SUSTAINABLE MANUFACTURING: TURNING WASTE INTO PROFITABLE CO-PRODUCTS

SUSTAINABLE MANUFACTURING: TURNING WASTE INTO PROFIT

Thesis submitted in accordance with the requirements of the
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by

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ABSTRACT

At 2009 rates of disposal, there are only 8 years of remaining landfill capacity at permitted sites in England and Wales. Industry – encouraged by financial penalties from the Government – faces the challenges of cleaner and more sustainable production whilst trying to remain competitive in the market place. This thesis presents development of several theoretical propositions: a ‘fit thinking’ design framework, the ‘All Seeing Eye of Business’ (All-SEB) and the ‘waste alchemist’ industrial role. The ALL-SEB is a model to understand the impact and potential uses of manufacturing waste. The insights provided by the All-SEB model, resulted in a general waste elimination framework developed to serve as a guiding strategy for waste elimination.

The main objective of this study was to investigate a major hypothesis derived from the All-SEB: unavoidable waste could be transmuted into profitable co-products as a measure to divert waste from landfill. The ATM (analyse, transform and market) methodology was developed as a way to help companies transmute waste into ‘co-products’. A tool for idea generation (the wheel of waste) was developed to be used in the Analysis phase of the ATM methodology.

Case study research was undertaken in order to test the ATM methodology and the way in which unavoidable waste could be transmuted into a profitable co-product in a real world manufacturing setting. The case study results revealed the generative mechanisms that enable waste transmutation into profitable co-products; based on these findings a refined ATM methodology for waste transmutation was proposed.

The implementation of the theoretical propositions in industrial settings shed light into strategic aspects of resource efficiency: from waste prevention through ‘fit thinking’, to manufacturing process innovation all the way to a better company integration into the industrial ecosystem. Companies looking to achieve zero waste to landfill status would benefit from using the refined ATM methodology. It was found that the ATM methodology and the wheel of waste are useful to several other actors in the industrial ecosystem: waste management companies looking to transform themselves into ‘resource and energy providers’, to external consultants and to third party companies dubbed ‘waste alchemists’ that could offer waste transmutation services to manufacturers.

ACKNOWLEDGEMENTS

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NEW DEFINITIONS

Sustainable manufacturing: Sustainable manufacturing in the Anthropocene is a paradigm for developing techniques to transform earth's resources into economically valuable goods-services that meet the needs of the present whilst safeguarding Earth's life-support system, on which the welfare of current and future generations depends.

Fit thinking: is a design framework is proposed as a way to integrate knowledge about product design and the insights from the Kano model in order to create a framework for the design of products that create customer satisfaction whilst using the optimal amount of material and energy.

The All Seeing Eye of Business (ALL-SEB): is a novel construct to focus business attention on output analysis and to create awareness about the true cost of waste and potential sources of profit (or loss).

Co-product output: non-product outputs that are transformed into products that generate profit. An organization that transforms waste into saleable co-products has a "cash your waste" strategy.

Salvage: transform non-product output into a co-product that adds low levels of profit.

Upgrade: transform non-product output into a co-product that satisfies profit objectives.

Alchemy: non-product output that is transmuted into a co-product that adds high levels of profit.

Waste transmutation: the process of transforming a non-product output into an "alchemy" co-product.

The ATM of waste/The ATM methodology: a methodology that helps companies transform unavoidable waste into co-product output.

The wheel of waste: a tool designed to generate ideas for co-product development.

Chapter 1. Introduction

1.1 Research background

Waste avoidance is an intuitive concept that has been present in the collective mind throughout time. In Victorian Britain, for example, Mrs Beeton's book of household management was a guide to all aspects of running a household. Advice was given to cooks and kitchen maids to "never throw away or waste anything that can be turned into account" (Beeton 1863).

Misuse of resources, economic losses and environmental pollution have long ago been recognized as the consequences of waste generation in industry, but the extent and impact of such consequences are only just beginning to be understood in the context of sustainability. Hawken's et al. seminal work "Natural Capitalism" (1999) devotes a chapter analysing waste and its impact in modern society; another chapter gives practical examples of reducing waste through lean and whole systems thinking. Arguably, this approach could lead the transition from a "goods economy" to a "lean solutions" economy. The elimination of waste has always been a pillar of business competitiveness and with increasing environmental awareness it becomes even more crucial.

Existing theories and methodologies for waste elimination should incorporate concerns about sustainability. The sustainability agenda of a firm should always include waste elimination in the top priority list. The production of waste affects many key performance indicators such as: resource efficiency, emissions and pollution levels, productivity, profitability levels and corporate image amongst others. Waste is visible and tangible, so it becomes an ideal candidate to become one of the first issues to be tackled in order to improve the triple bottom line of a firm.

The focus of the research presented in this thesis is an analysis of waste generated during manufacturing processes. Taking the UK context as an exploratory ground it is known that in 2004 the type of waste categorized as commercial and industrial (C&I) accounts for approximately 25% of the total annual waste, this 25% is equivalent to an estimated 83mt (million tonnes) (DEFRA 2006). Because each country in the UK carries out separate waste surveys there are no official updates on the total annual waste generation since 2004. However, using available data published by each country (ranging from 2007-2009) one can estimate a more recent C&I waste output, this data adds up to 62mt. This indicates that here has been an estimated 25% reduction in commercial and industrial waste generation compared to the 2004 baseline. In spite of that reduction, the environment Agency (2009) estimates only 614 million cubic metres of available landfill capacity at existing permitted sites in England and Wales, enough to accommodate landfill requirements (for non-hazardous waste) for nearly eight years, this at 2009 rates of disposal. Such scenario has led to the implementation of policies aiming to encourage waste reduction and resource efficiency in industry and commerce. There is an increase in landfill tax rates for 2010/11; a charge of £48.00/ton and £2.50/ton for active and inactive waste respectively. The UK government announced in the budget for 2010 that the rate for active waste will continue to escalate by £8 per year until at least 2014/15, when it will reach £80 per tonne (DEFRA 2010).

Funded by the UK government, WRAP (the waste & resources action program) has become the single point of contact for businesses and organisations looking for support and guidance on improving their resource efficiency. WRAP delivers an efficient and integral range of programs that encompass the whole life cycle of products. Among these programmes two are focused on reducing waste in industry: “rethink waste” is a free online initiative to help manufacturers reduce waste, improve resource efficiency and save money; and the National Industrial Symbiosis Program (NISP), the first industrial symbiosis initiative in the world that has been launched on a national scale. The findings of this research thesis will contribute to expand the knowledge in the area of industrial ecology and once the method, concepts and tools reach maturity they will be ready to be disseminated by organisations such as WRAP and consultants alike.

1.2 Research aim

The aim of this study is to contribute to the advancement of knowledge in industrial ecology and sustainable manufacturing by developing, frameworks, concepts, methods and tools that will help manufacturing organisations divert waste from landfill in a sustainable manner whilst improving their profitability and competitiveness.

1.3 Research questions

Improving the way in which waste is managed requires, firstly, an understanding of the nature of waste and its impact in sustainable manufacturing processes. This became the first stage of the research, and so, the most natural questions arose:

- What is manufacturing waste?
- Why is there manufacturing waste in the first place?
- What is the impact of waste on the sustainability performance of companies?
- What is the current state of the literature with regards to the elimination of waste?
- What is the current practice for waste elimination?

If the elimination of waste is not a new topic in manufacturing research and business practise, then:

- Why are businesses and industry still sending large quantities of waste to landfill?
- What is the gap in the literature that could help businesses divert more waste from landfill?

The second stage of the research aimed to create new knowledge to improve the current theory and practice of managing manufacturing waste. Strategies to divert waste from landfill within the framework of a sustainable manufacturing were proposed. At this stage, the research questions were more concerned about the way in which to achieve the research aim:

- How to help industry to improve resource efficiency and divert waste from landfill?
- What concepts and frameworks could improve the current understanding of manufacturing waste?
- What new methods and tools could companies use in order to divert more waste from landfill?

The third stage of the research studied the effectiveness of the theoretical propositions. The frameworks, concepts, methods and tools were tested in industrial settings using case study research methods as a way to collect observations that could test and improve the theoretical propositions. Here another set of questions arose:

- Do the theoretical propositions support manufacturers in diverting waste from landfill?

