and a tight loom routing resulted in fatigue over an extended period.

Ease of separation was also an issue for the Stiffener Safety Pad and the Footrest Webbing, which are riveted together.

6.2.4 260 footrest design optimisation

Based on the results of the EOLO assessment of the 260 footrest, the design can be optimised in a number of ways to improve the product for end of life reprocessing.

Effort should be focused on redesigning the Footrest Block, which wears due to friction. Removing this point of contact would reduce the reprocessing required in remanufacturing the component back to a like-new condition. Setting fixing locations on the Footrest Block would also enable the footrest module to be upgraded with a newer version, whilst maintaining compatibility with the carriage.

Either increasing the durability of the Footrest Loom or loosening the loom routing, would reduce the wear and extend the expected life of this component.

Ease of separation could be improved through redesigning the product so that components are not permanently fixed together with rivets.

6.3 Implementing the EOLO model into Stannah's NPI process

Stannah's current new product introduction (NPI) process was used as a case study to determine where the EOLO model would add the most value in influencing the optimisation of a product for end of life reprocessing, Figure 6.10.

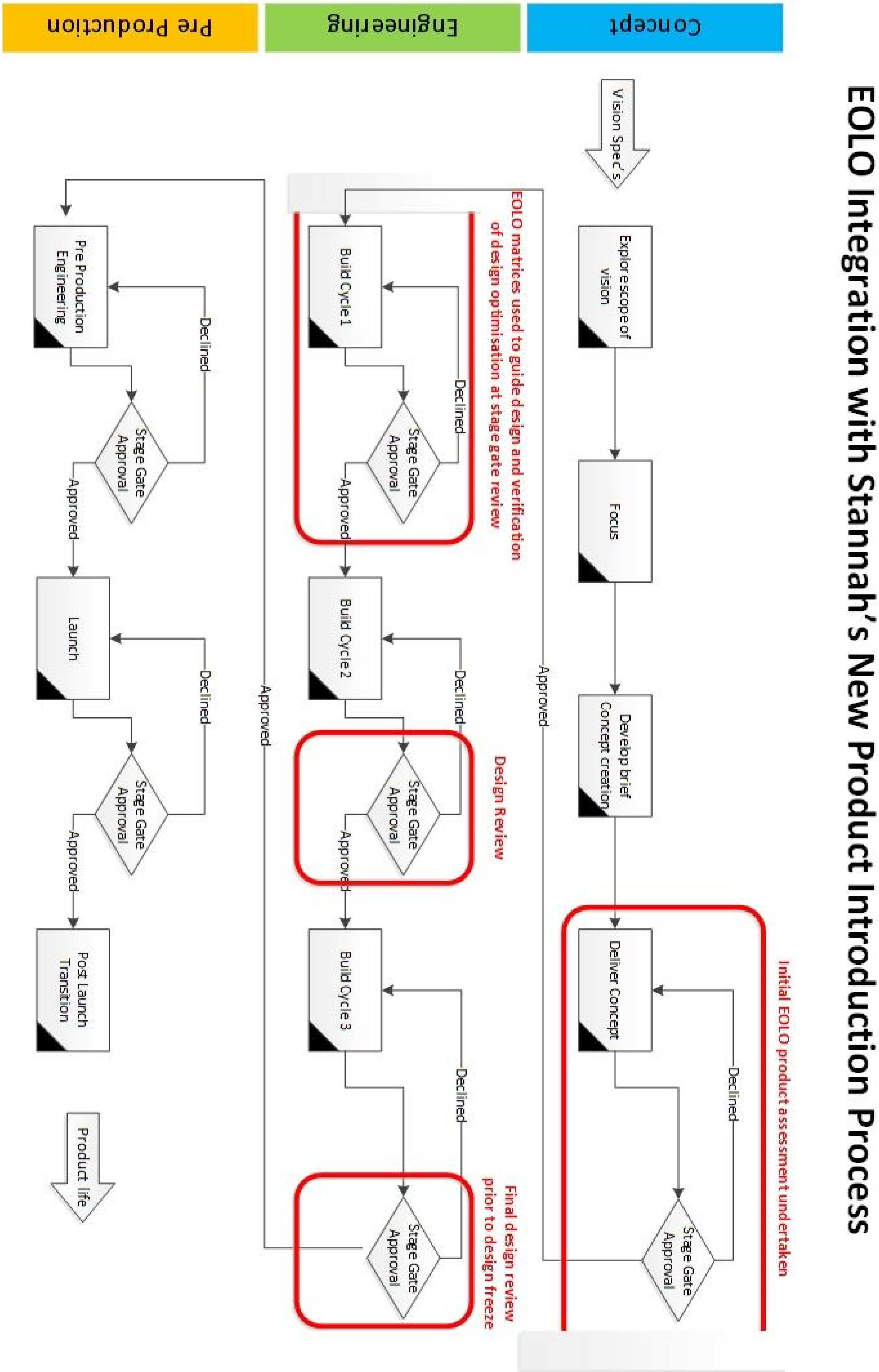


Figure 6.10 – EOLO integration with Stannah's NPI process

Early concept development should be allowed freedom to ensure that the creativity of developing new products is not hindered. Once a concept has been developed though, it is at this early stage when the design is still fluid where the EOLO model should be used. An initial assessment should take place before the product is signed out of concepts to select the critical components for remanufacture, and resolve any design decisions such as product form which would hinder end of life reprocessing.

As the product crosses over into engineering constraints such as production capability start to also influence the product's design. Using the EOLO matrices here will help guide the engineer to design-in positive product characteristics such as fixing methodologies and component surface finishes. Considering the results of the early life and fatigue tests will likely direct further work to optimise the selected components for remanufacture. The design should again be assessed to ensure that it is optimised to an acceptable level before being signed out of build cycle one.

By the time the product reaches build cycle two early soft tooling is being considered and by build cycle three hard tooling has been created making changes to the product more and more complex and costly. Checks should be performed at the end of build cycle two and three to ensure that any design changes have not negatively affected the end of life reprocessing. This is especially important at the end of build cycle three prior to the design freeze and release of the engineering change note (ECN).

Surrounding systems such as order fulfilment and customer communication should also be considered as part of build cycle three. This ensures that the right messages are communicated to the customer on the remanufactured nature of the product and instructing the return of the core at end of life. Without these in place there may be no demand for the product or cores to reprocess, no matter how optimised the design is. Simply integrating the EOLO model into Stannah's NPI process at the most suitable points is unlikely to succeed. The model needs supporting to ensure it is used and given sufficient importance, being seen as a tool to help deliver the larger objective of product remanufacture and end of life reprocessability. It is therefore also recommended that the project requirements and product design brief contain sections on the desired end of life reprocessability of the product. Product specifications should then be written to meet these requirements. These top level objectives will then be reviewed as part of each the build cycle sign off, not passing unless they are met.

6.4 Chapter Summary

- In order to optimise products for end of life a model was needed to aid designers.
- The EOLO model developed by the author, helps designers identify which of the product's components should be optimised for remanufacture and which should simply be recycled at end of life.
- The EOLO model gives the designer an indication of future remanufacturability and recyclability of the product at an early stage in the design process, when the concept is still fluid enough to make changes.
- Layered results intend to give the designer increasing levels of detail without becoming overwhelming.
- The model demonstrates how different components need different product properties, depending on their intended end of life reprocessing.
- The EOLO model is a qualitative approach based on value judgements made by the designer. Some of this judgement was removed by providing the remanufacturing and recycling scoring matrices.
- The scoring matrices guide the designer on where the product currently sits on a best to worst practice scale. They can then also be used to guide the designer on how to optimise the design further.
- The model only considers product properties that affect the disposal stages of life. The model now needs expanding to include the remaining product lifecycle stages.
- By defining the product characteristics required by the product for each lifecycle stage this helps bridge the product lifecycle and traditional requirements of the design cycle.
- Getting designers to think about the required product characteristics brings them a step closer to considering each stage of the product lifecycle.

Chapter 7 – Discussion

This chapter evaluates the stages of experimental work, brings together the research findings and reviews this research in the context of existing literature. Finally, the research question was answered and novelty of the research discussed.

7.1 Introduction

Product sustainability is undoubtedly beneficial for electro-mechanical products bringing saving to both businesses and the environmental impacts. When measuring environmental impacts of products, LCA offers a methodology to assess the impact on chosen impact categories over the whole life of a product. LCA is not however without its challenges such as data quality and its resource intensive nature. These challenges have a big impact on the success of using LCA in product development, when the design is fluid and resource is often stretched. When the design is stable enough to conduct detailed assessments, the design is often too advanced for the results to influence changes. Another area where LCA has not seen wide adoption is its use in guiding business decisions and improving the efficiency of wider business sustainability.

With the vast majority of the lifecycle impacts associated with electro-mechanical products dictated by the designer, alternative tools are therefore needed. These are required to assist designers with decision making, as many traditionally have not had an education in developing products with reduced impacts on the environment.

What happens to the product at end of life dictates how much of its material and embedded energy are recovered. Remanufacturing was found to be well established in some industries, although it is one of the lesser known end of life options. This is the only end of life option for electro-mechanical products that returned a product of like-new quality, without first destroying the form of the component and losing all the embodied energy that went into making it. With a high level of reprocessing required to achieve the like-new quality, the remanufacturing process is simplified if products are designed to be remanufactured.

Current design for end of life models offer top level guidance on assisting designers with designing products for different end of life disposal routes, such as remanufacture. Despite whole products rarely being remanufactured, to date there was little guidance identified to assist the designer in selecting end of life routes on a component level, ensuring all components were optimised for predefined disposal routes.

There was also a lack of detailed guidance on how to achieve the outcomes specified in current models. Where specific design rules were specified, these can sometimes conflict with one another depending upon the chosen end of life disposal option. There was currently little guidance on which design philosophy to use in which situation, consequently leading to confusion.

It was in these areas that the experimental work of this study focused; looking to reduce the environmental impacts of electro-mechanical products, in this case a stairlift, by considering it on a component level and designing it to operate over multiple lives without increasing cost or reducing its quality.

7.2 Discussion of Experimental Work

In order to answer the research question within this study, the experimental work followed three distinct phases:

1. A case study on the Stannah 260SL stairlift to determine the current product lifecycle and opportunities for reducing its impacts.
2. A case study to remanufacture a Stannah 260SL stairlift at end of life, determining the benefit of doing so on the product lifecycle impacts and cost.
3. To produce a tool to guide the design process in developing products for optimal disposal at end of life.

The processes undertaken, challenges faced and a critical evaluation of each phase of this experimental work was made. The results of each phase are discussed and findings were evaluated in the context of prior literature.

7.2.1 Life cycle assessment

In chapter 4 an initial lifecycle analysis was conducted on a Stannah 260SL Stairlift. Since the environmental impacts of a stairlift had not been assessed before there was no prior knowledge in this area. The purpose of this stage of the case study was to identify which lifecycle stages had the largest impacts in terms of carbon dioxide equivalent (CO_2e) emissions. Breaking the data down further allowed the product to be examined at a component level, determining which components made up the bulk of the product's impact for each stairlift module. This data was then used throughout the study to highlight where improvements could be made to reduce the impact of the product and to provide a benchmark for assessing the benefit of any changes to the product system.

7.2.1.1 Summary of results

Following the methodology set in PAS 2050, the study only considered the one impact category of global warming potential, measured in the form of Carbon Dioxide Equivalent (CO_2e). This narrowed the data collection required and provided clear and simple results to interpret, which would not depend on tradeoffs being made when assessing benefits. As suggested by the University of Bath ([no date]), this decision did however, prevent an evaluation of whether impacts were simply shifted to other impact categories, which were not seen, when changes were applied later in the study. This somewhat limited the robustness of the study but for an initial analysis of the system it was felt that it did not detract from the findings identified.

The Ellen Macarther Foundation (2012) suggested that despite growing engagement with circular economy models, currently industry mainly operates in linear methodologies. The lifecycle of the Stannah 260SL stairlift was no exception to this theory and despite much of the material being recyclable; it invariably ended up being cascaded down into lower grade materials. There were also a number of components designed in such a way that they actually prevent recycling. Examples of these include the upholstery, which was an inseparable mix of materials and choice of expanded polystyrene for packaging, which was deemed non recyclable due to the relatively low volumes available.

The lifecycle assessment, Figure 6.7, indicated that the most significant stage for the Stannah 260SL stairlift was the production of the materials it was made from. Whilst the material content of the product was high, the vast majority of the product was recyclable. When the recovered benefit of recycling material at end of life was subtracted from the upfront raw materials in production, the next most significant stage of life was the manufacturing processes, converting the raw materials into component parts.

Looking at the results on a component level, Figure 6.12 - Figure 6.16, revealed that the majority of the material and manufacturing impacts for each stairlift module came from very few components. There was however, great opportunity to recover these components at end of life and consequently to recover as much of the embedded material and manufacturing energy as possible. Therefore it was these relatively few components that were targeted to reduce their impact on the product's lifecycle.

7.2.1.2 Evaluation of LCA

In total, the LCA of the Stannah 260SL stairlift took eight months to complete. Whilst the study could have been compressed if further resource had been allocated, this does highlight one of the main drawbacks to LCA. Most businesses would struggle to commit this level of finance and time to completing a study of this nature. This work supports that by Lewis, et al. (2001), in identifying the high cost and time required for LCA as a major limitation, which prevents the wider use of life cycle assessment. Once an initial assessment has however been undertaken, the existing model, data acquired and lessons learnt, would significantly cut the resource required to maintain model with product changes or conduct further studies on similar products.

The lifecycle assessment was however, invaluable to this study; assessing where the largest impacts occurred and providing a benchmark for assessing the impacts of future changes made to the product lifecycle in this research.

7.2.2 Remanufacturing

It was noted in the findings from the LCA that the major product impacts were from the production (materials and manufacture) of very few components in the Stannah 260SL Stairlift. If at end of life, as much of the embedded impact associated with these components could be maintained and used again, this would bring significant benefit towards reducing the whole life impacts of electro-mechanical products, in this case a stairlift.

Figure 7.1 is an adaptation (by the author) of the work by Nasr, et al. (2006). The original model looked to close the loop on material flows by exploring where each re-enters the product lifecycle at end of life. The original model however only included the end of life options of recycling, remanufacturing and reuse. With the exception of landfill, the other disposal options explored in this research also circulate material and energy through various stages of the product lifecycle and surrounding earth and ecosystem. For this reason, these have also been added to the model to provide a more complete picture of the disposal options for electro-mechanical products.

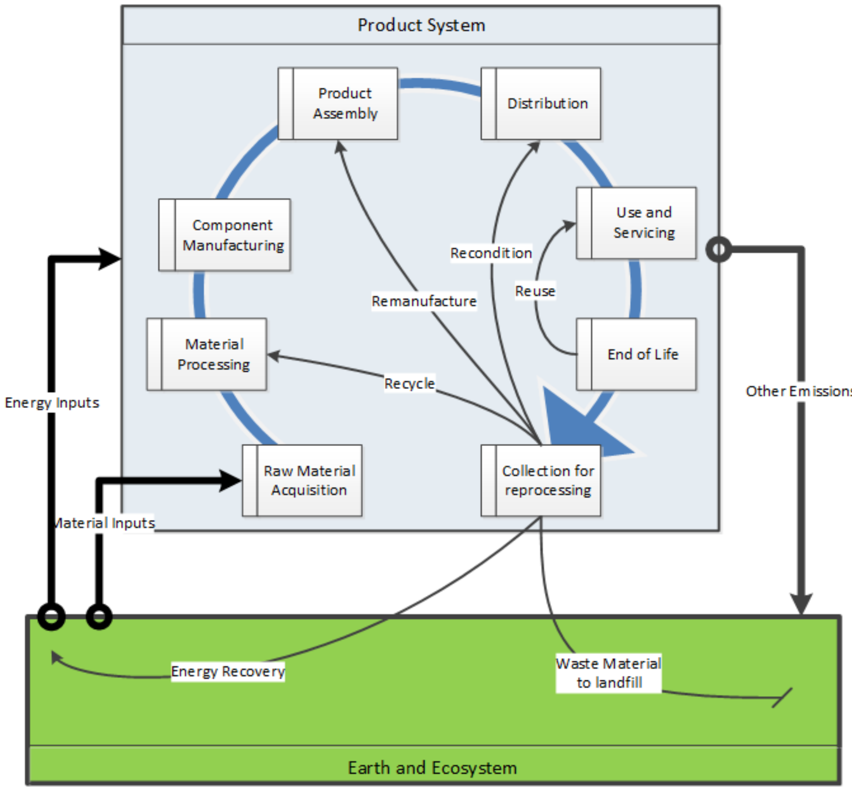


Figure 7.1 - Closing the loop on end of life flows

Whilst each disposal route feeds energy, materials or components back into the product lifecycle or surrounding ecosystem at different stages, varying amounts of embedded material and energy are recovered in each option. The closer to the beginning of the product lifecycle the resource re-enters, the less that is recovered.

The final difference between each disposal route is that products/components are returned to use of differing qualities. In this instance, the closer to the beginning of the lifecycle that the resource re-enters the system, then the closer the product is to being like-new. This concept is demonstrated graphically in Figure 7.2 (produced by the author).