- Are the theoretical propositions useful in an industrial setting?
- Can the theoretical propositions be readily implemented in a manufacturing organisation?
- Could the theoretical propositions be improved?

1.4 Research objectives

This research project has been divided in three stages, each requiring a specific set of objectives shown in the following table.

Table 1.1 Research objectives

Research stage	Objectives
1. Understanding current theory and practise	a. Critically review a substantive literature on waste in manufacturing. b. Identify the underlying causes and origins of manufacturing waste. c. Describe how waste elimination contributes to build a sustainable global production system. d. Identify the state of the art in theory and practice for eliminating waste in manufacturing processes.
2. Developing new theory and practice	a. Identify the gap in the literature of waste in manufacturing process b. Generate novel theoretical propositions to improve the theory and practise of waste management in manufacturing settings. c. Integrate the new theoretical propositions with the state of the art theory and practise. d. Present the theoretical findings to the research community.

3. Implementing and testing the theoretical propositions.	a. Design a case study research protocol b. Test the theoretical propositions in a diverse range of companies c. Identify ways to improve the theoretical propositions d. Synthesize research findings into a coherent theory or framework.

1.5 Scope of research

This research is focused solely on studying waste arising in manufacturing processes in industry; waste arising in commerce falls out of the scope of research. In industry it is common practice to consolidate the management of all waste streams into a single operation, this means that packaging waste arising from the transport of raw materials and subcomponents is accounted for as manufacturing waste, but strictly speaking these wastes do not arise as part of the production process, so they fall out of the scope of this research.

Given the background of the research, the aim is to generate knowledge that could be implemented in a wide range of industries and production processes. Mature and proven concepts such as lean manufacturing systems and Six Sigma have become widely accepted and are currently delivering benefits to industry. In a similar way, it is intended that the research propositions will be able to be generalised to a level that is applicable to a wide range of industry sectors, e.g. food and beverage, chemical, engineering and allied industries, oil and gas, pharmaceutical, etc. The propositions also need to make sense and be equally applicable to small, medium and large industries.

This research is exploratory in nature, so it is expected that the theoretical propositions improve with each successive implementation of the case studies. As a way of improving the consistency and comparability between case studies, the pilot case study should be treated as preliminary research, and not included in the analysis of results.

One of the factors limiting the research is the willingness of companies to take part in the case studies and the cooperation shown during the case study development; some companies might not have the time and resources to implement the proposed solutions. So, the research is limited to testing the validity of the theoretical propositions, any further research and development needed in order to transform waste into co-products falls out of the scope this research project.

1.6 Primary issues

There are three primary issues addressed in this research. These are represented in three topics addressed in different stages of this research:

1. Manufacturing waste and its importance in sustainable manufacturing
2. Improving current theory and practise of managing manufacturing waste
3. Testing and validation of the theoretical propositions in real manufacturing settings.
4. Generate a theory about the transformation of waste into profitable products.

Chapter 2. Sustainable manufacturing: literature review

This thesis subscribes to the new definition of sustainable development in the Anthropocene; under a unified framework, this new definition integrates the Millennium Development Goals (MDG) with environmental targets for the protection of life's support systems. Sustainable development in the Anthropocene is defined as

"development that meets the needs of the present while safeguarding Earth's life-support system, on which the welfare of current and future generations depends." (Griggs et al. 2013)

In their definition Griggs et al., provide a set of six sustainable development goals which are described in Table 2.1. (Rockstrom et al. 2009) provides a more exhaustive discussion of the planetary boundaries and quantifies the trajectory of seven indicators, from pre-industrial levels to the present.

Table 2.1 Goals for sustainable development in the Anthropocene [adapted from Griggs et al. (2013)].

Updated Millennium Development Goals	**Planetary Must haves**	**Sustainable Development Goals**
End poverty and hunger	Material use	Thriving lives and livelihoods
Universal education	Clean air	Sustainable food security
Gender equality	Nutrient (N and P) cycles	Sustainable water security
Health	Hydrological cycles	Universal clean energy
Environmental sustainability	Ecosystem services	Healthy and productive ecosystems
Global partnership	Biodiversity	Governance for sustainable societies
	Climate stability	

Sustainable manufacturing has been defined in terms of the (Brundtland et al. 1987; WCED 1987) definition of sustainable development: sustainable manufacturing is “a new paradigm for developing socially and environmentally sound techniques to transform materials into economically valuable goods” (Despeisse et al. 2011). Hannon’s (2011) research has confirmed and highlighted the need to provide a deep, rigorous and integrated understanding of sustainability at managerial levels for organisations to become sustainable. Executive leaders must be able to develop and articulate a clear and concise definition of sustainability as the starting point of their strategic and operational planning (Hannon & Callaghan 2011). Following this advice, this thesis proposes a new definition of sustainable manufacturing according to Griggs’s et. all new definition of sustainability.

Sustainable manufacturing in the Anthropocene is a paradigm for developing techniques to transform earth’s resources into economically valuable goods-services that meet the needs of the present whilst safeguarding Earth’s life-support system, on which the welfare of current and future generations depends.

2.1.1 Theory of waste in manufacturing

The waste issue in modern industry was analysed as long ago as 1926, when Henry Ford began to examine it, albeit in a different context. Ford’s conclusions still hold valid; he insisted that materials should be used to their utmost so that the labour of men embedded in the material should not be lost. In this way Ford recognized the true cost of waste and even suggested the idea of zero waste stating that “the ideal is to have nothing to salvage” (Ford & Crowther 1926), Ford recognized that reclaiming materials required rework and expenditure of labour.

During the First and Second World War, countries experienced a sense of urgency to utilize their resources with maximum efficiency. Dyson (1941) noted the importance of waste prevention by illustrating the material inefficiency in a motor company where only 26% of the weight of purchased materials constituted the finished products. However he also recognized the existence of unavoidable waste, requiring solutions such as "*salvaging*" for recycling or reuse, reclaiming materials for reprocessing, rebuilding or remaking of parts, and the creation of profitable by-products by means of chemical processing.

In the 1980's, the concept of waste was furthered by Taiichi Ohno, who not only improved the work flow concept engrained in Ford's assembly line but also refined the concepts of waste and ways to eliminate it (Ohno 1988). Ohno summarizes Toyota's strategy is shown in Figure 2.1, the time line from the moment a customer places an order to the point where the cash is collected is reduced by removing the non-value-adding wastes.

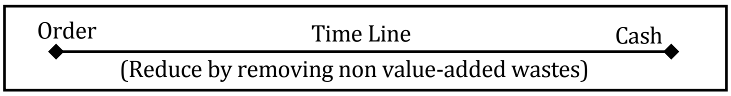

Figure 2.1 Ohno's summary of the Toyota strategy. Source: (Ohno 1988)

Ohno identified and classified production waste into seven categories: overproduction, waiting time, transporting, over-processing, inventories, movements, and the waste of making defective parts and products. Womack and Jones (2003) re-defined the Toyota production system concepts for a western audience, creating the concepts of "lean thinking". They noted that, even in the leanest factory, waste is created by making the wrong product efficiently.

In 2004, Bicheno introduced an environmental perspective into lean thinking (Bicheno 2004). "New wastes" for manufacturing and service were added, including: the waste of untapped human potential; the waste of inappropriate systems; wasted energy and water; and wasted materials (pollution waste). In an economy where labour is a bigger expense compared to materials, Ohno emphasized the elimination of non-physical wastes like labour and capital, but the same attention should now extend to material efficiency and the elimination of physical wastes once the true cost of waste is taken into account. These concepts have also moved to the sustainable development arena; for instance, the concept of zero emissions was introduced by Pauli (1997) when he argued that

> "*the ultimate goal of cleaner production is thus zero waste ... [moving] industry from pollution prevention and control into the new paradigm that is to become the industry standard*."

It is clear that the zero waste ideal has always been present in manufacturing philosophy since Ford's assembly line; however, the systematization of such concepts, methods and tools to achieve the zero waste goal has been developing slowly throughout time.

More recently, considerable efforts have been spent developing frameworks, models and concepts in a move towards zero waste and emissions. Kjaerheim (2005) proposes the Norwegian method for Cleaner Production alongside Greening of the Supply chain, as a route towards sustainability, whilst Almeida et al. (2010), Ravichandran et al. (2011) and Yang et al. (2011) provide a variety of tools, techniques and technologies to prevent and minimize waste across various key material streams. Seadon (2010) reports on attempts to systematise waste management knowledge in order to achieve greater sophistication, suggesting what a sustainable waste management system must do, without saying how the system should do it.

However, the adoption of best practices proves to be a difficult challenge in business environments (Baumgartner & Zielowski 2007; Danihelka 2004), thus contributing to the perception that real progress of our societies to become more sustainable is very slow (Baumgartner 2011). For instance, Allwood et al. (2011) report that 50% of cast metal is discarded through ingot scalping, rolling trim and blanking skeletons; in aerospace manufacturing, the "buy to fly" ratio for material purchased compared to material in the product could be as poor as 10:1. This illustrates the magnitude of the challenge – and there is plenty of room for improvement. Indeed, Cagno, Trucco and Tardini (2005), note that “the scarce use of systematic techniques and tools suggests that adoption ... is still in the early stage, mainly based on pilot projects ...”. Such pilot projects are very much in evidence in the literature, including approaches by Altham (2007) and Greyson (2007), the former being related to the dry cleaning industry whilst the latter a new economic instrument to help direct towards sustainability and zero waste.

Whilst the literature may suggest different ways of tackling waste, crucial to any attempts—and particularly relevant to the research presented in this thesis—will be the management/corporate approach to and understanding of waste. Baumgartner and Zielowski (2007) discuss the impact of zero emission technologies on organisational culture in the context of sustainability – and consequently the ways in which culture must develop for companies to move towards sustainability. Cagno, Trucco and Tardini (2005), alongside their point on pilot projects (above), note that many companies have changed “from a compliance point of view into a strategic issue for company long-range competitiveness” – and yet this is happening with the “scarce use of systematic techniques and tools”. Clearly industry could benefit from a clearer understanding of waste and its costs, in the path towards cleaner production.

The remaining of this section will discuss in more detail the literature that deals with the nature of waste in production processes. Whilst analysing the heat engine according to the Carnot cycle, the term unavoidable “entropic cost” was first introduced in order to denote the inevitable loss of some incoherent energy to a colder sink for reasons unrelated to friction (Khalil 2004). Acknowledging that it is impossible to have 100% efficient engines Khalil (1990) states that: "production is a purposeful activity undertaken to harness free gifts of nature to generate effects, products and services. This activity engenders unavoidable waste – broadly defined”.

Focusing on the material origins of waste and employing the laws of thermodynamics as an analytical framework it is possible to estimate to what extent the occurrence of waste is actually an unavoidable necessity of industrial production and to what extent it is an inefficiency that may in principle be reduced. For example, it has been shown that roughly two thirds of the waste currently generated in iron production is due to thermodynamic inefficiency, whereas one-third is actually necessary for thermodynamic reasons (Baumgärtner & Arons 2003).

Khalil shows that the heat engine, found at the core of production processes, unavoidably wastes some energy in order to function; then Baumgärtner and Arons proved that production processes could have unavoidable waste outputs. Unavoidable waste is also recognized in the 'green chemistry' field. Some waste is unavoidable, because energy is required to break the bonds in the starting materials of a reaction, which leads to the generation of by products or the use of solvents (Poliakoff & Licence 2007).

Researchers have proposed a thermodynamic analysis based on exergy to account for resource inputs and waste outputs in a systematic and uniform way (Ayres, Ayres & Martinás 1998). A widely accepted measure of waste in the chemical industry is the 'e-factor'. This is defined as the mass ratio of waste to desired product. The e-factor could also be multiplied for an arbitrarily assigned unfriendliness quotient in order to account for toxicity. This and other metrics for the chemical industry are discussed in detail in the literature (Sheldon 2007, 2008).

An illustrative case about the importance of managing unavoidable industrial waste is related to the red mud spill in Ajka, Hungary. In 2010, about 700,000 m^3 of highly caustic slurry—resulting from the production of alumina from bauxite from the Bayer process—flooded three settlements and about 40 km^2 of agricultural land and caused the death of 10 persons (Gelencsér et al. 2011). On a dry basis, for every tonne of alumina produced, the Bayer process generates approximately another tonnes of bauxite residue or “red mud”, this residue consists of various metal oxides (Fe, Al, Ti, Si, K, Na, V and Ga) along with inclusions of unwashed sodium aluminate solution (Balomenos et al. 2012). Prior to the Ajka accident, several reutilisation schemes had been developed for the red mud, including *its use for adsorption of metals from water, the retention of phosphorus in soil and its use for* $C0_2$ *sequestration* (Gelencsér et al. 2011); however common industrial practise is to store the red mud in giant open-air ponds. Orbite states that “*no environmentally acceptable use for red mud exists, nor have there been good options available for its treatment*” (Cote, Caudron & Wilson 2012) until they developed an alternative process for the production of alumina that does not generate toxic residues.

Orbite notes that, generally, materials obtained from the treatment of red mud are of low commercial value and need to be shipped in large quantities to be able to absorb the production cost their incur, thus becoming economically unfeasible (Cote, Caudron & Wilson 2012).

It was not until the aftermath of the red mud spill at Ajka, when more viable solutions emerged. Orbite intends to initiate operations for its full size smelter-grade alumina plant in Quebec plant by 2014 (Cote, Caudron & Wilson 2012). Meanwhile, (Balomenos et al. 2012) have designed a process for the transmutation of red mud into pig iron and viscous slag by means of reductive smelting; these products can be converted into mineral wool. Mineral wool is a versatile product with multiple applications; it is also produced with 70% less energy than conventional products and the transmutation process leaves no solid residues (a zero waste solution).

2.1.2 Product output, non-product output and the true cost of waste

The consolidation of material flow cost accounting, as highlighted in the special issue of the Journal of Cleaner Production (Jasch 2006) and the international standard ISO 14051:2011, represents another achievement aiming towards material efficiency; it provides key concepts for the model proposed in this paper.

According to Jasch (2009b) Material flow cost accounting considers all products, wastes and emissions that leave an organization to be outputs. Product Outputs (POs) are products and by-products including their packaging. By definition, any output that is not a product output is a Non-Product Output (NPO); examples of these include solid waste, wastewater and air emissions. By-products are products incidentally produced during the manufacture of the primary product; according to Jasch (2009b) anything being sold and showing as earning in the accounts can be considered a by-product.

Material flow cost accounting captures the true cost of waste by treating it as a separate negative product; proper amounts of costs are allocated to waste in proportion to the weights of product and non-product output (Jasch 2009b). Using environmental management accounting procedures it has been demonstrated that in some manufacturing sectors the cost of wasted materials accounts for 40-70% of total environmental costs - depending on the business sector, (Jasch 2009b).

As Dyson recognised (see section 2.1.1), waste is unavoidable in some cases. For example, Khalil (1990) states that: “production is a purposeful activity undertaken to harness free gifts of nature to generate effects, products and services. This activity engenders unavoidable waste – broadly defined”. It has equally been shown that roughly two thirds of the waste currently generated in iron production is due to thermodynamic inefficiency, whereas one-third is actually necessary for thermodynamic reasons (Baumgärtner & de Swaan Arons 2003). Focusing on the material origins of waste and employing the laws of thermodynamics as an analytical framework, it is possible to estimate the extent that the occurrence of waste is an unavoidable necessity rather than an inefficiency that may in principle be reduced.

2.1.3 Profitability analysis of the firm's output

In order to grasp the impact of waste on profitability, it is crucial to understand what profitability is and where is the source of profits. As a definition, a product can be considered to be fully profitable if the revenue generated by the product is greater than the cost incurred to produce and sell the product (South & Oliver 1998).