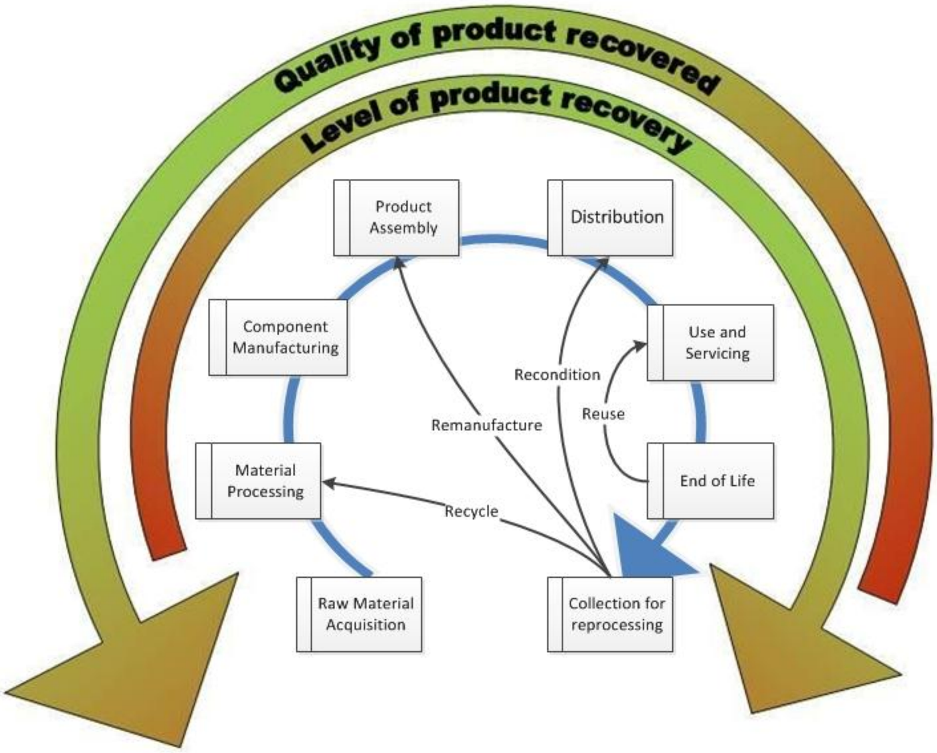


Figure 7.2 - Quality versus recovery for different end of life options

Analysing this, recycling recovers the product's materials but not the processing energy and ultimately returns a like-new product to the market as everything has to be recreated. Product reuse on the other hand requires the least amount of reprocessing and virtually everything is recovered, but the product is returned to use in its current state, which may be of an inferior standard. Remanufacturing takes products back to a component level before reprocessing, but the product is importantly still returned to the market in a like-new condition.

7.2.2.1 Selecting components for remanufacture

The LCA highlighted that the majority of the impact was associated with very few components. A selection process was needed to predefine which components would be remanufactured from the product.

In prior literature no reference was found to detail a methodology for selecting components from a product intended for remanufacture. This is despite the fact that products are rarely remanufactured in their entirety. A methodology therefore needed to be created setting out rules that would determine which of the products components would be remanufactured and which would simply be sent for recycling.

Table 7.1 demonstrates the number of components selected in the case study under each cut off criteria, >5% and >1% for CO_2e and cost. Finally, the table also shows how many of the identified components went on to be selected as suitable for remanufacture due to their material or design.

Stairlift module	Number of components on BOM	Number of components identified at 5%		Number of components identified at 1%		Selected from CO_2e and £ and deemed suitable for reman.
		CO_2e	£	CO_2e	£	
260 Carriage	346	5	4	9	11	12
SL Chair	172	5	3	8	10	11
260 Footrest	33	2	3	4	8	4
Kit Box	62	1	1	6	5	1
Rail	1	1	1	1	1	0

Table 7.1 - Initial component selection options for remanufacture

This methodology of only remanufacturing selected components with the highest worth would only be suitable for either original equipment manufacturers (OEM) or third parties operating on behalf of the OEM. This is because as Hammond, et al. (1998) points out, often the biggest challenge for remanufactures is the availability of spare components. If these are freely available, then the components not remanufactured can be easily replaced. However, if the remanufacture was conducted by an independent third party then not remanufacturing as much as possible would result in a greater number of components needing to be sourced.

7.2.2.2 Results of remanufacturing case study

At the present time, the majority of electro-mechanical products, including stairlifts are recycled at end of life. In this process all the components are reduced back to raw materials which are often of a lower grade than the desired feed stock.

Figure 7.3 (produced by the author) shows the traditional recycled component lifecycle in a closed loop system, here using an aluminium casting. The inital stage is to mine, refine and smelt the raw material before casting it into an ingot. The ingot is then remelted and used to cast the component part, which is built into a product during manufacture. After which the consumer uses the product for a period of time, before disposing of it at end of life. At this point the product is broken down and the aluminium casting shredded, melted back into an ingot and combined with virgin aluminium to maintain purity. The production process then starts again to reproduce the component before being built back into another product. This system can be taken as a reduction process as recycling components in this way at end of life reduces everything back to its raw material state.

Alternative methods of product disposal were evaluated and remanufacture was chosen for further investigation because it was the only method that allowed component recovery without degrading the quality of the product.

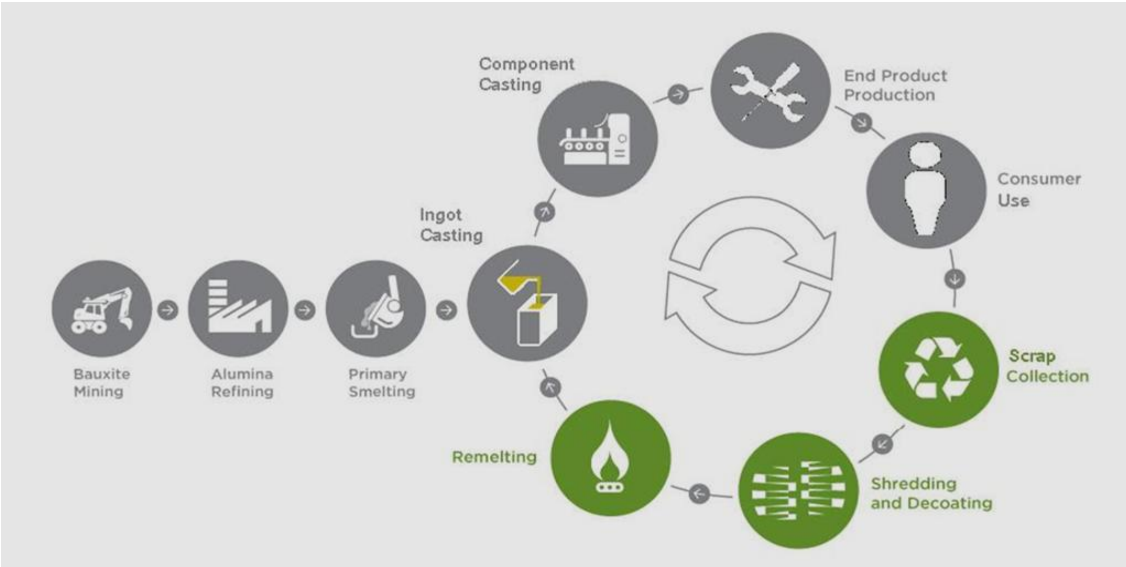


Figure 7.3 - Aluminium component lifecycle with recycling at end of life

When a component is remanufactured at end of life, much more of the embedded energy/CO_2e value of the component is retained instead of being reduced through recycling. Comparing Figure 7.3 and Figure 7.4 (produced by the author), it can be seen that in the case of the adapted product lifecycle, the scrap product is collected and broken down before having value added to what is already in existence, to bring it back to a like-new condition. Hence, remanufacture is known as an additive process.

Intercepting components for remanufacture negates the need to shred the component, re-melt, add virgin material and recast the raw material ingot, and finally recast the component. As Ijomah (2010) points out, in many cases it is the material production and subsequent shaping processes that have the highest impact on the product's lifecycle as is the case with a stairlift. Consequently, maintaining as much of the product and not using energy to destroy what you already have, is where the potential savings lie in remanufacturing.

Figure 7.4 - Aluminium component lifecycle with remanufacturing at end of life

In many cases, recycling material results in a lower grade material being produced which does not perform to the well characterised properties of a virgin material, making it less desirable for designers, Fiksel (2012). By no longer recycling the component, the original grade material is retained for future reuse demonstrating another benefit of remanufacture over recycling.

In this case study, the application of remanufacture to electro-mechanical products as the desired end of life option for the few high impact components, recycling the remainder, indicated that attractive savings were possible both environmentally and financially. Re-running the product LCA with the remanufactured selected components and replacing the recycled components with new, resulted in a reduction in the product's whole life impact by 79 Kg CO_2e. This represented a 13% saving on the recycled product lifecycle. The biggest savings came from the reduction of material and manufacturing required to create the components with the largest impacts. This saving more than offset the additional impacts of the remanufacturing process stages.

Each of the 260SL Stairlift modules that were remanufactured demonstrated significant savings in CO_2e and cost. The carriage impacts were reduced by 39 Kg CO_2e (23%) and revealed a production saving of £148 (31%). The SL Chair's impacts reduced by 22 kg CO_2e (38%) and production costs were reduced by £100 (44%). The kit box's impacts reduced by 19 kg CO_2e (64%) and production costs were reduced by £12 (26%).

A number of suggestions have been made in the literature about the potential savings that can be achieved by remanufacturing products. Steinhilper (1998) suggested that remanufactured products require 85% less energy and Ijomah, et al. (2007) estimated a 20-85% cost saving. Ijomah's estimate is very wide, but the average cost saving achieved by the 260SL module was 33%, so whilst at the lower end, was still within this range. Steinhilper's estimated saving in energy was not a range, but was also double the average saving for the remanufactured modules which only achieved a 42% saving of CO_2e.

Estimating the cost of implementation compared to a typical new product release, the savings achievable would indicate a very short payback period. This is in stark contrast to the suggestions of Matsumoto, et al. (2011), who indicated high initial investment and long paybacks of greater than 10 years to implement a remanufactured range.

7.2.2.3 Evaluation of remanufacturing

The case study clearly showed that whilst remanufacturing the 260SL stairlift could be improved by optimising the product for remanufacture, the selected components from Stannah's 260SL Stairlift are already relatively easy to remanufacture back to a like-new condition.

Identifying components that have the highest worth (environmentally or financially) and targeting remanufacture at these, rather than the whole product vastly improved the efficiency of the remanufacturing process and still achieved significant savings on a new product.

A further benefit to selected component remanufacture is that it is only these components that require stability of design. Provided fixing points and such like remain constant, surrounding components can be modified and upgraded to improve the product. In the case study, design control of this nature was not present and 12 of the original 28 selected components for remanufacture were excluded due to design change. If these components had been of current revision the results of the study would have been even more favourable, Figure 7.5 and Figure 7.6.

The biggest benefit of including these components, both environmentally and financially would have been to the 260 carriage. An additional 69Kg CO_2e and £151 would have been saved leading to a total saving of 63% and 63% retrospectively on a new product.

Further savings were also achieved on the SL chair but with less components being excluded from the study due to design change from this module, these were only marginal. An additional 1.3Kg CO_2e and £3 were achieved leading to a total saving of 40% and 45% retrospectively on a new product.

The 260 footrest was totally removed from the case study due to design change. If the components had been of a current revision then a saving of 3Kg CO_2e and £10 would have been achieved. Whilst this saving is the least of each module considered, it still represents a 30% and 50% saving retrospectively.

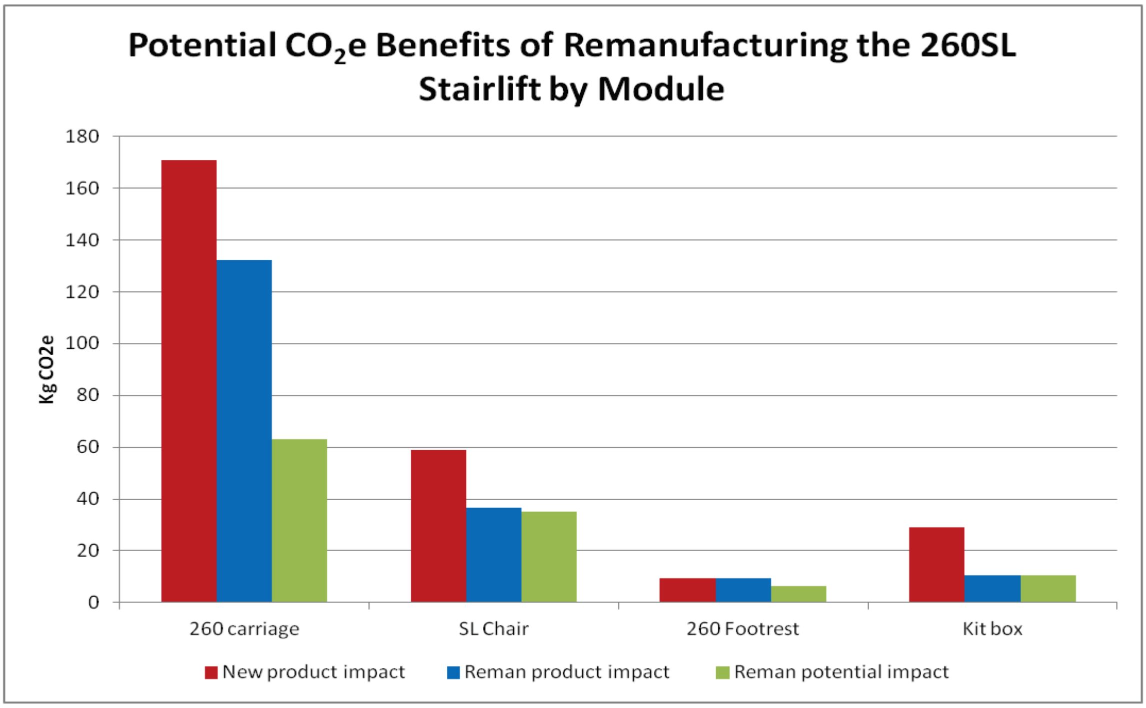


Figure 7.5 - Potential remanufactured 260SL CO_2e benefit by module

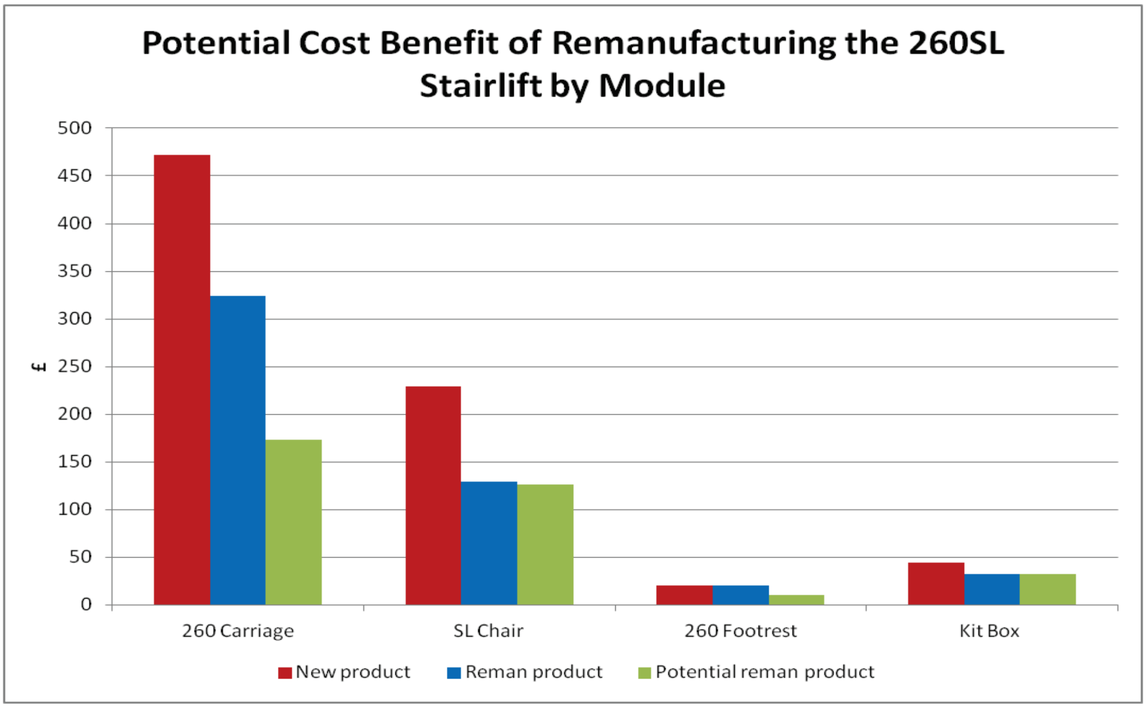


Figure 7.6 - Potential remanufactured 260SL Cost benefit

Overall these additional saving would equate to another 73Kg CO_2e removed from the product lifecycle, Figure 7.7. This would bring the whole life impact of a remanufactured 260SL stairlift down to 479Kg CO_2e, representing a total saving of 24% on a new product.