To become profitable, a product must prove successful in the market place. Successful products are characterized by generating customer satisfaction. Keiningham et al. (2005) provide a description of the pathways in which customer satisfaction leads to profitability. Customer satisfaction is positively linked to a set of desirable business outcomes, for example: positive impact on purchase intentions, customer retention, share of wallet, volume of business and ultimately higher profits. The caveat is when products are "non-profit" (as further discussed in the Kanthal effect), in which case improving customer satisfaction has the counteracting effect of lowering a firm's net income (Keiningham et al. 2005). Another consideration to take into account is that customers' overall satisfaction is determined mostly by their expectations and perceived quality; in turn, these two aspects can be influenced by word of mouth, personal needs, past experiences and external communications (Tseng & Hung 2013). In these regards, Tseng and Hung (2013) have adopted a service quality model to understand and measure the gaps between customer's expectations and the perceptions of quality for eco-friendly products.

A review of the business literature reveals that organizations show different approaches when setting profit objectives. In particular, profit objectives trigger two types of behaviour: maximizer and satisficer (Hague 1971). The former aims to the highest possible gain, whilst the later defines 'satisfactory' levels of profit to be reached. Interestingly, the same type of behaviour has also been observed and studied in consumer decision theory (from a social psychology perspective). Consumers display two types of behaviour, choosing the best possible product option (maximizing) or a good enough option (satisficing) as studied by (2002).

In order to have satisfied customers, companies need to deliver quality products. Product features have different levels and ways of impacting on customer satisfaction. Kano identified three important types of product attributes: must-be, one-dimensional and attractive (Berger et al. 1993) as shown in the Kano diagram of Figure 2.2. Must-be attributes do not improve customer satisfaction even if their performance is high, however, if there is a lack of performance, customer satisfaction decreases exponentially. Customers are sensitive to one-dimensional attributes, thus, they show a linear positive correlation between product functionality and customer satisfaction. Attractive attributes, as opposed to must-be attributes, are not sensitive to customer dissatisfaction when their performance is poor, but when performance becomes fully functional the levels of customer satisfaction increase exponentially.

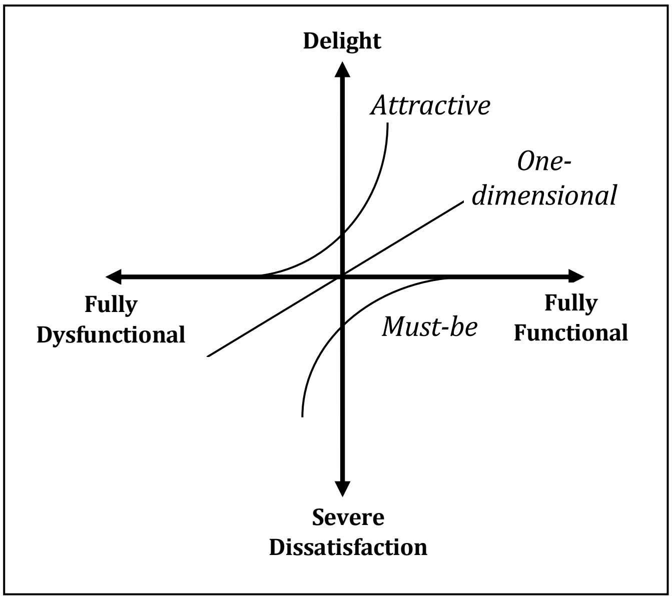

Figure 2.2 Kano Diagram, adapted from Berger et al. (1993)

Based on an understanding of customer needs, requirements and expectations the product development process specifies a balanced mix of product features that optimises customer satisfaction; for instance, Sauerwein et al's (1996) advice to

> "fulfil all must-be requirements, be competitive with regard to one-dimensional requirements and stand out from the rest as regards to attractive requirements!".

Companies should be aware that products and customers have different levels of impact on profitability. The Kanthal effect (or "whale curve") of Figure 2.3 is frequently seen when cumulative profitability is plotted against products ranked from most profitable to least profitable (Kaplan & Atkinson 1998; Kaplan & Cooper 1998; Sievänen, Suomala & Paranko 2004). Typically 20% of a company's products generate about 300% of the actual profits of a company; the remaining 80% of products either break even or make a loss, thus losing the remaining 200% of the company's profits. A similar picture emerges for customers: in the Kanthal case, 5% of the customers generated 150% of the division's profit. The least profitable 10% of customers lost 120% of the profits.

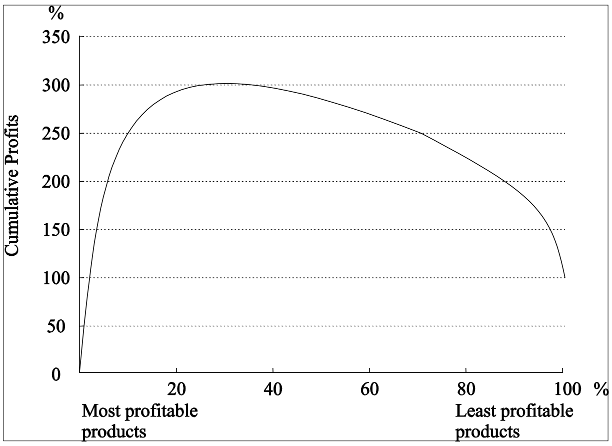

Figure 2.3 Cumulative profitability, adapted from Kaplan and Atkinson (1998)

Designing competitive advantages requires the selection of target markets for the firm's profitable growth which in turn requires market segmentation and analysis. Differential advantages are developed into a strategic marketing mix that positions the firm in the market place against competitors (Doyle & Stern

2006). Therefore, product mix decisions can have a critical impact on both the profitability and competitive position of a firm (Porter 1980; South & Oliver 1998). Typically a product mix decision is made by considering sales, profit margins and non-quantitative criteria including “carrying a complete line of products” (Boyd & Orville 1990; Kotler 2003; South & Oliver 1998). The model proposed in this chapter could illustrate the composition of the product mix in relation to profit levels.

2.1.4 Industrial symbiosis

Industrial symbiosis is one of the current ways to tackle the landfill challenge; this concept falls into the recently created field of industrial ecology which began to appear sporadically in the literature of the 1970s (Erkman 1997). As the theory of industrial ecology developed, the concept of industrial symbiosis emerged. Industrial symbiosis “engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and or by-products” (Chertow 2000). This exchange relationship is justified for different reasons; at times it provides economic or ecological advantages and, at times when those advantages are not clear, it forms part of long term strategic decisions (e.g. Jacobsen 2006).

The National Industrial Symbiosis Program (NISP) has improved Chertow’s concept of industrial symbiosis for UK purposes, adding other organizations to the symbiosis, including collaboration, shared use of assets, logistics, expertise and knowledge transfer (Laybourn 2007). NISP outputs in the UK for 2005/2006 attribute cost savings for business at £145,768,655 with 1,360,395 tons of materials diverted from landfill (Agarwal & Strachan). The most recent figures from April 2005 to March 2010 puts these figures in the range of 35 million tons of landfill diversion, £780 million in cost savings and £880 million in additional sales for businesses respectively (NISP 2009). These are promising results and represent evidence that wastes can be turned into cost savings that add to the triple bottom line of a company.

Costa et al. (2010) recognized that governmental institutions play an important role in the development of Industrial symbiosis but also warned against the potential risk of withdrawing governmental funding from industrial symbiosis programs: companies may no longer wish to participate once the services cease to be supplied at zero cost.

2.1.5 The role of design in profit creation and waste prevention

Waste prevention is the ultimate aim of eco-efficient strategies applied towards cleaner production as illustrated by Deif (2011). Weenen (1990) points out that because a product (and the manufacturing process to make it) has to be designed before it can be manufactured, then "it is therefore justifiable to argue that the environmental effects of the product are already fixed to a large extent in the design phase". Given that waste occurs as a consequence of design decisions, it seems appropriate to consider its elimination at the design stage where some have speculated that 80 to 90%[1] of economic and environmental[2] impacts of products are determined (Bhamra 2004). Barton, Love and Taylor (2001) provides evidence about the speculative nature of this figure but also recognizes that it is not the exact figure that is important, but the understanding that product design determines the majority of the total costs.