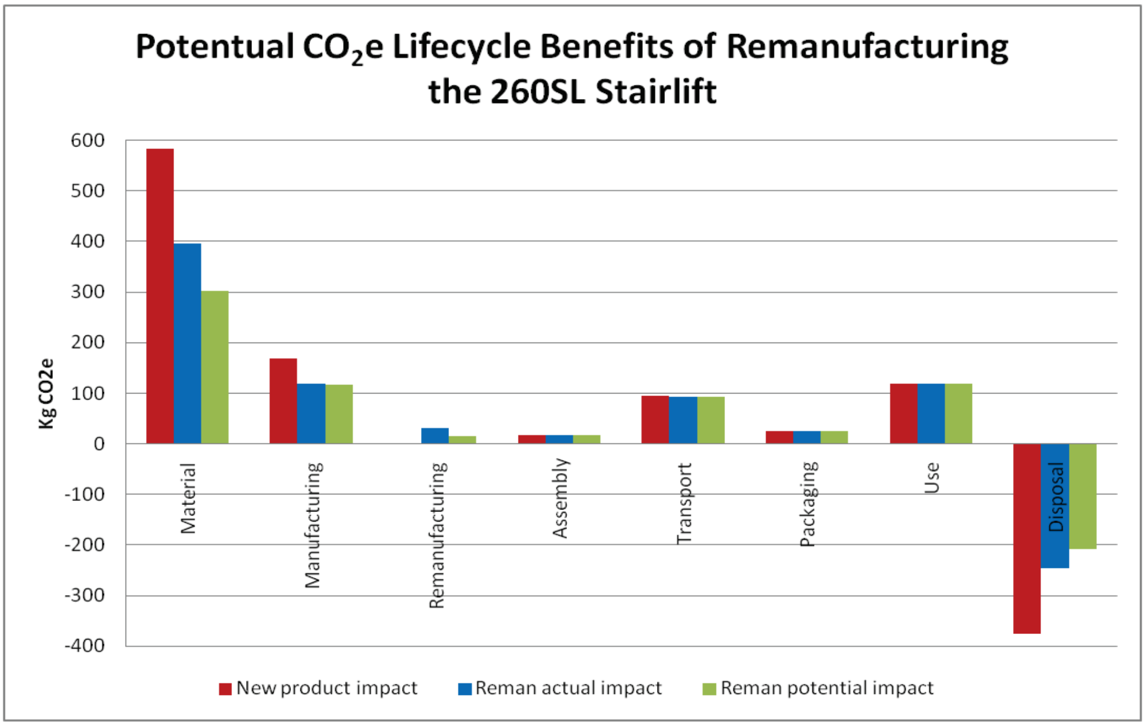


Figure 7.7 - Potential remanufactured 260SL lifecycle assessment

At the beginning of the remanufacturing stage of work, components were selected based on the results of the LCA study and a cost analysis. An estimation of the savings that could be achieved from remanufacturing these components for each stairlift module was made, based on savings identified in literature. Table 7.2 outlines how accurate these initial estimations were to the overall results of the study in terms of CO_2e and cost. The estimated savings however, did not take into account the fact that some of the selected components were not suitable for remanufacture due to design changes. To provide a fair evaluation, the potential savings from remanufacturing all selected components, were used in the comparison.

The outcome of this was that the original estimates were within +/- 5% when estimating the carbon dioxide equivalent savings that might be achieved. When considering cost however, the estimates were considerably out. It was therefore suggested that the equations derived in chapter 5 of the study are not accurate and it is not sufficient to estimate an 85% manufacturing saving with a doubling of labour.

Stairlift Module	Estimated Saving		Case Study Potential Savings		Accuracy of Estimate	
	Kg CO_2e	£	Kg CO_2e	£	Kg CO_2e	£
260 Carriage	112	250	108	299	4%	-16%
SL Chair	23	61	24	103	-4%	-41%
260 Footrest	3	7	3	10	0%	-30%
Kit box	18	18	19	12	-5%	50%

Table 7.2 - Accuracy of estimated benefits when remanufacturing

The biggest challenge in the remanufacturing process was dealing with design change post product launch which eliminated many components from the study. Analysing the components that were remanufactured, it was evident that if the design of some had been optimised, the efficiency of some of the remanufacturing stages such as disassembly, cleaning and reprocessing would have been increased. Therefore if product remanufacture is to be considered, it is important that design teams are aware and sympathetic to that fact when designing new products or proposing changes to existing ones.

7.2.3 The End of Life Optimisation (EOLO) design tool

The case study to remanufacture the 260SL stairlift demonstrated that whilst it was possible to remanufacture a product not originally designed with these characteristics in mind, the process of returning the core back to a like-new condition could have been far more optimised if it had been. By optimising products for end of life reprocessing, greater efficiency and therefore profitability can be gained.

Components intended for remanufacture required very different product characteristics to those intended for recycling. These individual component characteristics need to be implanted into the design at the early stage of the process, when in concepts and the design is still fluid enough to make changes.

The fluidity of the design at this point however, does present a challenge for assessing the design's current suitability for different routes. Investing the time in quantitative LCAs and extensive component costing exercises is not advisable, because the design is likely to change, invalidating this work. At this stage in the design process, eco design tools need to be quick to use and provide the designer with guidance, without hindering the creativity of product development. Qualitative assessments can therefore often be more appropriate.

In order for the right characteristics to be designed into each component, the intended disposal route needs to be considered up front by the designer. The end of life optimisation

(EOLO) Model was developed to optimise products in the product development stage for end of life reprocessing.

7.2.3.1 Developing the EOLO model

The first stage of the EOLO model is to select the desirable disposal route for each of the products components. The decision tree, Figure 6.1, identified which of the components should be optimised for remanufacture and which should be directed towards recycling at end of life. The purpose of the decision tree is to guide the process and does not assume any or require any prior knowledge by the designer unlike other tools such as REPRO[2].

Once the desired disposal routes had been identified, desirable product characteristics for each group were needed. The RemPro matrix by Sundin, et al. (2008) identifies specific product characteristics which are important for promoting remanufacturability, Table 7.3.

	Ease of Identification	**Ease of Verification**	**Ease of Access**	**Ease of Handling**	**Ease of Separation**	**Ease of Securing**	**Ease of Alignment**	**Ease of Stacking**	**Wear Resistance**
Inspection	*	*	*						
Cleaning			*						*
Disassembly	*		*	*	*				*
Storage	*			*				*	
Reprocessing			*	*	*				*
Reassembly				*		*	*		*
Testing	*		*						

Table 7.3 - Rempro matrix (Sundin, et al., 2008)

The EOLO remanufacturing matrix, Table 7.4, developed by the author, adapts and builds on the RemPro matrix. A number of the RemPro matrix top line product characteristics and paired processes were maintained, however some were also altered based on the findings from the remanufacturing case study in this research.

	Ease of Identification	Ease of Verification	Ease of Access	Ease of Separation/ Securing	Ease of Upgrade	Physical Attributes	Wear Resistance
Inspection	*	*	*				
Cleaning			*			*	*
Disassembly	*		*	*		*	*
Storage	*					*	
Reprocessing	*		*	*	*	*	*
Reassembly	*			*	*	*	*
Testing		*	*				

Table 7.4 - EOLO Remanufacturing matrix

The RemPro matrix had separate characteristics for ‘ease of securing’ and ‘ease of alignment’. However, ‘ease of alignment’ only impacts upon the reassembly process and in many respects could be seen as a strategy for achieving ease of reassembly. When looking at improvement strategies, many of the recommendations that could be made to improve assembly would also improve disassembly. Examples of these include minimising thread lengths, number of fixings and assembly/disassembly paths, all of which impact both process stages. For these reasons, the product characteristics of ‘ease of separation’ and ‘ease of securing’ and ease of alignment’ were combined into ‘Ease of Separation/ Securing’ to simplify the matrix.

The RemPro matrix also had several product characteristics that referred to the physical attributes of the component such as ‘ease of handling’ and ‘ease of stacking’. These were again combined into one category. One area the RemPro matrix doesn’t pick up on is the impact the physical form of the component has on processes, such as cleaning and reprocessing. Examples would include deep grooves, coarse textures and tight radii corners which all gather dirt and require greater levels of cleaning. Similarly very polished or smooth surfaces would be more easily damaged requiring greater reprocessing to bring them back to a like-new condition. These strategies were also picked up in the ‘physical attributes’ product characteristic.

‘Ease of upgrade’ has been added to the matrix as a new category previously not touched upon. This characteristic plays a big part in how successfully the product can handle design improvement and allow both new and old components to be reassembled side by side with one on other.

Which remanufacturing process stages each characteristic were paired with, were also adapted from the RemPro matrix. Unlike the RemPro matrix, 'ease of identification' was not deemed to be so important for final testing so it was removed. At this stage the product is reassembled and would simply be tested to ensure it meets the same specification as a new product. 'Ease of identification' was however, deemed to be important to the stages of reprocessing and reassembly. In these stages identification was important to ensure that the history of the exact component was known to determine its safe reuse and the level of reprocessing that needed to take place. Identification was important at reassembly to speed up the reassembly process. If components had worn together and need reassembling as a pair, then identifying these was very important to ensure correct operation after reassembly.

The RemPro matrix only considers the end of life option of remanufacturing. Therefore, a similar matrix was next developed (by the author) for recycling. No previous literature was available setting out product characteristics for recycling, so these were developed based on the available literature and the findings of the remanufacturing case study.

Whilst the RemPro matrix and other models such as $REPRO^2$ provide some top level guidance on the desirable characteristic for remanufacture, it did not provide the designer with a method of assessing a design's current suitability for remanufacture, or give the designer any practical hands on guidance with how to improve the design for each characteristic going forward.

The EOLO model builds on the functionality of the RemPro matrix, and not only identifies important product characteristics, but also scores them and provides the guidance required for designers not familiar with designing for these requirements. Within both remanufacturing and recycling, the same product characteristics were often required by different process stages within each. Scoring the product characteristics therefore increased the speed of the assessment process and improved the efficiency of the model. The scoring matrices, developed by the author, guide the designer as to where the product currently sits on a best to worst practice scale, which removes some of the value judgement required by the designer.

Once the current performance of the design is known, it was hoped that the scoring matrix will guide the designer with practical strategies to improve the product in the low scoring areas. This was an improvement on the RemPro matrix as it offers strategies for the designer to achieve the identified characteristics and therefore to improve the design. The matrices also assist the designer who until now has been reliant on confusing and often conflicting guidance.

Providing independent matrices for remanufacture and recycling, makes it very clear which rules to apply to which group of components.

7.2.3.2 Implementing the EOLO model

Again using Stannah Stairlifts as the case study, an investigation was undertaken to explore how the EOLO model would integrate with Stannah's new product development introduction (NPI) process.

Goepp, et al. (2014) argued that eco design should be considered as early on in the design process as possible in order for it to be most effective. Deutz, et al. (2012) however, argued that eco design tools should not be used in the divergent concept development stage as this would stifle creativity. Instead they should be used to aid decision making after concepts have been created.

The EOLO model was intended to be used early on in the concepts stage of product development, but after the initial concept has been created through to the build cycle 1 stage gate review. It was this stage between a developed concept and the initial engineering stages where the characteristics affecting end of life are defined.

Prior to this point it was felt that the design would not be established enough to meaningfully assess the concept's current performance, and after build stage 1 the product would be too finalised to make significant change if needed. The period of the NPI process where eco design activity should take place is highlighted in Figure 7.8 (produced by the author). As can be seen it was at this point in the NPI process where multiple concepts are narrowed down but the fluidity of design was still present.

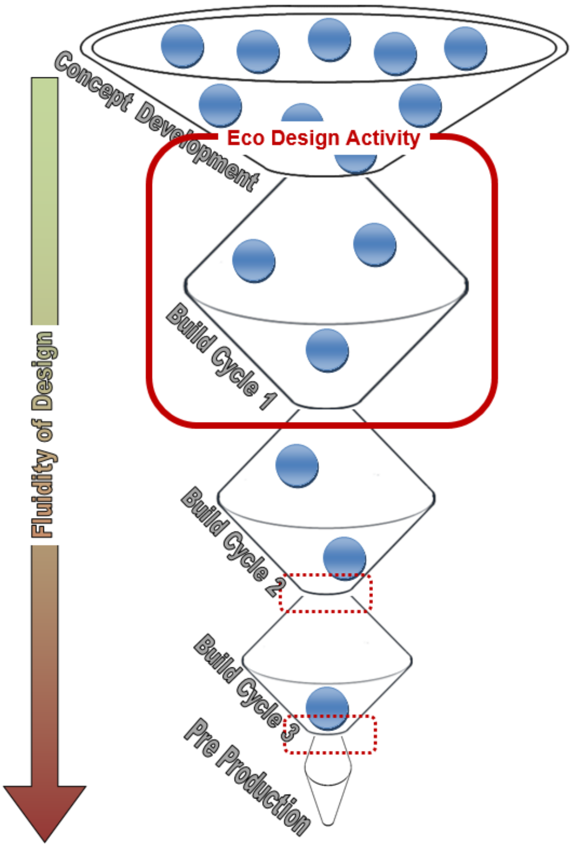


Figure 7.8 – Eco design activity in the NPI process

After the product moves out of the build cycle 1, the EOLO model should continue to be used in stage gate reviews to ensure that changes made to the product have not negatively affected the optimisation of the product for end of life reprocessing. As Fiksel (2012) points out, including environmental factors in reviews also increases the importance of these issues within design teams, as the product will not be signed out of that build cycle until the requirements are met. This demonstrates an additional benefit to the continued use of the model.

Knight, et al. (2008) identified that a significant enabler in implementing eco design was to customise processes and tools to the industries using them. Whilst as it stands the matrices within EOLO model offer more general guidelines for the optimisation of electro-mechanical products, they could easily be modified to offer industry/business specific guidance. This is a real strength of the model as it will help design teams relate more closely to the tool. Expertise would however be needed prior to implementing the tool to identify the relevant characteristics and insert them into the tool under the correct -2 to +2 score.

Another challenge identified by Knight, et al., (2008) and Fiksel (2012) to implementing eco design is the conflict between the design cycle and the product life cycle. The strongest focus is often the delivery of the product within pressures such as budget, and consequently the design cycle is often the stronger driver. Designers are as such; more used to thinking about the product in development than the lifecycle it will operate in, seeing eco design as an additional burden requiring resource.

The EOLO model focuses not on the product lifecycle, but on positive product characteristics that aid each stage of life. It was suggested that focusing away from eco design, towards just good design which promotes beneficial characteristics on the product, brings eco design closer to the current design practices within industry. This approach may help bridge the gap between the two cycles and result in more sustainable products being designed.

7.2.3.3 Evaluation of EOLO model

The first stage of the model selected components for remanufacture or recycling. Assessment of components at the early stages of design may be difficult and some experience of the designer may be required to make an initial judgement based on component size or complexity, confirming this choice as the design develops.

Assessing product characteristics speeds up the process of assessment as many of the characteristics are important for multiple stages in the remanufacturing or recycling process but only need scoring once. A downside to this approach was different lifecycle stages requiring different levels of any given product characteristic, e.g. wear resistance. An example of this was seen when testing the model on the 260 footrest; where the cleaning process stage was highlighted as being poor due to poor wear resistance. The poor wear resistance score was a result of wear seen in life, not through the cleaning process, and all components are in fact robust enough to sustain cleaning. This information may mislead the designer in suggesting improvements to the design going forward. An area for further work would be to expand the model slightly so that more clarity is seen in some areas, such as chemical resistance for cleaning being differentiated from physical resistance to wear.

The few components that are to be designed with remanufacturing in mind are scored individually so they can be benchmarked and specific improvements suggested on a component level. The components intended for recycling make up the greatest number of components, but also those with the least impact. Scoring these components as a collective improves the efficiency of the model, but does not indicate to the designer specific design improvements on a component level, which could be seen as a negative.

The scoring matrices were designed with a scoring range of -2 to +2. This was intended to allow quick scoring of components as there were only five categories to choose from. In testing the model with the 260 footrest there were instances where partial compliance to a scoring category was met. It was concluded that offering a slightly greater range of scores or allowing the designer to select points between scores may improve the model.

The EOLO model was developed to assist product designers to develop products more suited to either remanufacturing or recycling from the outset. One of the biggest eliminators of components in the 260SL stairlift remanufacturing case study was design change post launch by engineers looking to incrementally improve upon the product. The EOLO model had less of an impact on preventing changes to the components intended for remanufacture. It was hoped however, that if a modular design philosophy was designed into the product from the outset, this would continue to be followed allowing product modules to be updated without impacting the remanufacturability of the rest of the product.

In some cases however, after assessment and the use of the design for remanufacture scoring matrix, it was found that some components were not suitable for remanufacture. An example of this was the plastic covers, where any damage would result in their removal as they could not be returned back to a like-new condition. These components therefore were optimised for recycling going forward. Whilst the desired outcome was that all highlighted components were successfully optimised for remanufacture, there was still a benefit in highlighting these components to the designer so that an informed decision to recycle can be made.

The EOLO model only considers the product lifecycle stage of end of life. However, as noted in the literature review, it is important that all lifecycle stages are assessed to ensure that impacts are not simply shifted to other stages of the lifecycle, University of Bath ([no date]). Further development of the EOLO model should expand the philosophy of assessing product characteristics and be applied to the remaining lifecycle stages, consequently expanding the matrix of the model. This would allow the benefits of scoring product characteristics rather than lifecycle process stages to be replicated, which would maintain the simplicity and efficiency of the model.

7.3 Key Findings from the Experimental Work

The aim of this research was to identify and evaluate methods for improving the sustainability of electro-mechanical products, focusing on improving the product through design, for end of life reprocessing. In this study this was validated in the context of a stairlift.

7.3.1 Answering the research question

The research question posed at the start of this study asked if and how the environmental impacts of electro-mechanical products could be reduced, by considering them on a component level and designing them to operate over multiple lives, without increasing cost or reducing quality.

The environmental impacts of electro-mechanical products will influence each stage of the product lifecycle varying amounts depending on the product system being studied. The predominant impacts of Stannah's 260SL stairlift were those associated with the production of very few of its components.

If the high impact components can be recovered and returned to a quality where they can be reused, then this presents significant opportunity for reducing the upfront impacts of future products. Remanufacture can present this opportunity, returning components to a like-new standard whilst maintaining not only the material but also embodied energy that went into manufacturing the part in the first instance.

Considering these products not as a whole, but on a more granular component level revealed that different components would ideally suit different disposal methods. Putting the time and resource into remanufacturing the few high value parts, and accepting the remainder of the product would be recycled.

Traditionally the disposal of electro-mechanical products has not been in the forefront of the designer's mind when designing new products. In order for products to efficiently operate over multiple lives, designers need to start considering the lifecycle stage of end of life and designing with remanufacture in mind. Equally, components intended for recycling can greatly benefit for being designed with this in mind. The EOLO model produced in this research aimed to assist the designer with meeting these requirements.

The results of the case study demonstrated that the benefits of remanufacturing the few components with the highest impacts, and recycling the remainder of the product was significant. Rerunning the life cycle assessment demonstrated that the whole life environmental impact of a Stairlift, representing a sample electro-mechanical product, could be reduced by 13% overall.

Using the LCA data in combination with cost allowed only the high impact components to be targeted with remanufacture, thus improving the efficiency of reducing the impact of the product on the environment. This not only avoided any increase in cost to the manufacturer, but in fact achieved a 34% reduction in overall production cost. These savings in both environmental impact and cost were achieved with no detectable reduction in quality or functionality of the product in future use.

Whilst these savings were significant, if the product had been optimised for remanufacture in its design, then these savings would be even more significant (11% additional environmental savings and 33% additional cost deduction). This further highlights the importance of optimising electro-mechanical products for a pre-determined disposal route in the early stages of the NPI process. The EOLO model offers designers a tool to assist them in this end of life methodology when they have no background or the knowledge to make the required decisions.

It was therefore concluded that by considering electromechanical products on a component level, and designing each for the most appropriate end of life reprocessing route; the whole life impact of the product could indeed be reduced without increasing cost or reducing quality of the product.

7.3.2 The Novelty of the Research

This research has demonstrated several areas of novelty to advance thinking in the field of improving product sustainability, in particular design for end of life optimisation:

1. Current design for remanufacture models assume that the whole product would be remanufactured, and the product optimised accordingly. In reality, remanufacturing the whole product in its entirety might not be the most desirable option. The current approach of applying a remanufacturing philosophy across the whole product does not consider what happens to the components that are not remanufactured, or to components that are incorrectly optimised for remanufacture. A remanufacturing methodology was developed selecting components for remanufacture from within a product. This cut-off criteria was based on the results of the LCA and/or their financial value. Only the high worth components were destined for remanufacture, sending the remainder of the product for recycling. The recovery of only high worth components for

remanufacture maximised the efficiency of the remanufacturing, and ultimately improved the profitability of the process whilst maintaining significant environmental benefit.

This philosophy of considering a product on a component- by- component basis was built into the EOLO model. The early stage life cycle assessment data, along with other drivers such as cost were used to select components from a product specifically for remanufacture or recycling. This allowed each group of components to be optimised in the design phase with different characteristics, based on the most desirable end of life option.

2. The guidance previously available to designers in the area of end of life optimisation was all of a high level, offering overviews and assessment models, not practice advice on how to achieve the desired design outcomes. This was seen as a barrier to implementation as many designers do not possess the skills to make the required decisions. Consequently, the development of the EOLO model looked to address these issues and provide the designer with a practice framework for optimising the design of components for end of life, even if they were not skilled in the knowledge of eco design.

3. The examination of current design for end of life models generally showed that there were no end-to-end frameworks available, initially selecting the most suitable EOL route for components and then provide a link back to design rules. These stages tended to exist in separate models, initially selecting the most suitable route and then optimisation taking place separately.

   Whilst optimisation tactics such as ‘durability’ are given in design for end of life models, these were not expanded to aid the designer in how to achieve these. Considering the design for end of life guidance that was available, it was found to be often non-descriptive and could conflict with each other depending on end of life route chosen. Limited guidance on when to apply which rules was available, with the potential to lead to confusion.

   The EOLO model provides that end-to-end process, initially selecting components for end of life reprocessing routes and then providing the designer with a scoring matrix and how-to guides for assessing and improving the product further within the same model.

Chapter 8 – Conclusions

It was clear that businesses must change radically in order to reduce their environmental impacts. For businesses developing electro-mechanical products, the impacts of the goods produced stem from the design decisions made early on.

Through the use of a case study, this study set out to explore whether the impacts of electro-mechanical products could be reduced, by considering products on a component level and designing them to operate over multiple lives, without increasing cost or reducing quality. This proved to be true in the case of a stairlift.

The life cycle assessment demonstrated that the whole life environmental impact of a stairlift, representing a sample electro-mechanical product, was significantly reduced by remanufacturing components at end of life. Using the LCA data in combination with cost allowed only the high impact components to be targeted, thus improving the efficiency of reducing the impact of the product on the environment.

Through the use of a life cycle assessment framework, overall environmental savings of 13% were witnessed. Incorporating sustainability in this fashion not only avoided any increase in cost to the manufacturer, but in fact achieved a 34% reduction in overall production cost. It was concluded that if the product was optimised for remanufacture in design in the future, then these savings would be even more significant. This led to the development of the EOLO model.

8.1 Specific Research Outcomes

The findings of this work have made an original and significant contribution to the existing knowledge in the field of electro-mechanical product sustainability. This Research has delivered outcomes in two specific areas:

1. Using an LCA framework in combination with component cost to identify hotspot components provides a new methodology for remanufacturers, remanufacturing only those components with the greatest worth and sending the remainder of the product for recycling. This offers original equipment manufacturers (OEM), or those affiliated to them, a methodology to return end of life products back to a like-new condition

with greater efficiency. This increases potential profits whilst still reducing the environmental impact of the materials and manufacturing stages of life.

2. The EOLO model provides a framework for designers unskilled in eco design to confidently identify high worth components and the knowledge required to optimise each component for its chosen, predefined lifecycle. Identifying key component characteristics for life cycle stages and then using these to guide the development of products will assist designers in eco design. The EOLO model allows designers to consider the desirable product characteristics required for end of life reprocessing. This is a step towards bridging the gap between the traditional requirements of design and designing with product lifecycle thinking in mind.

8.2 Study Limitations

- The study was conducted using a single case study. If multiple cases had been investigated then the study may have produced a broader range of results.

8.2.1 Life cycle assessment limitations

- The study only considered products going into the United Kingdom market place and sold from the Andover branch. This decision limited the distribution impacts.
- The supply chain was only considered as far as the first tier, and second tier where possible. Any impacts between tier two and extraction of raw materials were not included.
- Location and transport of raw material to the supplier before being transported to Stannah was not modelled. These would have increased the transport impacts if measured.
- Where inline power meters could not be used to measure process power consumption, maximum power consumption was used which may not necessarily be a true representation of the machining power used in the production of that component. Where this was not possible life cycle inventory data was used which again may not have been representative.
- The study only considered carbon dioxide equivalent and not a wider range of impacts. Therefore only the following emissions were considered as part of CO_2e: Carbon Dioxide, Methane and Nitrous Oxide. However, only measuring one impact category would mask any shift of environmental burden to other categories.

8.2.2 Remanufacturing limitations

- The remanufacturing process was undertaken in house by the Author or by existing Stannah suppliers where equipment or specific knowledge was required. This approach limited the external remanufacturing expertise that could have been obtained if an expert with knowledge of remanufacturing electro-mechanical products had conducted the remanufacturing.
- The study was all based around the Stannah 260SL stairlift. This is Stannah's most premium product and so is expected to contain the components with the highest value and environmental impact. Stannah's cheaper products may not be as financially or environmentally attractive to remanufacture.
- The non-destructive testing undertaken was conducted on components that had been subjected to an unknown life. It would have been more robust to test components which had sustained maximum load and had been subjected to a hard life.

8.2.3 EOLO design model limitations

- The EOLO model was tested using the 260 footrest. This however did not validate the model or test its usability or usefulness as a design tool in the development of a new product.
- The EOLO model only considers the life cycle stages of end of life. This may result in improvements in the remanufacturability of the product negatively affecting other lifecycle stages.
- The EOLO model currently scores components on a -2 to +2 scoring range however, some components can fall between one score and the next.
- There are cases where the results of the model can indicate confusing results, for example not separating chemical resistance and physical resistance to wear.

8.3 Further Work

Areas of further work were identified throughout the remanufacturing process to improve and commercialise the reprocessing of a Stannah 260SL stairlift. These included identifying more environmentally sound methods of powder coat removal and additional testing to artificially stress components to a worst-case scenario, to build confidence in their continued safe reuse.

There were however, three areas of further work identified with wider industrial relevance. These lie in the further development of the end of life optimisation (EOLO) model and present significant opportunity for further research:

1. The scoring range needs to be widened to remove value judgements as to which score a component should achieve. This is especially important when the designer or stage-gate review team are not proficient in weighing up trade-offs in sustainability. More detail is also required in the scoring of product characteristics, so clearer results are obtained from the model.
2. The concept of assessing product characteristics rather than lifecycle stages shows promise, and may be suitable for expanding across the rest of the product lifecycle. Further research is required to identify the desirable product characteristics for the remaining lifecycle stages. Matrices need developing in order to score components and guide the designer in further product development.
3. The EOLO model needs validating as a design tool in the development of a new product. The first element of validation needed is by a design team using the model in a stage gate review, to assess component scoring and the results generated by this. The second stage of validation is for a designer to use the results and matrices to guide design optimisation.

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Appendices

Appendix A – Eco design for remanufacture

Reman. Stage	Design Guidelines	Reference
Designing for Core Collection	• Communication to the user that a collection is offered by the manufacturer to return the core at end of life. • Product may not be suitably packaged, unless it is provided. Minimise any potential for damage when returning the core to the remanufacturing location.	(Charter, et al., 2007) (Shu, et al., 1999)
Designing for Disassembly	• Reduce the total number of fasteners used. • Reduced the variety of different fasteners used. • Avoid long disassembly paths. • Use gravity where possible to aid in component removal. • Design snap fits for removal, avoiding inaccessible locations resulting in force being required to open. • Reduce the number of parts in the product. • Reduce the number of different materials used (especially plastics). • Reduce the number of assembly axes. • Eliminate adhesives, ultrasonic welding and irremovable fixings such as rivets, which are likely to lead to component damage during separation. • Use active disassembly methods where suitable. • Minimise the length of threads to reduce disassembly times. • Don't place fixings where they are likely to corrode and become difficult to remove. • Minimise the damage caused to core components in the disassembly process. • Isolate parts that are expected to have sustained damage in life so they can be replaced. • Ease of access for component removal.	(Shu, et al., 1999) (Charter, et al., 2007) (Sundin, et al., 2008) (Ijomah, et al., 2007)

Design for Cleaning	• Forms should be avoided that collect and gather dirt, such as sharp groves and recesses. • Surface characteristics such as coarse texture and light colours should be avoided, so not to require excessive cleaning. • Corners and bends should have large radii to stop dirt collecting. • Consider access and ease of introducing cleaning fluids into hard to reach areas to flush out contamination. • Choose components that can survive the relevant cleaning process. E.g. melting point higher than process temperature. • Identify components that require similar cleaning processes and agents.	(Shu, et al., 1999) (Sundin, et al., 2008) (Ijomah, et al., 2007)
Design for Inspection	• Product testing points should be easily located. • Components requiring inspection should be located under easily removable covers and in the line of sight. • Sacrificial features can be used to indicate component condition. • Sensors can be integrated to determine component history and condition.	(Sundin, et al., 2008) (Ijomah, et al., 2007)
Design for Reliability and Durability	• Select materials for durability. • Select materials appropriate for repetitive remanufacturing. • Design components that have extended service life or are capable of being easily reprocessed. • Design specifications should dictate the required reuse quality of components. • Reduce wear due to friction between components. • Reduce ineffective/unnecessary coatings which may flake or wear. • Very smooth and gloss surfaces should be avoided as substantial effort will be needed to restore them. • Anticipated wear and expected part failures should be replaceable by using techniques such as inserts and sleeves.	(Charter, et al., 2007) (Ijomah, et al., 2007) (Shu, et al., 1999)

Design for Upgradeability	• Platform or modular design so that the core can be upgraded. • Group components according to their technical market life which can be replaced together. • Design aesthetics to be easily upgraded using external covers. • Design products to need remanufacturing at an optimum point in their life e.g. design in time related failures. • Standardisation of parts and fixing locations. • Structure the product to facilitate expected areas of future upgrade.	(Charter, et al., 2007) (Hatcher, et al., 2011) (Ijomah, et al., 2007)
Design for Reassembly	• Provide deeper threaded holes so a longer fixing can access a fresh thread on reassembly. • For areas where fixings may corrode or become damaged in disassembly, provide additional fixing points for reassembly. • Self tapping screws should be avoided as when the screw is reinserted new threads are formed in a previously weakened material. • Use either identical parts or design parts to look distinctly different from one another. • Clearly identify parts that look similar, eg. Dot matrix identification. • Choose fixing methods that will aid future remanufacturing.	(King, et al., 2010) (Shu, et al., 1999) (Ijomah, et al., 2007)

Table A.1- Design for Remanufacturing Guidelines

Appendix B – Eco design for recycling

Recycling Stage	Design Guidelines	Reference
Manufacturing	• Design products with recyclable materials. • Design products to be made with recycled material. • Use materials that are sourced locally to the end of life reprocessing location. • Avoid the use of hazardous materials. • Chose low embodied energy materials. • Reduce material content through structural design. • Design products with as fewer material types as possible. • Use compatible material types that can be recycled together. • Composites and laminates should be avoided as separation back to their raw materials is often difficult. • Material coding should be marked onto components for easy identification of materials.	(AFNOR Standardization, 2010) (Fiksel, 2012).
Disassembly	• Avoid components that will tangle such as ropes, pulleys and springs. • Avoid the use of adhesives joining incompatible materials. • Avoid ultrasonic or solvent bonding when components will need to be separated at end of life. • Avoid the use of threaded fixings as they are slow and increase disassembly costs. Use snap fits or spring clips where possible. • Minimising contaminants such as inks, paints pigments will also increase material purity for recycling. • Avoid the use of labels which can add contamination to the material feedstock. Where possible, information should be moulded or etching into the part. • Active disassembly can be used to automate the disassembly process using smart memory alloys and polymers. • Use materials with different densities to ease separation. • Pressing metal inserts into plastic can be difficult to remove and cause damage to recycling equipment.	(Fiksel, 2012) (Bhamra, et al., 2007) (Shu, et al., 1999)

Disposal	• To maximise economic value, the material needs to be as close as possible to the manufacturing feedstock. • When making material choices, consideration should be given to the recycling markets and attractiveness of the end of life material. • The existence of a mature recycling steam and recycling infrastructure for the chosen material is important.	(Fiksel, 2012).

Table B.1- Design for Recycling Guidelines

Appendix C – Implementing eco design standards

Stage	Detail	Reference
Top level Management of Eco Design	• Design processes should be linked to and detailed in the businesses Environmental Management system. • Develop an environmental improvement strategy defining where the business will focus its efforts. Highlight environmental indicators important to the business, the products it produces and their customers. • A continual improvement should be promoted for each environmental indicator and outputs recorded.	(International Organization for Standardization, 2011)
	• All functions of the business must commit to eco design, contributing to improving their environmental performance. • A communication strategy is required for promoting environmental measures, performance and improvement. • Time and resource needs allocated to meeting eco design requirements.	(International Organization for Standardization, 2002)
	• All aspects of the design process should revolve around product life cycle thinking.	(British Standards Institute, 2009)
Design Brief	• Considerations and targets should be set for each stage of the product life cycle from materials through to end of life.	(British Standards, 2011)
Product Specification	• Specify the functions of the product in terms of usability, useful lifetime and appearance. • For each environmental aspect set targeted reductions for the product. • Identify legal and legislative obligations for the product	(International Organization for Standardization, 2011)

Concept Generation	• Map out the product life cycle and identify what significant environmental impacts are present for each phase. • Life cycle thinking should be considered from the outset of the design process. • Develop technical solutions to meet the environmental objectives/targets, while taking into account other design considerations such as function, technical, quality, performance, business risks and economic requirements.	(British Standards Institute, 2009) (International Organization for Standardization, 2011)
Environmental Assessment of Concepts	• Establish which concepts to take forward using life cycle analysis, evaluating each against the environmental aspects highlighted in the design brief.	(British Standards, 2011)
Design Development	• Develop concepts to meet the requirements of assembly and disassembly. • Develop concepts for use considerations including power, consumables, maintenance and repair.	(British Standards, 2011)
Cost Considerations	• Cost the design for each life cycle stage including materials, manufacture, consumables, maintenance and overhaul, recycling and disposal. • Include fiscal benefits such as tax breaks, grants and incentives.	(British Standards, 2011)
Environmental Assessment and Review	• Reviews should be conducted at the end of key design stages. • Reviews should be an iterative process, which highlight incremental improvement of the design as it develops. • Reviews should consider the impact of changes to each stage of the life cycle, ensuring there is no adverse shift of impact to another stage of the lifecycle or new significant impacts created. • Overall there should be a net reduction across all life cycle stages. • Reviews should be recorded.	(International Organization for Standardization, 2011)

Suppliers	• Encourage two way communications on performance and actions needed to improve environmental credentials. • Inform suppliers of eco design methodologies and enforce their use.	(International Organization for Standardization, 2011)
Review	• Checking that the detailed design/prototype has achieved the targeted reductions and legal obligations. • Review of the eco design process updating, recording and implementing changes.	(International Organization for Standardization, 2011) (International Organization for Standardization, 2002)
Launch	• Look to promote the products environmental features to customers.	(International Organization for Standardization, 2002)
Validation	• Evaluate the behaviour of the final product in use against the environmental product specification. • Monitor and measure the uptake of eco design within the company. • The management review should assess opportunities to improve the environmental performance of the organization's products and its eco design process. • Provide a framework for decision making and actions to be taken.	(International Organization for Standardization, 2011)

Table C.1 - Stages of the eco design process

Appendix D – Life Cycle Process Stage Maps

Figure D.2 - Paint plant process flow

After components were fabricated, they were painted using a powder coating process. The components were washed through a series of preparation processes, to remove oil and debris from the surface of the part. Components were then dried before the powder was applied to the surface. Finally the components travelled through a curing oven to adhere the paint to the surface. The main input to this process was the gas to fire the ovens.