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[1] (Barton, Love & Taylor 2001) provides the background for the origins of this speculative figure; it originates from an unproven assumption that design determines 70% of production costs. The figure arises from a misunderstanding of the difference between total cost and unnecessary design costs; although the majority of total cost is determined by product design, design decisions cannot be associated to a specific proportion of the total costs (Barton, Love & Taylor 2001). In order to study this subject Ulrich and Scott (1998) had measured the variation in design performance (quantified as manufacturing content) among a set of competing design efforts to prove that manufacturing decisions are both "highly significant and of roughly the same importance in determining costs" as design decisions. Ulrich and Scott (1998) conclude that design matters: differences in design practices correspond to significant differences (50% variation) in manufacturing content. On this basis, the quoted 80-90% economic and environmental impact attributed to product design remains speculative because the authors do not provide substantive proof to sustain the claim whilst the issue of cost association still remains unsolved.

[2] No substantive proof is provided to support the claim that the design stage determines 80 to 90 per cent of environmental impact; this figure seems based on the assumption that environmental impact is determined in the same way as economic costs is during the design stage.

The impact of product design on the profitability of a firm remained unclear for a long time; based primarily on anecdotal evidence, managers knew that good industrial design was profitable but success stories were mixed with anomalies of unsuccessful “good” design and successful “poor” design (Hertenstein, Platt & Veryzer 2005). In their review paper of product design in management studies, Ravasi and Stigliani (2012) point out that “between the mid-1980s and the mid-1990’s scholars began to acknowledge the strategic relevance of design”; scholars showed how firms used design to gain differential advantage in the marketplace. Ravasi and Stigliani (2012) shows how the product design field evolved from early work based on insightful case-based research towards more systematic studies in which design increases the competitive and financial performance of a firm. The evidence of industrial design having a positive impact on company performance remained extremely light until “how” and “when” questions begun to be answered (Gemser & Leenders 2001). For example, in their analysis of two Dutch manufacturing industries, Gemser & Leenders (2001) provide evidence that firms that integrate design in new product development projects experience improvements in company performance (profit, averaged turnover and export sales). The generalizability of Gemser and Leenders’s (2001) findings was corroborated by analysing a larger sample and using stock market returns as the ultimate arbiter of financial performance; in this way, Hertenstein, Platt and Veryzer (2005) provide convincing evidence that “good industrial design is related to corporate financial performance and stock market performance”.

The term product design is used in practice in different ways and even varies in usage regionally; hence the importance of stating clearly what definition and assumptions guide a particular line of enquiry in academic research (Ulrich 2011). Ulrich’s definition of product design stated as “*conceiving and giving form to goods and services that address needs*” serves as a reference framework. In Ulrich (2011) words,

> "*design is part of a human problem-solving activity beginning with a perception of a gap in a user experience, leading to a plan for a new artifact, and resulting in the production of that artifact*".

As pointed out by Ulrich (2011), artifact may refer to any result of intentional creation, including physical goods, software and services; however this thesis focuses only on the design of products—in particular products that will be supplied repeatedly. This chapter also subscribes to the pragmatic definition of design (what it is and what it does) as conceived by (Ravasi & Stigliani 2012): design is

> "*a set of choices regarding both the form and the function of an object, as well as the activities that underpin these choices*".

In their review of the product design literature, (Ravasi & Stigliani 2012) portray the field in a holistic way by grouping research streams in three main categories depicting the fundamental stages in the design process:

1. *design activities* (how design decisions are or should be made),
2. design choices (how design decisions affect formal and functional properties of products) and
3. design results (how formal and functional properties of products influence firm performance)

The theoretical proposition in section 4.1 proposes a design framework that prevents waste by means of design. This proposition falls into the research branch concerned with design choices; the core findings in this area point out that

> "*good design results from fit between the functionality of the product and user's needs and expectations*" (Ravasi & Stigliani 2012).

In order to understand good design, Clark and Fujimoto (1990) proposed two dimensions of product integrity (internal and external).

Internal integrity is the extent with which a product is consistent in function and structure whilst external integrity is the consistency between a product's performance and customer expectations. Berthon, Hulbert and Pitt (2005) however, argue against this typical view of Marketing. The typical marketer presumes that technology must somehow match pre-existing customer needs and wants; however, technology is not just a means, it is a creative agent that interacts with consumers and brings forth new needs and wants that create new markets (Berthon, Hulbert & Pitt 2005).

The understanding of human needs and wants becomes important from a sustainability perspective, in particular with regard to "sufficiency strategies". A corporate level a sufficiency strategy cannot result in in lower demand in general but it will lower demand for materials and products (Schaltegger et al. 2009); for instance, a business could consider "*how many functions in a product or service are really adding significant value for its customers and then eliminating whatever features are not justified by this criterion*" (Schaltegger et al. 2009). Although Schaltegger et al. (2009) acknowledge that sufficiency strategies can support cleaner production their research does not focus on how it could be done; instead, it provides the information requirements and the environmental management accounting (EMA) that is needed to ensure the successful implementation of efficiency, consistency and sufficiency strategies for cleaner production.

The intellectual discussion of human needs, wants, desires and demands is as old as Plato and Aristotle, but the 1960's was marked by a revival of need theory in relation to politics (Fitzgerald 1985); in his article on the ideas of Christian Bay and Hebert Marcuse, Fitzgerald (1985) outlines the major developments of need theory. Marcuse attempts to distinguish between "true" and "false" needs; the former begins with vital needs (nourishment, clothing, lodging at the attainable level of culture) which must be satisfied for the realization of all needs, the latter are "superimposed upon the individual by particular social interests in his repression" (Fitzgerald 1985). Bay criticizes Marcuse's dramatic distinction of true and false needs and proposes an alternative classification that distinguishes between needs (which, by definition, are genuine) and wants, desires, and demands (which may, or may not, correspond to true or genuine needs). Bay began defining needs from a pathological perspective but then moved to define needs in terms of a positive model of human kind. Bay subscribed to Maslow's theory of human motivation which recognized five categories of universal human needs (areas) prioritised as follows: (1) physical (biological needs), (2) safety needs, (3) affection or belongingness needs, (4) esteem needs—by self and others; and (5) self-actualisation or self-development needs. Bay restructured Maslow's need-hierarchy in order to reduce value judgements; this resulted in three categories of needs: (1) basic physical needs for sustenance and safety, (2) community needs and (3) individuality and subjectivity needs. Bay admits that it is difficult to disentangle authentic human needs from alienated wants, for want is considered an empirical term that refers to every kind of verbally stated or otherwise manifest wish, preference, demand, desire, interest, etc. The knowledge accumulated by social scientist has influenced marketers and designers in their understanding of customer wants and needs; for example in the use of Maslow's theory of motivation as a guiding framework for decision making during product design (Yalch & Brand 1996). Unlike social scientist, practitioners are less concerned with the ethical issues of determining what customers really need. Marketers are not afraid to research what customers really want and deliver products and services that satisfy their desired outcome in a way that also satisfies their individual and subjective needs, i.e. to be the envy of the neighbourhood (Gitomer 2006).

When products are sold, expectations are expressed in customer's beliefs about how services would/should or will perform (Dasu & Rao 1999). This has been studied in the service quality literature. Johnston (1995) provides a summary of the five major debates that took place in the service quality area and how the concepts evolved. There appears to be a consensus with regards to the definition of satisfaction and service quality; the former refers to the outcome of individual service transactions and the overall service encounter, whereas the later refers to the customer's overall impression of the relative inferiority/superiority of the organization and its services (Johnston 1995). Zeithaml, Berry and Parasuraman (1993) proposed a conceptual model for understanding the nature of service expectations: desired service, adequate service and predicted service. This model became widely accepted and became the basis for further developments in the identification of the determinants of service quality—as outlined by Johnston (1995).

The concepts of need theory and service quality helped designing a new framework (see section 4.1) to improve the design choices and eliminate waste during the early stages of product design. Design has an immediate impact on manufacturing performance. "D*esign transforms a gap into a plan. Production transforms a plan into an artifact*" (Ulrich 2011). A fully functional new product development (NPD) team consists of industrial design, engineering, manufacturing and marketing departments working together to "*come to a consensus on the general product concept and on the most feasible solution for efficient manufacturability*" (Hertenstein, Platt & Veryzer 2005) .