Figure D.3 - Product assembly process flow

Once painted the internally manufactured components arrived on the assembly lines, along with purchased components to be built into stairlifts. These were then packaged. The process was nearly identical for carriages, chairs, footrests and kits. The main inputs at this stage were the supplier components and the electricity and compressed air to power the line. The main output generated from assembly was the waste delivery packaging from suppliers.

Figure D.4 - Rail manufacture process flow

The rail was another fabricated assembly that starts with steel tube being bent into the correct form and then cut to the required length. The sections of tube were then manually welded together to form the rail. Various air tools such as drills and sanding pads were used throughout the fabrication process. The main inputs to this flow were the raw material and the electricity and compressed air needed to operate the equipment. The main output was the off cuts of steel tube. Next the rail was transported to an external paint facility, where it was powder coated before being packaged and returned. This process followed the same flow as Figure D.2.

Figure D.5 - Product distribution process flow

The warehouse picked the required product and assembled this into a contract on a pallet ready for shipping to the customer. Transporting the contract to the customer was the main impact in this flow.

Figure D.6 - Product installation and use process flow

An engineer installed the stairlift into the customer's home and the packaging was discarded. The use phase of life saw the product consuming electricity, along with any consumables and spares required to maintain operation.

Figure D.7 - Product disposal process flow

Finally, when the product was no longer required, a Stannah engineer removed it from the property and it was eventually broken down for recycling and Landfill. The main impacts were the engineer travelling to site to remove the product and then the recycling/landfill of material.

Process Flow Diagram Key for Figure 4.3 - Figure D.7:

- Black Lines- Product flow
- Red Lines – Electricity
- Orange Lines – Gas
- Blue Lines – Compressed air
- Green Lines – Recycling
- Brown Lines – Landfill