The design framework for waste prevention (presented in section 4.1) was developed in order to help the NPD team design products that increase the firm's profitability by maximising customer satisfaction whilst optimising resource efficiency. As pointed out by Bhamra (2004),

> *"the cost of any environmental intervention is at its lowest and most flexible at these early stages [of product development], also known as 'front loading'."*

Chapter 3. Research methodology

3.1 Theory and the production of knowledge

Gibbons et al. (1994) proposed the thesis that the process of knowledge production in contemporary society falls into two contrasting categories, which they describe as "mode 1" and "mode 2".

In mode 1 knowledge production is driven primarily by an academic agenda in which discoveries are built upon existing knowledge in a linear fashion. In this mode, limited emphasis is placed in the dissemination of knowledge; essentially, in mode 1 there is a gap between what is fundamental and what is applied knowledge (Bryman & Bell 2007; Gibbons et al. 1994). Although the theoretical propositions of this research thesis were built on existing knowledge from the literature as the mode 1 category suggests, the researcher had always in mind considerations about the dissemination and applicability of the research in the real world.

The research presented in this thesis follows Gibbons et al. (1994) description of mode 2 where knowledge is produced (from the beginning) in a context of application; such knowledge is intended to be useful to someone whether in industry, government or society. More specifically, in the context of management and business research, mode 2 is the trans-disciplinary mode of research in which knowledge production involves academics, policy makers, and practitioners who apply a broad set of skills to tackle a shared problem in the business or industry sector (i.e. the landfill issue). As Bryman and Bell (2007) point out, findings are closely related to the context and may not easily be replicated, so knowledge production is less of a linear process. Following the advice of mode 2 of knowledge production, this research took place in a real manufacturing setting; it drew help from practitioners and explored the policies that have an effect on waste reduction in industry.

The research approach in this thesis intends to answer the questions posed by the theoretical propositions arising from the analysis of the literature; it was found that the idea of transforming unavoidable manufacturing waste into a profitable co-product has not been formalised and that existing approaches for diverting waste from landfill are deficient. This research used generation of 'middle range' type of theories to progress towards the research aim; the knowledge generated is suitable for dissemination in the manufacturing sector as a way of helping companies divert waste from landfill in a profitable way.

As summarised by Perry (1998), there are two major approaches to theory development, deductive theory testing and inductive theory building. This research started with a deductive theory development as described in the following section.

3.1.1 A deductive theory of knowledge

The researcher, on the basis of what is known about manufacturing waste (from the literature review) created a knowledge framework (the all seeing eye of business) from which a series of hypotheses were drawn in order to test the theoretical propositions; the hypotheses were then subjected to empirical scrutiny. Following the process of deduction, the theoretical propositions guide and influence the collection and analysis of data as shown in Figure 3.1

Figure 3.1 The process of deduction, adapted from Bryman & Bell (2007).

3.2 Epistemological considerations

"An epistemological issue concerns the question of what is (or should be) regarded as acceptable knowledge in a discipline" (Bryman & Bell 2007). There are three main epistemological considerations used in business research namely positivism, interpretivism and realism.

Positivism is an epistemological position that advocates the application of the methods of the natural sciences to the study of social reality and beyond. It operates within the following principles (Bryman & Bell 2007):

1. Following Auguste Comte, positivism asserts that only phenomena and hence knowledge confirmed by the senses can genuinely be warranted as knowledge.
2. The purpose of theory is to generate a hypothesis that can be tested and that will thereby allow explanations of laws to be assessed.

3. Knowledge is arrived at through the gathering of facts that provide the basis for the laws.
4. Science must be conducted in an objective way. Real knowledge (as opposed to mere believes) is limited to what could be logically deduced from theory, operationally measured and empirically replicated (Patton 2002).
5. The domain of science is in the form of scientific statements as opposed to normative statements.

Interpretivism denotes an alternative to the positivistic orthodoxy. It is predicated upon the view that a strategy is required that respects the differences between people and objects of the natural sciences and therefore requires the scientist to grasp the subjective meaning of social action (Bryman & Bell 2007).

Realism shares two features with positivism: a belief that the natural world and the social sciences can and should apply the same kinds of approach to the collection of data and to the explanation, and a commitment to the view that there is an external reality to which scientists direct their attention. There are two major forms of realism (Bryman & Bell 2007):

- Empirical realism: simply asserts that through the use of, reality can be understood. It might be considered superficial because it “fails to recognise that there are enduring structures and generative mechanisms underlying and producing observable phenomena and events” (Baskar, 1989: as cited in (Bryman & Bell 2007)
- Critical realism[3] : is a specific form of realism whose manifesto is to recognise the reality of the natural order and the events and discourses of the social world and holds that “we will only be able

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[3] The ‘new’ type of realism (as opposed to ‘naive’ or empirical) is variously labelled as ‘scientific realism’, ‘critical realism’, ‘fallibilistic realism’, ‘subtle realism’, and ‘transcendental realism’ amongst other terms, each of which stresses particular features (Robson 2011).

> to understand – and so change - the social world if we identify the structure at work that generate those events and discourses" (Baskar, 1989: as cited in Bryman and Bell (2007)).

The positivistic approach adopted in this thesis seeks the fact or causes of social phenomena, with little regard to the subjective state of the individual (Collis & Husey 2003), positivism also requires that only observable phenomena can and should be researched (Perry 1998). The research presented in this thesis is more prescriptive than descriptive and thus proposes the use of experimental studies to verify the theoretical propositions. This research focuses on the mechanisms of the organisation, rather than the experience of the employees, it considers profitability (and observable and measurable phenomena) as the ultimate measure of the successful implementation of the theoretical propositions.

Experiments are conducted either in a laboratory or in a natural setting in a systematic way in order to identify causal relationships (Collis & Husey 2003). The aim is to manipulate the independent variable (the implementation of a methodology) in order to observe an effect on the dependent variable (transformation of manufacturing waste into a profitable co-product). Natural quasi experiments were used because they enabled valuable observations in real manufacturing situations. A quasi experiment is a study that has certain characteristic of experimental designs but does not fulfil all internal validity requirements (the issue of causality discussed further). A natural experiment is a particular form of quasi-experiment which entails the manipulation of a social setting, but as part of a naturally occurring attempt to alter social arrangements (Bryman & Bell 2007).

Experiments, particularly those involving randomisation, i.e. randomised controlled trials (RCT's), are frequently portrayed as the best way of establishing causation. Causation is central to the idea of the positivist view of science, but it does not give a direct answer to 'how' or 'why' questions (Robson 2011). In order to overcome the shortcomings of experiments, this research approach moved beyond positivism and adopted the critical realism approach to acknowledge that a scientist's conceptualization is simply a way of knowing reality. In this view, '*science is the systematic attempt to express in thought the structures and ways of acting of things that exist and act independent of thought*' (Bhaskar 2008). In the logic of scientific discovery Bhaskar observes '*a kind of dialectic in which a regularity is identified, a plausible explanation for it is invented, and the reality of the entities and processes postulated in the explanation is then checked*, this illustrated in *Figure 3.2.*

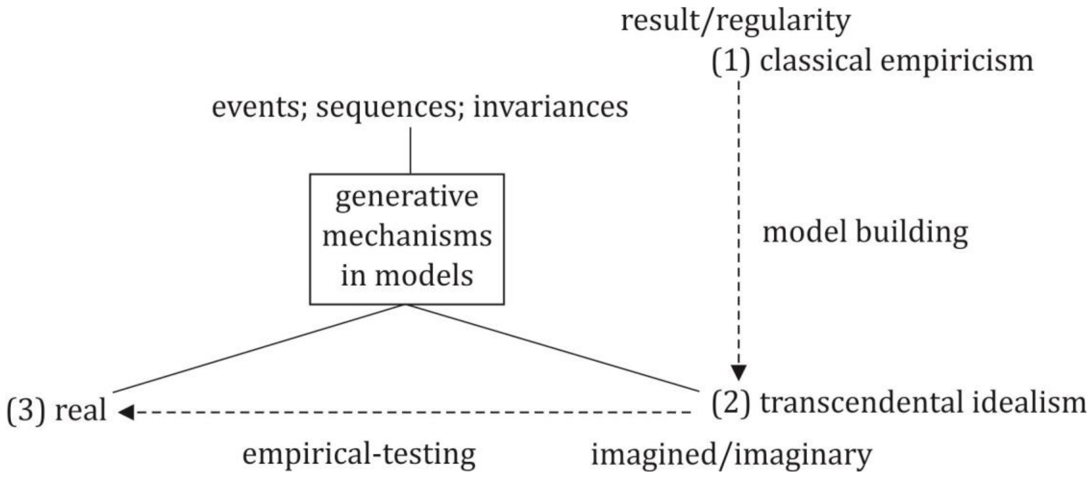

Figure 3.2 The logic of scientific discovery, adapted from Bhaskar (2008)

Bhaskar argues that '*if and only if the third step is taken and developed in the way indicated above can there be an adequate rationale for the use of laws to explain phenomena in open systems (where no constant conjunctions prevail) or for the experimental establishment of that knowledge in the first place (Bhaskar 2008)*'. It is in this line of thinking that the research approach adopted in this project aims to uncover the generative mechanisms that could enable the theoretical propositions to work in a real manufacturing setting.