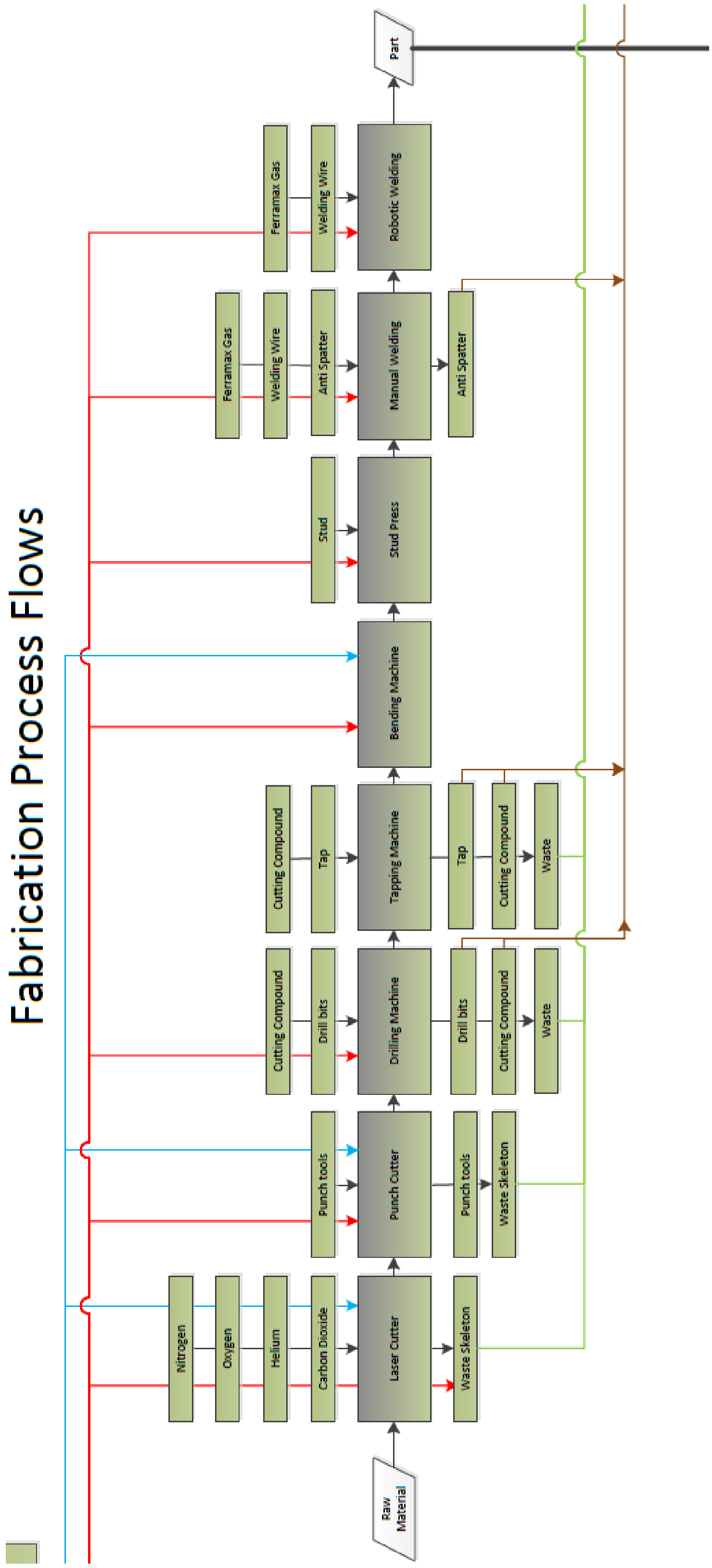


Figure D.1 - Fabrication process flow

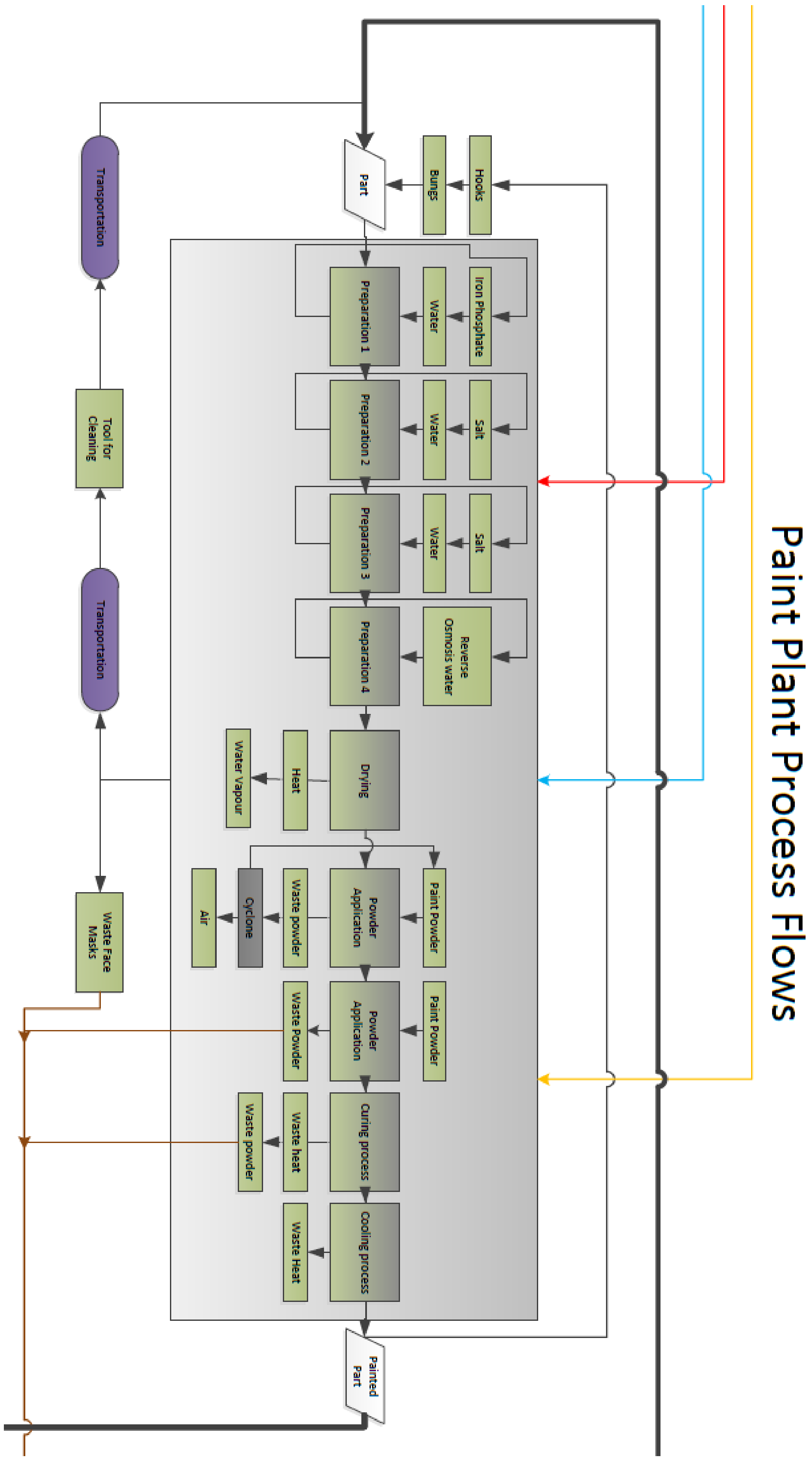


Figure D.2 - Paint plant process flow

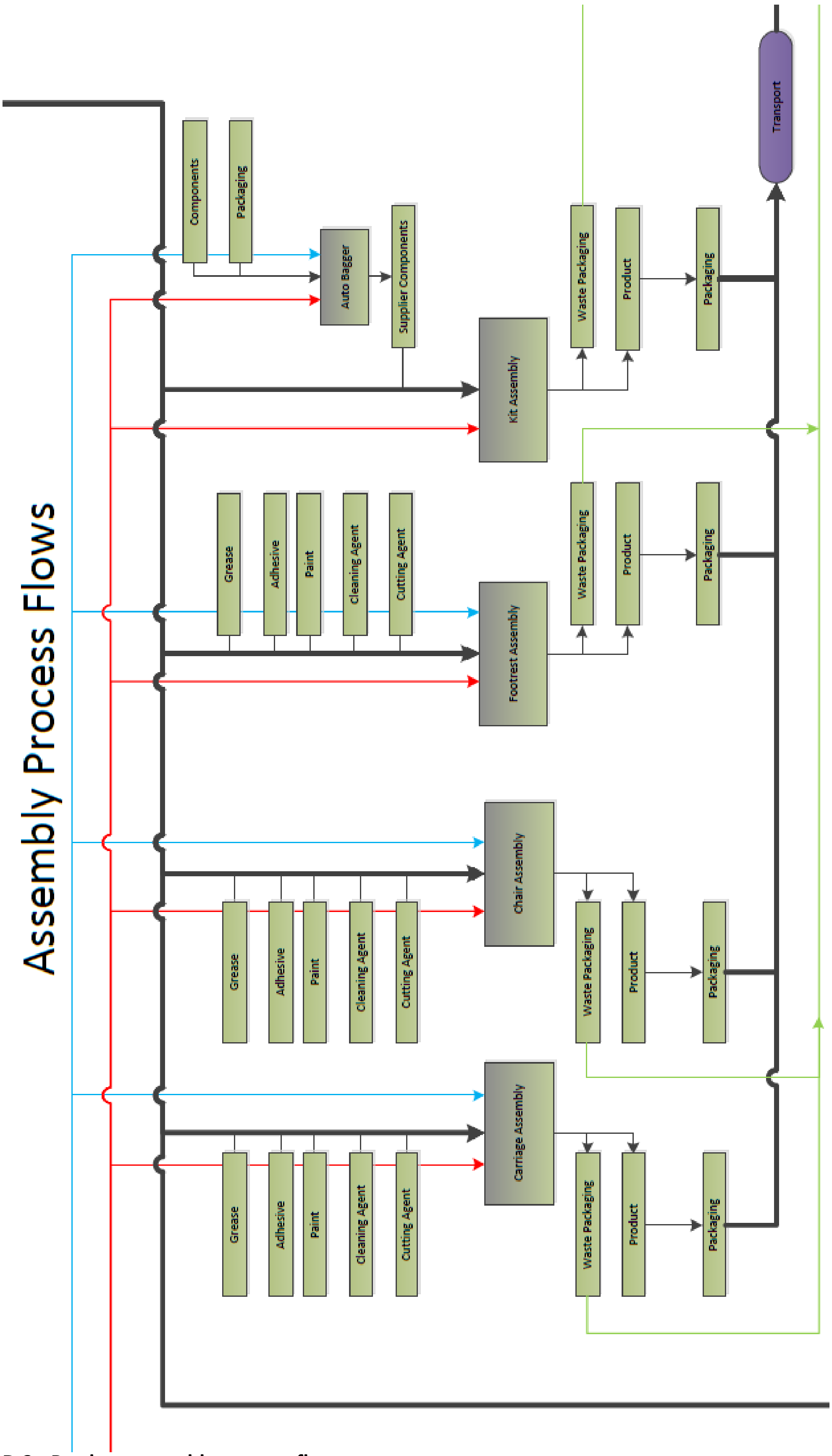


Figure D.3 - Product assembly process flow

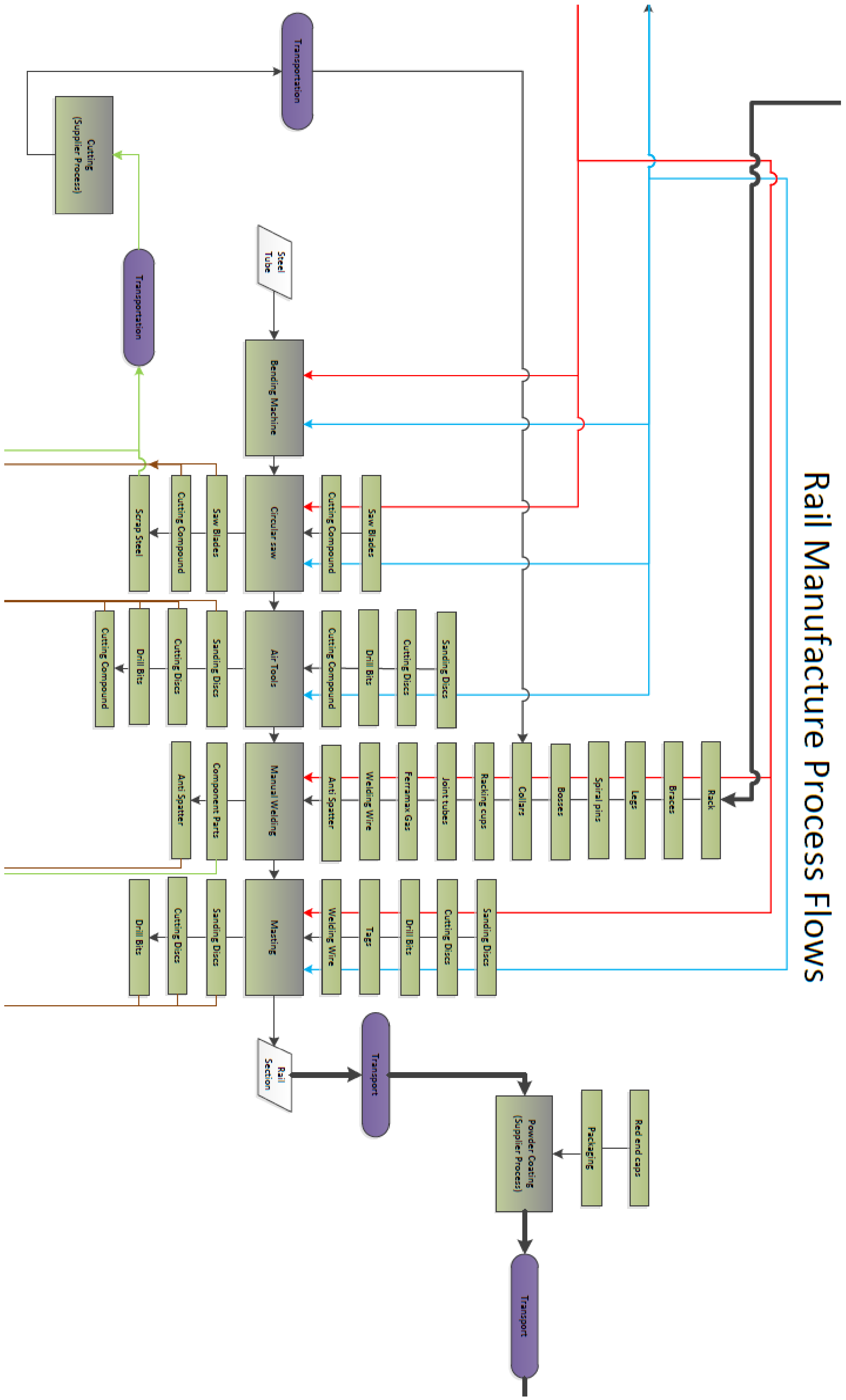


Figure D.4 - Rail manufacture process flow

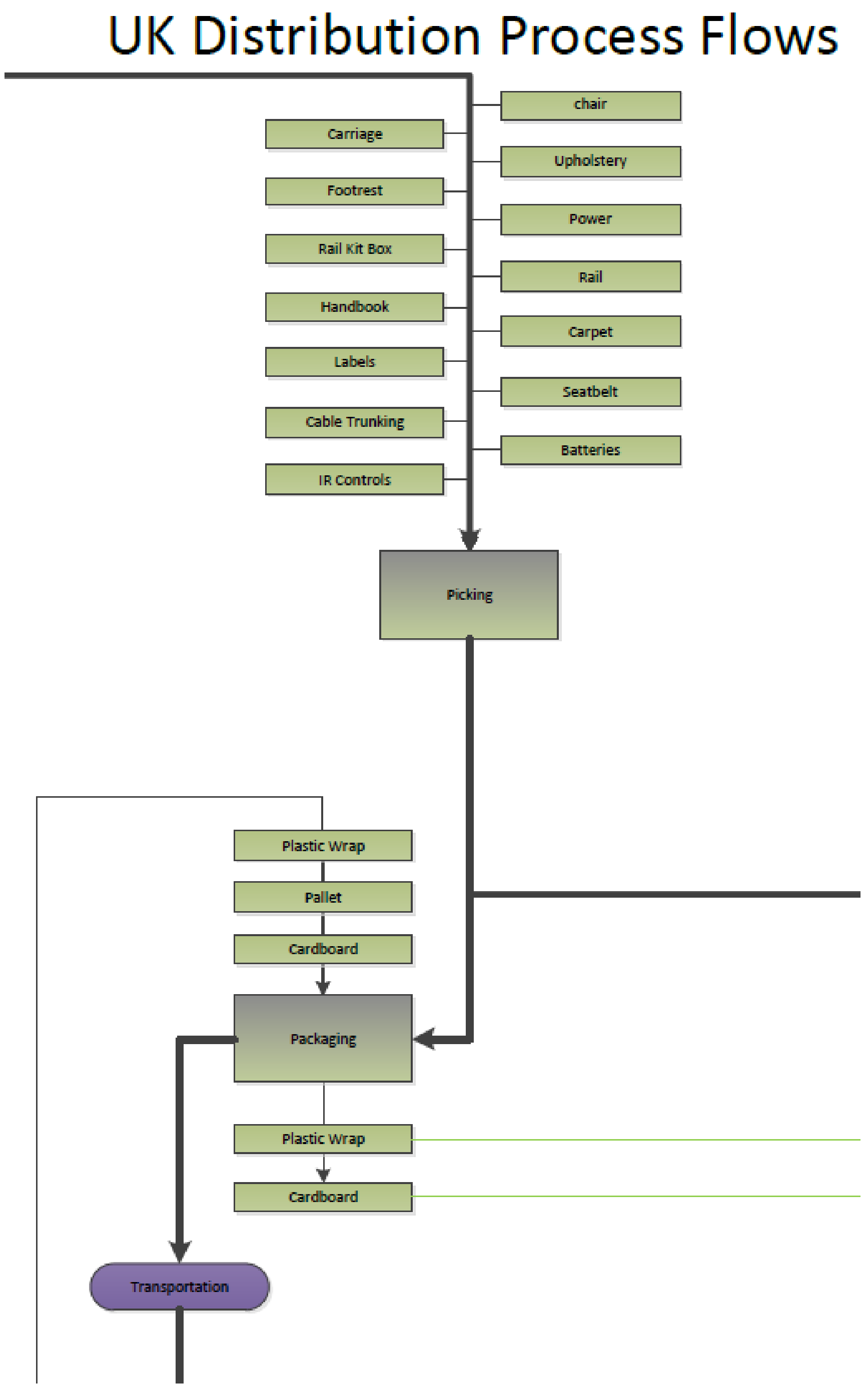


Figure D.5 - Product distribution process flow

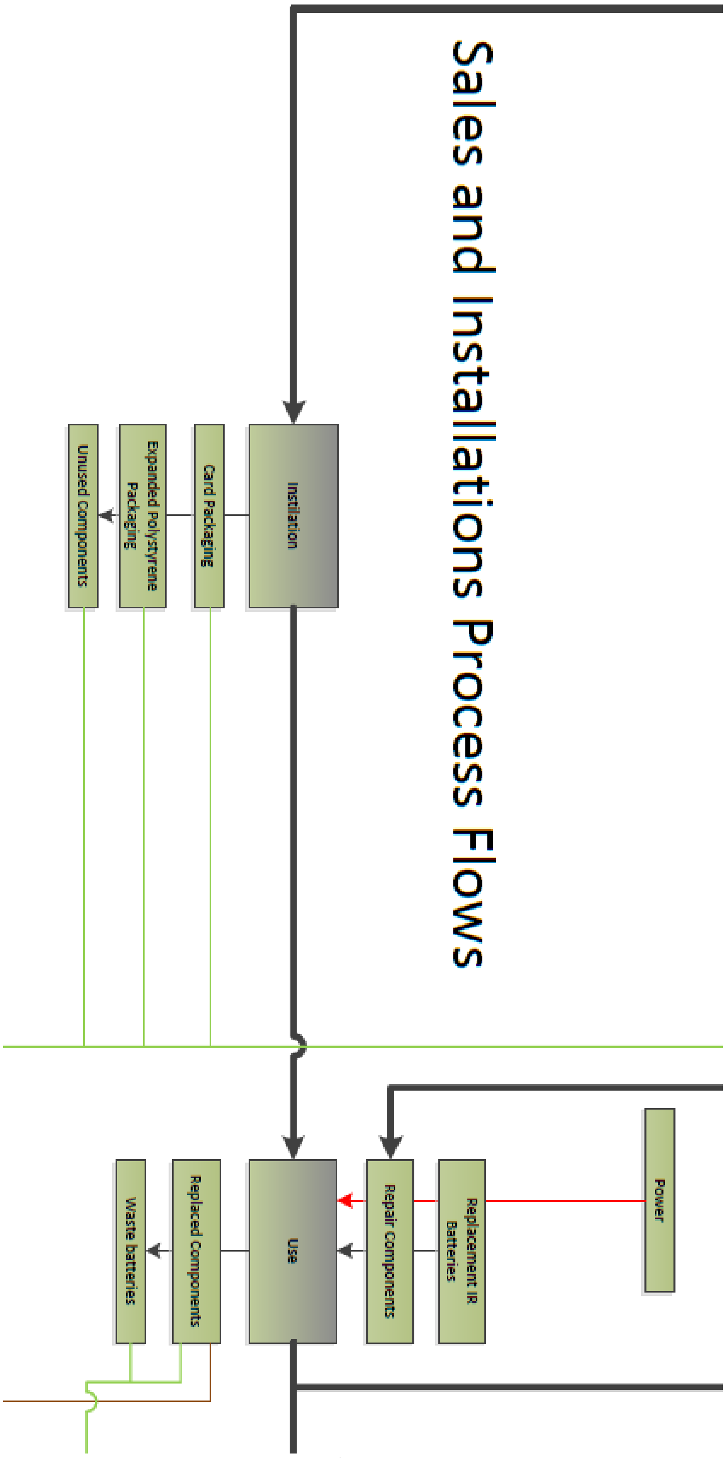


Figure D.6 - Product installation and use process flow

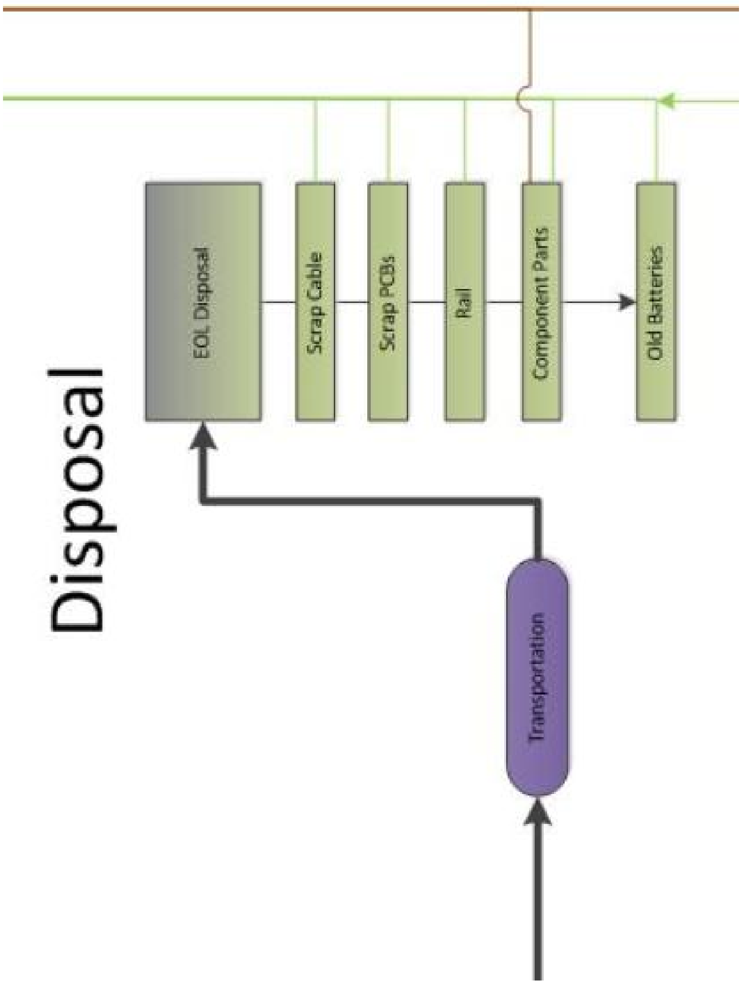


Figure D.7 - Product disposal process flow

Appendix E – Life Cycle Assessment Model

The critical components had their materials and manufacturing processes modelled in the first stage of the assessment model, Figure E.1. The remainder of the components had their materials and manufacturing methods modelled in the second stage of the study, Figure E.2. Each was assigned the closest material and manufacturing category derived from database data sets.

The assembly process was modeled totaling the power consumed to bringing together all the internal and supplier components. The impact of the compressors was also modeled at this stage. The waste generated from supplier packaging was also modelled at this stage, Figure E.3.

The use phase of the product life cycle was modeled based on the expected 4 years worth of life, making 14 journeys per day (being either up or down the stairs) along a six meter rail, Figure E.4.

All transport throughout the product lifecycle was inputted into the model at the same stage, Figure E.5. This included everything from the salesman visiting the customer to transporting the product for disposal. The bulk of the data measured the impacts of suppliers transporting components to Stannah from manufacturing locations around the world.

The disposal impacts were modelled as the final stage in the product life cycle, Figure E.6. This stage modelled the impacts of waste generated throughout the lifecycle, ranging from manufacturing waste to end of life product. Each waste stream was identified as being either recycled or sent to landfill.

Finally, the results from each stage of the lifecycle assessment were combined to give an overview of the product lifecycle, Figure E.7. These are explored in detail in the next section.

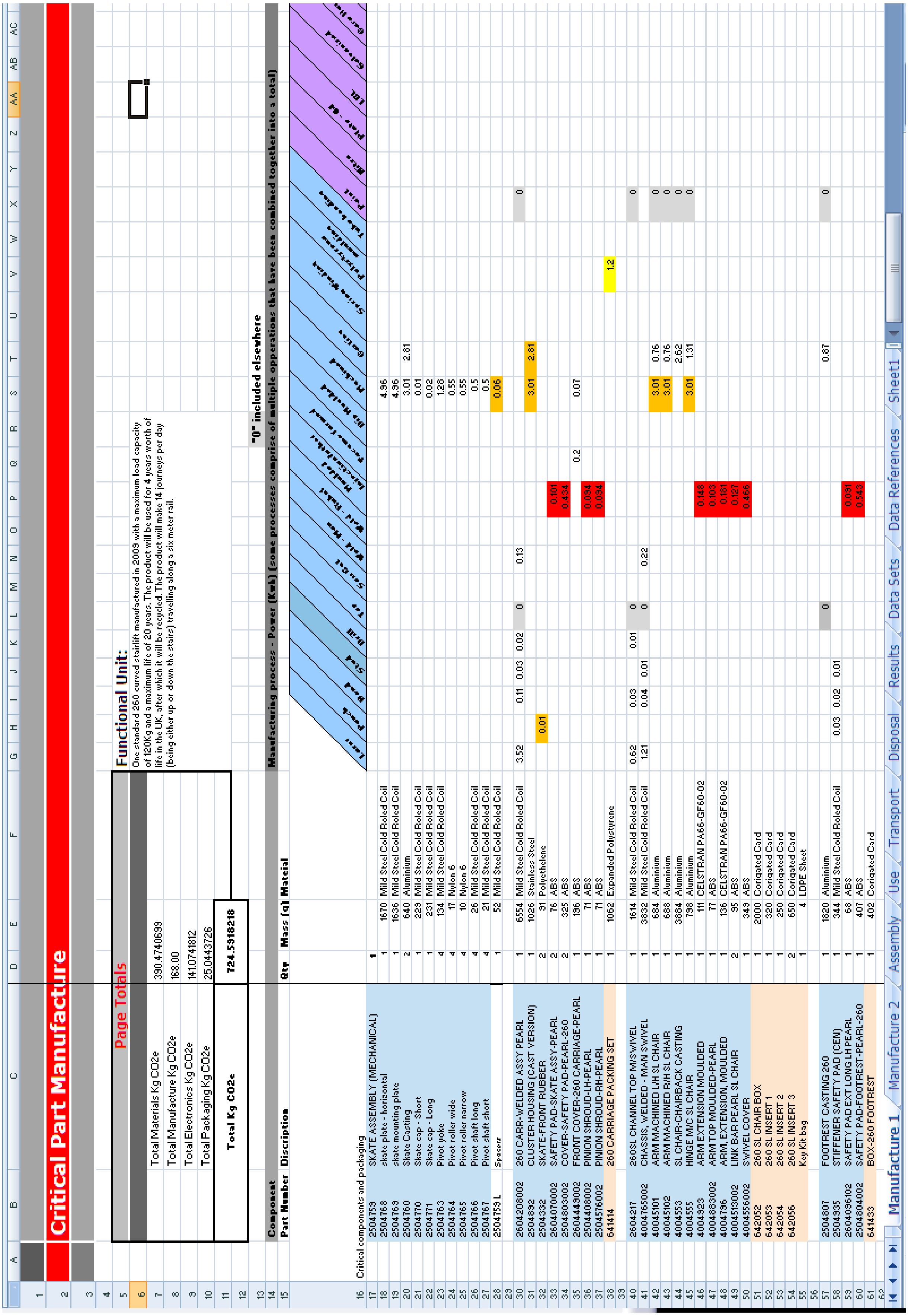
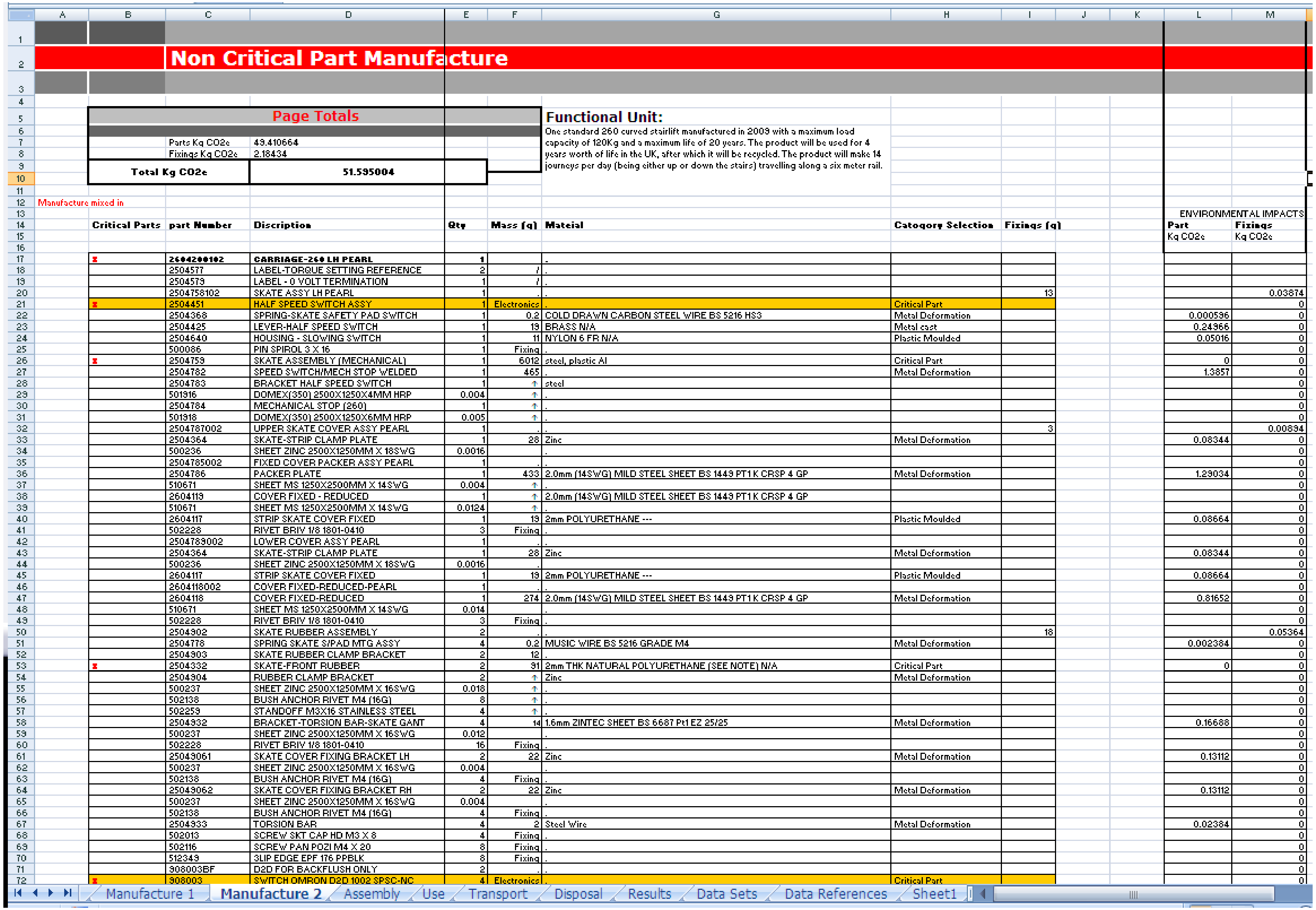


Figure E.1 - LCA model, critical parts



Non Critical Part Manufacture

Page Totals

Parts Kg CO2e	43.410664
Fixings Kg CO2e	2.18434
Total Kg CO2e	**51.595004**

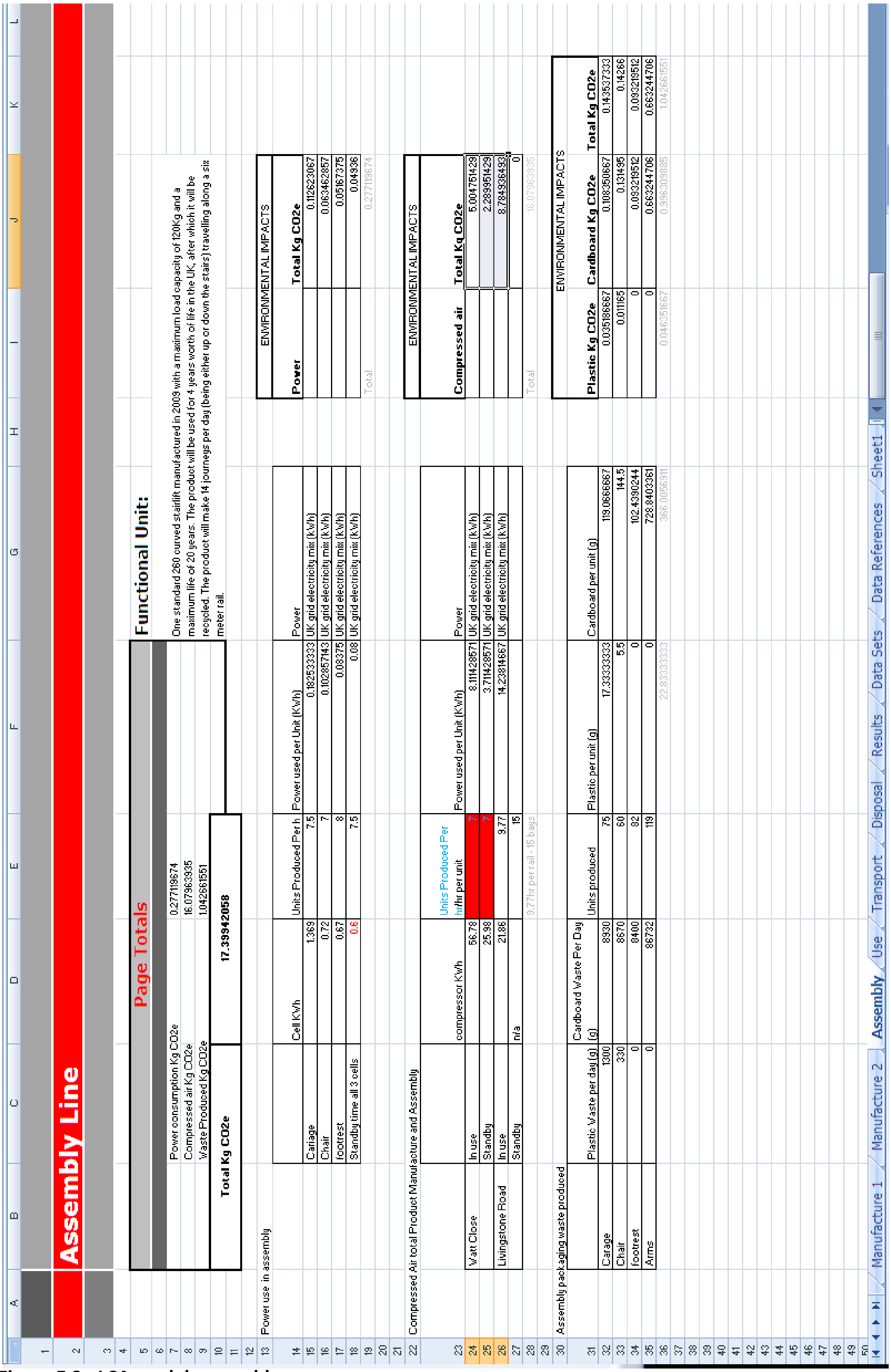
Functional Unit:
One standard 260 curved stairlift manufactured in 2009 with a maximum load capacity of 120Kg and a maximum life of 20 years. The product will be used for 4 years worth of life in the UK, after which it will be recycled. The product will make 14 journeys per day (being either up or down the stairs) travelling along a six meter rail.

Manufacture mixed in

Critical Parts	part Number	Discription	Qty	Mass (g)	Mateial	Catogory Selection	Fixings (g)	ENVIRONMENTAL IMPACTS Part Kg CO2e	Fixings Kg CO2e
x	2604200102	CARRIAGE-260 LH PEARL	1		.				
	2504577	LABEL-TORQUE SETTING REFERENCE	2	/	.				
	2504579	LABEL - 0 VOLT TERMINATION	1	/	.				
	2504758102	SKATE ASSY LH PEARL	1	.	.		13		0.03874
x	2504451	HALF SPEED SWITCH ASSY	1	Electronics	.	Critical Part			0
	2504368	SPRING-SKATE SAFETY PAD SWITCH	1	0.2	COLD DRAWN CARBON STEEL WIRE BS 5216 HS3	Metal Deformation		0.000596	0
	2504425	LEVER-HALF SPEED SWITCH	1	19	BRASS N/A	Metal cast		0.24966	0
	2504640	HOUSING - SLOWING SWITCH	1	11	NYLON 6 FR N/A	Plastic Moulded		0.05016	0
	500086	PIN SPIROL 3 X 16	1	Fixing	.				0
x	2504759	SKATE ASSEMBLY (MECHANICAL)	1	6012	steel, plastic Al	Critical Part		0	0
	2504782	SPEED SWITCH/MECH STOP WELDED	1	465	.	Metal Deformation		1.3857	0
	2504783	BRACKET HALF SPEED SWITCH	1	↑	steel				0
	501916	DOMEX(350) 2500X1250X4MM HRP	0.004	↑	.				0
	2504784	MECHANICAL STOP (260)	1	↑	.				0
	501918	DOMEX(350) 2500X1250X6MM HRP	0.005	↑	.				0
	2504787002	UPPER SKATE COVER ASSY PEARL	1	.	.		3		0.00894
	2504364	SKATE-STRIP CLAMP PLATE	1	28	Zinc	Metal Deformation		0.08344	0
	500236	SHEET ZINC 2500X1250MM X 18SWG	0.0016		.				0
	2504785002	FIXED COVER PACKER ASSY PEARL	1		.				0
	2504786	PACKER PLATE	1	433	2.0mm (14SWG) MILD STEEL SHEET BS 1449 PT1 K CRSP 4 GP	Metal Deformation		1.29034	0
	510671	SHEET MS 1250X2500MM X 14SWG	0.004	↑	.				0
	2604119	COVER FIXED - REDUCED	1	↑	2.0mm (14SWG) MILD STEEL SHEET BS 1449 PT1 K CRSP 4 GP				0
	510671	SHEET MS 1250X2500MM X 14SWG	0.0124	↑	.				0
	2604117	STRIP SKATE COVER FIXED	1	19	2mm POLYURETHANE ---	Plastic Moulded		0.08664	0
	502228	RIVET BRIV 1/8 1801-0410	3	Fixing	.				0
	2504789002	LOWER COVER ASSY PEARL	1		.				0
	2504364	SKATE-STRIP CLAMP PLATE	1	28	Zinc	Metal Deformation		0.08344	0
	500236	SHEET ZINC 2500X1250MM X 18SWG	0.0016		.				0
	2604117	STRIP SKATE COVER FIXED	1	19	2mm POLYURETHANE ---	Plastic Moulded		0.08664	0
	2604118002	COVER FIXED-REDUCED-PEARL	1		.				0
	2604118	COVER FIXED-REDUCED	1	274	2.0mm (14SWG) MILD STEEL SHEET BS 1449 PT1 K CRSP 4 GP	Metal Deformation		0.81652	0
	510671	SHEET MS 1250X2500MM X 14SWG	0.014		.				0
	502228	RIVET BRIV 1/8 1801-0410	3	Fixing	.				0
	2504902	SKATE RUBBER ASSEMBLY	2		.		18		0.05364
	2504778	SPRING SKATE S/PAD MTG ASSY	4	0.2	MUSIC WIRE BS 5216 GRADE M4	Metal Deformation		0.002384	0
	2504903	SKATE RUBBER CLAMP BRACKET	2	12	.				0
x	2504332	SKATE-FRONT RUBBER	2	31	2mm THK NATURAL POLYURETHANE (SEE NOTE) N/A	Critical Part		0	0
	2504904	RUBBER CLAMP BRACKET	2	↑	Zinc	Metal Deformation			0
	500237	SHEET ZINC 2500X1250MM X 16SWG	0.018	↑	.				0
	502138	BUSH ANCHOR RIVET M4 (16G)	8	↑	.				0
	502259	STANDOFF M3X16 STAINLESS STEEL	4	↑	.				0
	2504932	BRACKET-TORSION BAR-SKATE GANT	4	14	1.6mm ZINTEC SHEET BS 6687 Pt1 EZ 25/25	Metal Deformation		0.16688	0
	500237	SHEET ZINC 2500X1250MM X 16SWG	0.012		.				0
	502228	RIVET BRIV 1/8 1801-0410	16	Fixing	.				0
	25043061	SKATE COVER FIXING BRACKET LH	2	22	Zinc	Metal Deformation		0.13112	0
	500237	SHEET ZINC 2500X1250MM X 16SWG	0.004		.				0
	502138	BUSH ANCHOR RIVET M4 (16G)	4	Fixing	.				0
	25043062	SKATE COVER FIXING BRACKET RH	2	22	Zinc	Metal Deformation		0.13112	0
	500237	SHEET ZINC 2500X1250MM X 16SWG	0.004		.				0
	502138	BUSH ANCHOR RIVET M4 (16G)	4	Fixing	.				0
	2504933	TORSION BAR	4	2	Steel Wire	Metal Deformation		0.02384	0
	502013	SCREW SKT CAP HD M3 X 8	4	Fixing	.				0
	502116	SCREW PAN POZI M4 X 20	8	Fixing	.				0
	512349	SLIP EDGE EPF 176 PPBLK	8	Fixing	.				0
	308003BF	D2D FOR BACKFLUSH ONLY	2		.				0
x	308003	SWITCH OMRON D2D 1002 SPSC-NC	4	Electronics	.	Critical Part			0

Manufacture 1 | Manufacture 2 | Assembly | Use | Transport | Disposal | Results | Data Sets | Data References | Sheet1

Figure E.2 - LCA model, non critical parts



Assembly Line

Page Totals

Power consumption Kg CO2e	0.277119674
Compressed air Kg CO2e	16.07963935
Waste Produced Kg CO2e	1.042661551
Total Kg CO2e	**17.39942058**

Functional Unit:

One standard 260 curved stairlift manufactured in 2009 with a maximum load capacity of 120Kg and a maximum life of 20 years. The product will be used for 4 years worth of life in the UK, after which it will be recycled. The product will make 14 journeys per day (being either up or down the stairs) travelling along a six meter rail.

Power use in assembly

	Cell KWh	Units Produced Per h	Power used per Unit (KWh)	Power	Power	Total Kg CO2e
Cariage	1.369	7.5	0.182533333	UK grid electricity mix (kWh)		0.112623067
Chair	0.72	7	0.102857143	UK grid electricity mix (kWh)		0.063462857
footrest	0.67	8	0.08375	UK grid electricity mix (kWh)		0.051673375
Standby time all 3 cells	0.6	7.5	0.08	UK grid electricity mix (kWh)		0.04936
					Total	0.277119674

ENVIRONMENTAL IMPACTS

Compressed Air total Product Manufacture and Assembly

		compressor KWh	Units Produced Per hr/hr per unit	Power used per Unit (KWh)	Power	Compressed air	Total Kg CO2e
Watt Close	In use	56.78	7	8.111428571	UK grid electricity mix (kWh)		5.004751429
	Standby	25.98	7	3.711428571	UK grid electricity mix (kWh)		2.289951429
Livingstone Road	In use	21.86	9.77	14.23814667	UK grid electricity mix (kWh)		8.784936493
	Standby	n/a	15				0
			9.77hr per rail - 15 bays			Total	16.07963935

ENVIRONMENTAL IMPACTS

Assembly packaging waste produced

	Plastic Waste per day (g)	Cardboard Waste Per Day (g)	Units produced	Plastic per unit (g)	Cardboard per unit (g)	Plastic Kg CO2e	Cardboard Kg CO2e	Total Kg CO2e
Carage	1300	8930	75	17.33333333	119.0666667	0.035186667	0.108350667	0.143537333
Chair	330	8670	60	5.5	144.5	0.011165	0.131495	0.14266
footrest	0	8400	82	0	102.4390244	0	0.093219512	0.093219512
Arms	0	86732	119	0	728.8403361	0	0.663244706	0.663244706
				22.83333333	366.0056911	0.046351667	0.996309885	1.042661551