3.3 Ontological considerations

For Bryman and Bell (2007), the questions of social ontology are concerned with the nature of social entities. Researchers are faced with the dilemma of whether they can and should consider social entities as objective entities that have a reality external to the researcher, or whether they can and should considered social entities as social constructions built up from the perceptions and actions of the researcher; these two competing views are referred to objectivism and constructionism respectively, see definition in Table 3.1.

Table 3.1 Ontological paradigms, adapted from (Bryman & Bell 2007).

Objectivism	Constructionism (constructivism)
Objectivism is an ontological position that asserts that social phenomena and their meanings have an existence that is independent of social actors. It implies that social phenomena and the categories that we use in everyday discourse have an existence that is independent or separate from actors.	Constructionism is an ontological position that represents the antithesis of objectivism; it asserts that social phenomena and their meanings are continually being accomplished by social actors. It implies that social phenomena and categories are not only produced through social interaction but that they are in a constant state of revision.

The objectivist view adopted in this thesis recognises companies as social entities that have a reality of their own. A company has rules and regulations. It adopts standardised operational procedures and can therefore be studied as an object with its own reality. The objectivist paradigm is more appropriate because the researcher is interested in uncovering the generative mechanisms that could enable the transformation of waste into a co-product; adopting a constructivist approach would have put unnecessary attention to the particular views of the social actors inside a company. A constructivist approach would be more useful if the researcher was investigating how to best implement the theoretical propositions, but before moving to that stage of research one needs to test the validity of the theoretical propositions in the objective reality of the firm. The researcher is aware of the constructivist view, i.e. the reality of a company is always in the process of being formed and shaped by its social actors. Under a constructivist paradigm, the social actors would play a key role in the interpretation and construction of the theoretical propositions; also, each company would implement them given their own reality construct. However; the study of such variations of interpretation and implementation falls out of the scope of this research.

3.4 Research paradigm

Paradigm is a philosophical model or framework that originates from a world view or belief system which is based on the need to satisfy ontology and epistemology considerations (Holloway 1997). In other words, paradigm is ‘a cluster of beliefs and dictates which for scientists in a particular discipline influence what should be studied, how research should be done and how results should be interpreted’ (Bryman & Bell 2007).

Burrell and Morgan’s (1979) contribution to organisational analysis propose the use of four distinct and incommensurable paradigms which can be utilised for a wide range of social theories. Each paradigm - described in the context of business research by Bryman and Bell (2007) - contains assumptions about the nature of science that can be thought of in as either:

- objectivist – organisations are comprised of consistently real processes and structures, and could therefore be studied from an external view point; or,

- subjectivist – an organisation is a socially constructed product, a label used by individuals to make sense of their social experience, so it can be understood only from the view point of individuals who are directly involved in its activities.

Each paradigm also makes assumptions about the nature of society; in the world of business, this relates to the function and purpose of scientific research put in the regulation-radical change dimension, Bryman and bell (2007) describes it as follows:

- regulatory – the purpose of business research is to describe what goes on in organisations and, possibly suggest minor changes that might improve it but not to make any judgement of it; or
- radical – the point of management and business research is to make judgements about the way that organisations ought to be and to make suggestions as to how this could be achieved.

Plotting the two dimensions explained above illustrates the nature of these four paradigms. Figure 3.3 illustrates the four paradigmatic positions from the view of business research.

The sociology of radical change

Subjective | **Objective**

Radical humanist	*Radical structuralist*
Seeks the release of the constraint which existing social arrangements place upon human development; sees organisations as a social arrangement from which individuals need to be emancipated and research is guided by the need for change	committed to radical change, concerned with emancipation from the structures that limit the potential for human development; it views an organisation as a product of structural power relationships, which results in conflict
Interpretive	*Functionalist*
Seeks to understand the very basis and source of social reality; it questions whether organisations exist in any real sense beyond the conceptions of social actors, so understanding must be based on the experience of those who work within them	Is the dominant framework for the study of organisations, it has a problem oriented approach - concerned to provide practical solutions- which leads to rational explanation.

The sociology of regulation

Figure 3.3 Paradigms in business research. Adapted from: Bryman and Bell (2007) and Burrell and Morgan (1979).

The research presented in this thesis adopts the functionalist paradigm because it aims to provide practical solutions to help companies divert waste from landfill; in this way the research has a problem solving approach. The research paradigm is consistent with the previous ontological assumption which treats companies as social entities with a reality of their own.

3.5 Research strategy

Research strategy, put simply, is the general orientation to the conducting of business research. In order to analyse and classify research methods in the world of business research it might be useful to distinguish between two types of research strategies: qualitative and quantitative (Bryman & Bell 2007). For many years these two approaches were the basic choice to be made when carrying out social research. The quantitative route tried to apply the methods of the natural sciences to social research whilst the qualitative route developed an approach that take into account several social aspects such as, human consciousness and language, the interactions between people in social situations, the fact that both researcher and researched are both human, etc. (Robson 2011) A basic, though fundamental difference between quantitative and qualitative research strategies is presented in Table 3.2; although it is useful to contrast the two approaches, the status of this distinction is ambiguous because it is almost simultaneously regarded by some as a fundamental contrast and by others as no longer useful or simply as "false".

Table 3.2 Differences between quantitative and qualitative research strategies, adapted from (Bryman & Bell 2007)

	Quantitative	Qualitative
Principal orientation to the role of theory in relation to research	Deductive; testing of theory	Inductive; generation of theory
Epistemological orientation	Natural science model; positivism	Interpretivism
Ontological orientation	Objectivism	Constructionism

There has been a long worn out debate about the suitability of qualitative vs. quantitative research strategies to study the social world, however, there is a growing recognition of the value of combining the elements of both in a multi-strategy design (Robson 2011).

3.5.1 A pragmatic approach

Using a pragmatic approach provides one way of justifying bringing together qualitative and quantitative approaches. In pragmatism, the central idea is that the meaning of a concept consists of its practical implications. Hence, truth is simply defined as what works. A pragmatist research strategy would advocate using whatever philosophical or methodological approach works best for the particular research problem at issue (Robson 2011).

Robson (2011) lists some key features of the pragmatic approach, for example:

- A pragmatist rejects traditional dualisms (e.g. rationalism vs. empiricism, facts vs. values) and generally prefers more moderate and common sense versions of philosophical dualisms based on how they work in solving problems.
- Recognises the existence of and importance of the natural or physical world as well as the emergent social and psychological world.
- Knowledge is viewed as being both constructed and based on the reality of the world.
- Theories are viewed instrumentally, (they become true and they are true to different degrees based on how they currently work; workability is judged especially on the criteria of predictability and applicability).
- Endorses eclecticism and pluralism (e.g. different, even, conflicting theories and perspectives can be useful; observation, experience

and experiments are all useful ways to gain an understanding of people and the real world).

- Endorses practical theory (theory that informs practice).

Often, in pragmatism, values and visions precede a search for descriptions, theories, explanations and narratives. It is common amongst pragmatic researchers to decide what to research based on their personal value systems, and they see no reason to be concerned about that influence, that is they study what they think is important and look for the consequences he or she desires. They pick and choose how and what to research, including variables and units of analysis that they feel are the most appropriate for finding answers to their research questions (Robson 2011).