Figure E.3 - LCA model, assembly

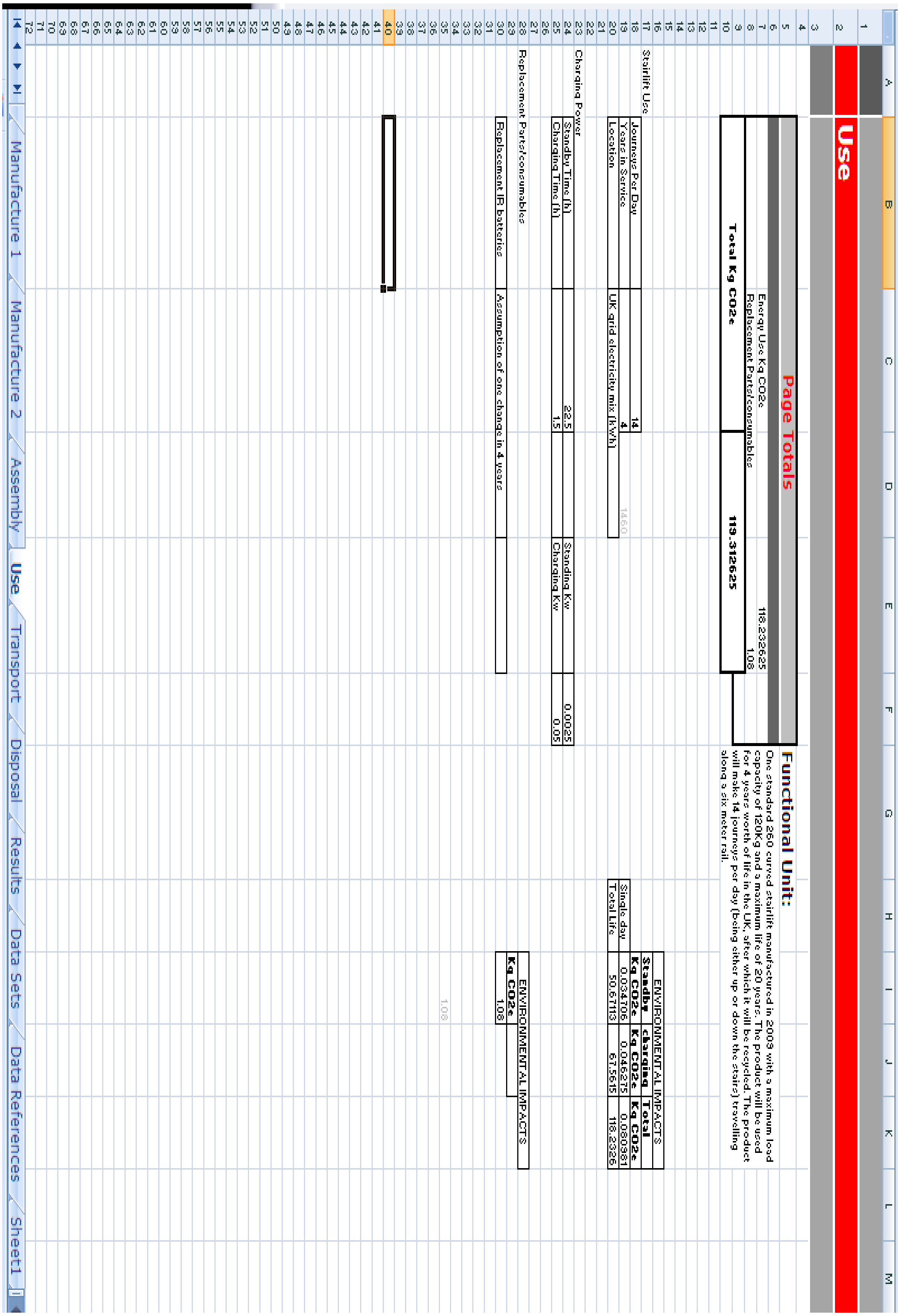


Figure E.4 - LCA model, product use

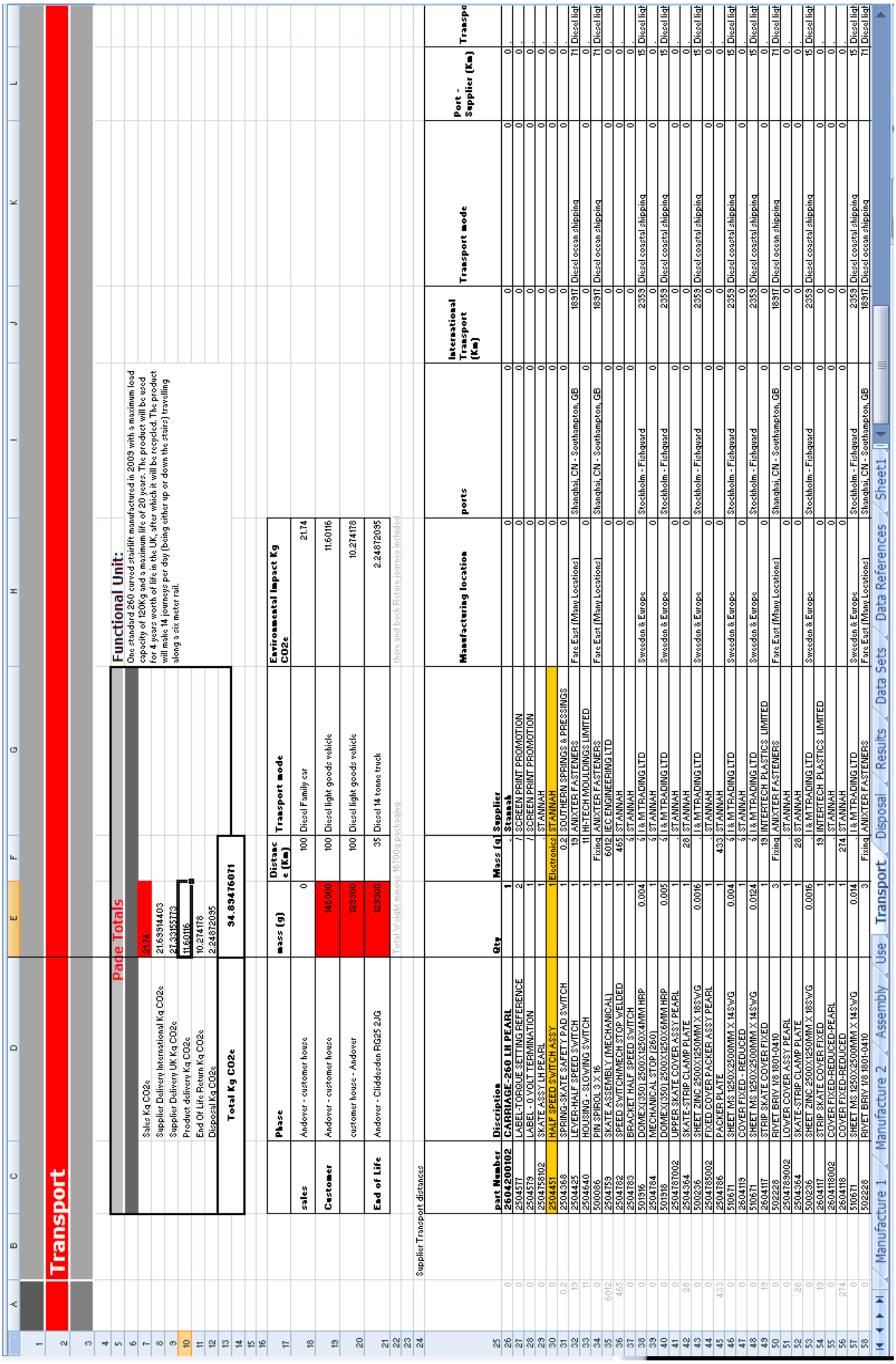
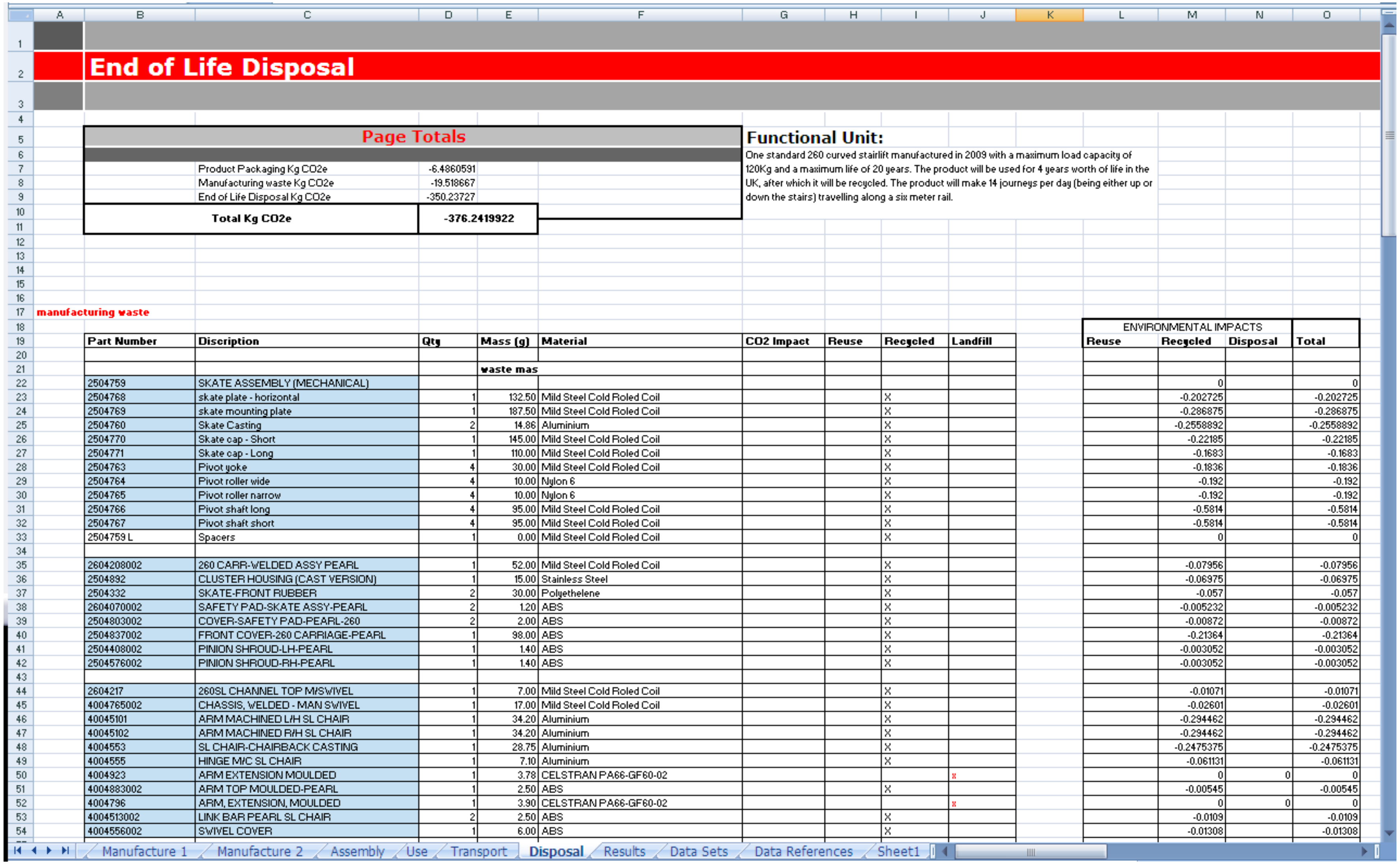


Figure E.5 - LCA model, transport



End of Life Disposal

Page Totals	
Product Packaging Kg CO2e	-6.4860591
Manufacturing waste Kg CO2e	-19.518667
End of Life Disposal Kg CO2e	-350.23727
Total Kg CO2e	**-376.2419922**

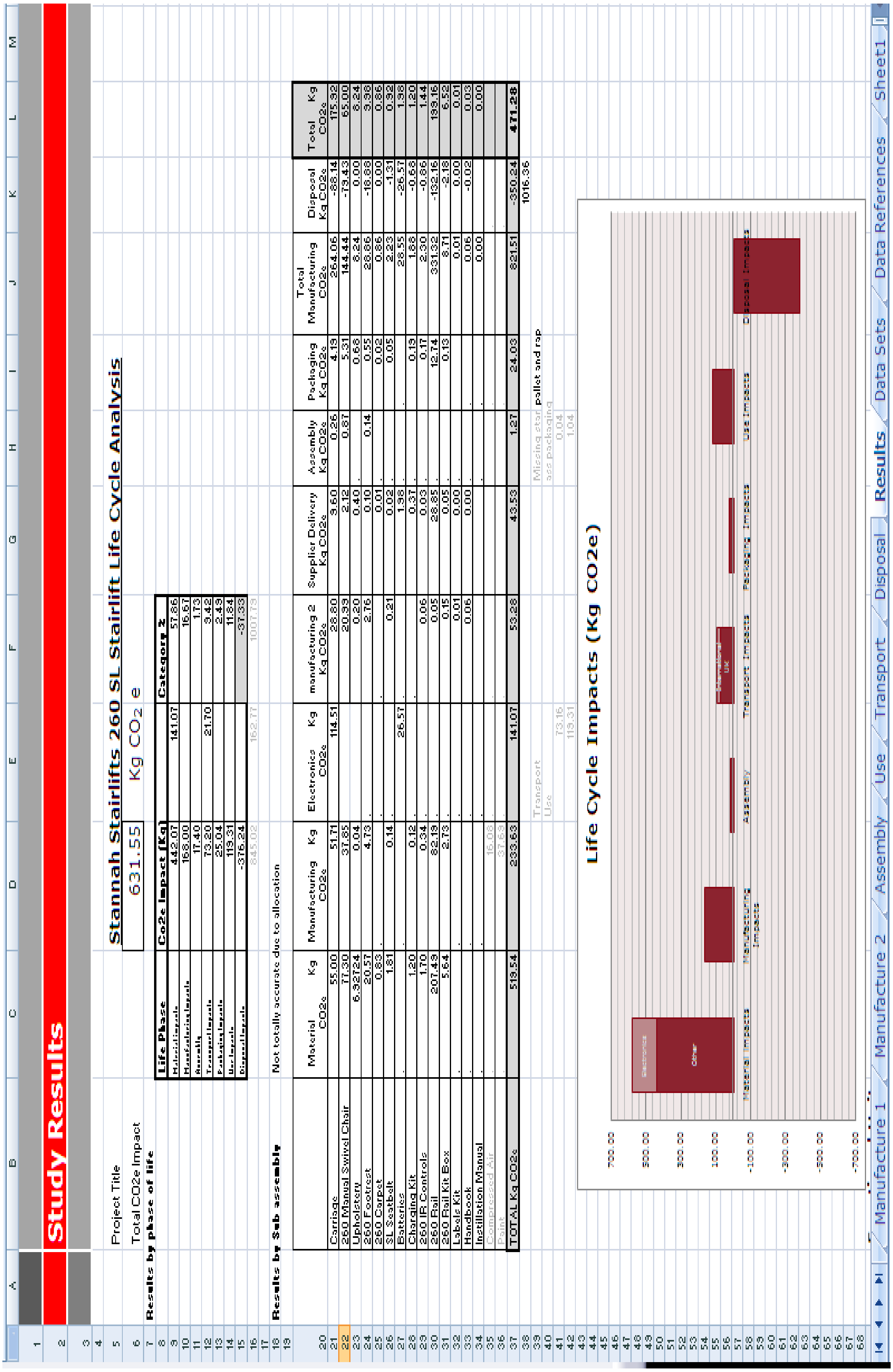
Functional Unit:
One standard 260 curved stairlift manufactured in 2009 with a maximum load capacity of 120Kg and a maximum life of 20 years. The product will be used for 4 years worth of life in the UK, after which it will be recycled. The product will make 14 journeys per day (being either up or down the stairs) travelling along a six meter rail.

manufacturing waste

Part Number	Discription	Qty	Mass (g)	Material	CO2 Impact	Reuse	Recycled	Landfill	ENVIRONMENTAL IMPACTS Reuse	Recycled	Disposal	Total
			waste mas									
2504759	SKATE ASSEMBLY (MECHANICAL)									0		0
2504768	skate plate - horizontal	1	132.50	Mild Steel Cold Roled Coil			X			-0.202725		-0.202725
2504769	skate mounting plate	1	187.50	Mild Steel Cold Roled Coil			X			-0.286875		-0.286875
2504760	Skate Casting	2	14.86	Aluminium			X			-0.2558892		-0.2558892
2504770	Skate cap - Short	1	145.00	Mild Steel Cold Roled Coil			X			-0.22185		-0.22185
2504771	Skate cap - Long	1	110.00	Mild Steel Cold Roled Coil			X			-0.1683		-0.1683
2504763	Pivot yoke	4	30.00	Mild Steel Cold Roled Coil			X			-0.1836		-0.1836
2504764	Pivot roller wide	4	10.00	Nylon 6			X			-0.192		-0.192
2504765	Pivot roller narrow	4	10.00	Nylon 6			X			-0.192		-0.192
2504766	Pivot shaft long	4	95.00	Mild Steel Cold Roled Coil			X			-0.5814		-0.5814
2504767	Pivot shaft short	4	95.00	Mild Steel Cold Roled Coil			X			-0.5814		-0.5814
2504759 L	Spacers	1	0.00	Mild Steel Cold Roled Coil			X			0		0
2604208002	260 CARR-WELDED ASSY PEARL	1	52.00	Mild Steel Cold Roled Coil			X			-0.07956		-0.07956
2504892	CLUSTER HOUSING (CAST VERSION)	1	15.00	Stainless Steel			X			-0.06975		-0.06975
2504332	SKATE-FRONT RUBBER	2	30.00	Polyethelene			X			-0.057		-0.057
2604070002	SAFETY PAD-SKATE ASSY-PEARL	2	1.20	ABS			X			-0.005232		-0.005232
2504803002	COVER-SAFETY PAD-PEARL-260	2	2.00	ABS			X			-0.00872		-0.00872
2504837002	FRONT COVER-260 CARRIAGE-PEARL	1	98.00	ABS			X			-0.21364		-0.21364
2504408002	PINION SHROUD-LH-PEARL	1	1.40	ABS			X			-0.003052		-0.003052
2504576002	PINION SHROUD-RH-PEARL	1	1.40	ABS			X			-0.003052		-0.003052
2604217	260SL CHANNEL TOP M/SWIVEL	1	7.00	Mild Steel Cold Roled Coil			X			-0.01071		-0.01071
4004765002	CHASSIS, WELDED - MAN SWIVEL	1	17.00	Mild Steel Cold Roled Coil			X			-0.02601		-0.02601
40045101	ARM MACHINED L/H SL CHAIR	1	34.20	Aluminium			X			-0.294462		-0.294462
40045102	ARM MACHINED R/H SL CHAIR	1	34.20	Aluminium			X			-0.294462		-0.294462
4004553	SL CHAIR-CHAIRBACK CASTING	1	28.75	Aluminium			X			-0.2475375		-0.2475375
4004555	HINGE M/C SL CHAIR	1	7.10	Aluminium			X			-0.061131		-0.061131
4004923	ARM EXTENSION MOULDED	1	3.78	CELSTRAN PA66-GF60-02				x		0	0	0
4004883002	ARM TOP MOULDED-PEARL	1	2.50	ABS			X			-0.00545		-0.00545
4004796	ARM, EXTENSION, MOULDED	1	3.90	CELSTRAN PA66-GF60-02				x		0	0	0
4004513002	LINK BAR PEARL SL CHAIR	2	2.50	ABS			X			-0.0109		-0.0109
4004556002	SWIVEL COVER	1	6.00	ABS			X			-0.01308		-0.01308

Manufacture 1 / Manufacture 2 / Assembly / Use / Transport / Disposal / Results / Data Sets / Data References / Sheet1

Figure E.6 - LCA model, disposal



Study Results

Project Title: **Stannah Stairlifts 260 SL Stairlift Life Cycle Analysis**

Total CO2e Impact: 631.55 Kg CO_2 e

Results by phase of life

Life Phase	Co2e Impact (Kg)		Category %
Material impacts	442.07	141.07	57.86
Manufacturing impacts	168.00		16.67
Assembly	17.40		1.73
Transport impacts	73.20	21.70	3.42
Packaging impacts	25.04		2.49
Use impacts	119.31		11.84
Disposal impacts	-376.24		-37.33
	845.02	162.77	1007.79

Results by Sub assembly — Not totally accurate due to allocation

	Material Kg CO2e	Manufacturing Kg CO2e	Electronics Kg CO2e	manufacturing 2 Kg CO2e	Supplier Delivery Kg CO2e	Assembly Kg CO2e	Packaging Kg CO2e	Total Manufacturing CO2e	Disposal Kg CO2e	Total Kg CO2e
Carriage	55.00	51.71	114.51	28.80	9.60	0.26	4.19	264.06	-88.14	175.92
260 Manual Swivel Chair	77.30	37.85		20.39	2.12	0.87	5.31	144.44	-79.43	65.00
Upholstery	6.92724	0.04		0.20	0.40		0.68	8.24	0.00	8.24
260 Footrest	20.57	4.73		2.76	0.10	0.14	0.55	28.86	-18.88	9.98
260 Carpet	0.83				0.01		0.02	0.86	0.00	0.86
SL Seatbelt	1.81	0.14		0.21	0.02		0.05	2.23	-1.31	0.92
Batteries			26.57		1.98			28.55	-26.57	1.98
Charging Kit	1.20	0.12			0.37		0.19	1.88	-0.68	1.20
260 IR Controls	1.70	0.34		0.06	0.03		0.17	2.30	-0.86	1.44
260 Rail	207.49	82.19		0.05	28.85		12.74	331.32	-132.16	199.16
260 Rail Kit Box	5.64	2.73		0.15	0.05		0.13	8.71	-2.18	6.52
Labels Kit				0.01	0.00			0.01	0.00	0.01
Handbook				0.06	0.00			0.06	-0.02	0.03
Instillation Manual								0.00		0.00
Compressed Air		16.08								
Paint		37.63								
TOTAL Kg CO2e	519.54	233.63	141.07	53.28	43.53	1.27	24.03	821.51	-350.24	471.28
									1016.36	

Transport 73.16
Use 119.31

Missing stair pallet and rap
ass packaging 0.04
1.04

Figure E.7 - LCA model, results