In view of the concept of pragmatism explained above, the researcher adopted a pragmatic strategy in order to pursue the aim of finding ways to reduce waste to landfill. The following paragraphs explain how the research evolved and how it was narrowed down to studying the landfill issue, this provides the background and explanation of the reasons why a pragmatic approach was adopted.

During the literature review on sustainability, it was realised that we can't do much to stop economic growth; people deserve a comfortable standard of living. The ideal solution to the sustainability challenge is to have companies that operate under a growth-ability[4] concept. Under the growth-ability concept it is crucial to have truly sustainable materials (benign materials), but such an issue would require an improvement of basic and fundamental science; such a project was beyond the expertise of the researcher.

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[4] Growth-ability is defined as the ability for companies to grow in the economy whilst contributing positively to the balancing of the ecosystem, in other words growth that restores the carrying capacity of the earth's life supporting systems.

The material flow analysis of national economies have shown that material efficiency is very poor; most materials end up becoming waste in a short period of time. Whilst analysing figures on landfill use in the UK, it became evident that available landfill space was scarce. It was surprising to find out that industrial waste accounted 13% of total waste to landfill; a quantity slightly higher than household waste (9%) (DEFRA 2009). One might think that companies would instinctively make the utmost use of their material resources as a way to maximise profits and minimise waste, but if industrial activities were producing more waste than households then that would be an issue worth studying. First and foremost, because companies have the ultimate responsibility of creating a sustainable production and consumption system: it is in their interest and it is their job. And secondly because when businesses reduce waste, they are naturally aligned to the goals of sustainability, in other words, producing waste and pollution brings no profits. It was this chain of reasoning and the researcher's background in Industrial Engineering that brought up a whole range of questions about waste in manufacturing systems and how it related to the sustainability agenda and thus sustainable manufacturing and waste became the topic of the research project.

From the beginning, the researcher wanted to study a real world problem and to contribute to build a more sustainable production and consumption system, so issues of implementation and effective practice were always in consideration. There was also an underlying assumption, that aligning a company's profitability objectives towards sustainability was necessary in order to create the fastest change towards sustainable behaviour. There was also an interest to find out if working on a visible and tangible problem such as manufacturing waste would trigger sustainable thinking in companies. The ultimate aim of the researcher is to inspire companies to adopt sustainable business practices and progress towards a growth-ability mode of production. So to take the first step meant studying manufacturing waste, an issue that could have implications on many aspects of running a business: from product design, product manufacturing, to waste management practices and social corporate responsibility reporting.

Finally, a summarising thought is that we are entitled to grow and prosper using the earth's resources, but if we extract those valuable resources from the Earth's crust, only for them to become waste in a short period of time, then we are severely compromising the possibility of creating a sustainable production and consumption system.

From a pragmatic perspective, it was important that the research project should implement and test the theoretical propositions in a real world setting.

3.6 Research design

This section describes the research design that was used to investigate the research questions - guided by a pragmatic approach.

3.6.1 Definition of Case study research

The term case study is commonly associated with a location or organisation in which an intensive examination of the setting takes place as a way to produce knowledge. Yin (2009) provides a comprehensive technical definition of case study research, the first part deals with the scope of a case study:

1. *"A case study is an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident."*

With regards to data collection and analysis strategies, Yin states that:

2. *"The case study enquiry copes with the technically distinctive situation in which there will be many more variables of interest than*

> *data points, and as one result relies on multiple sources of evidence, with data needing to converge in a triangulation fashion, and as another result benefits from the prior development of theoretical propositions to guide data collection and analysis.*"

It is important to highlight Yin's argument that case study method is not just a form of qualitative research; it goes beyond being a type of qualitative research, by using a mix of quantitative and qualitative evidence. Additionally, case studies need not always include the direct and observational evidence marked by other forms of qualitative research (Yin 2009).

3.6.2 Case study design:

A primary distinction is made between single and multiple case study designs. Because the aim of the research is to help manufacturers divert waste from landfill, the researcher has chosen to test and validate the theoretical propositions in a wide range of industries as to ensure wide applicability of the theoretical propositions, it is for this reason that multiple case study design was chosen; "*evidence from multiple case studies is often considered as being more compelling and the overall study is regarded as being more robust" (Yin 2009)*.

The unit of analysis in the case study was a clearly defined waste stream. Even though waste streams were also analysed in a holistic way in order to gain understanding of the company's resource efficiency performance, the focus of the case study is to transform a single waste stream into a profitable co-product, the case study design adopted in this research is illustrated in Figure 3.4.

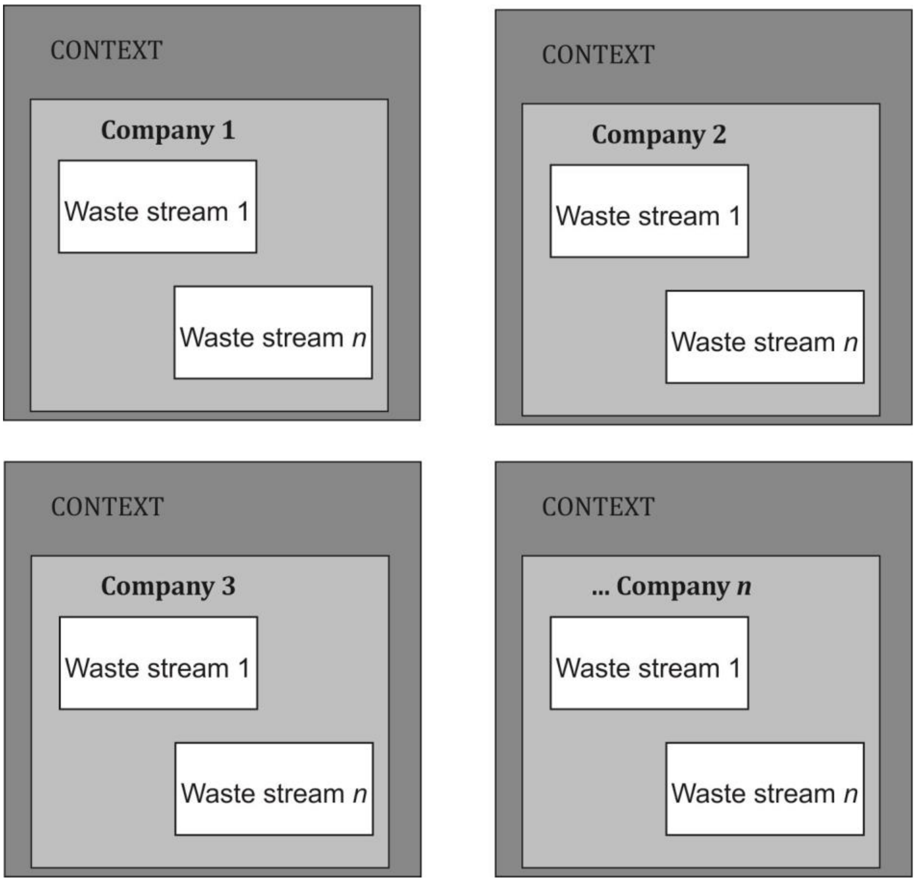

Figure 3.4 Multiple case study design using embedded units of analysis, adapted from Yin (2009)

Yin (2009)describes how doing multiple case study designs work in analogy to multiple experiments. Case study selection is based on replication logic, not on sampling logic (e.g. the multiple respondents of a survey). Each case must be carefully selected so that it either predicts similar results (a literal replication) or that predicts contrasting results but for anticipatable reasons (a theoretical replication). This case study design and sampling selection calls for analytic generalisation methods to be used to develop theory; the predictions from the All-SEB were used as a template to compare the empirical results of the case studies. If two or more cases are shown to support the theoretical propositions, replication may be claimed. Empirical results are considered more robust if they support the theoretical propositions but do not support an equally plausible rival theory.

A multiple case study research design allowed for comparative case study analysis, this type of case study design entails a study that uses more or less identical methods for two or more contrasting cases. Bryman (2004)explains that this design embodies the logic of comparison in that it implies that we can understand social phenomena better when they are compared in relation to two or more meaningfully contrasting cases or situations as shown in Table 3.3.

Table 3.3 Comparative design model, adapted from Bryman (2004).

Case $_1$	Time$_1$ Observation $_1$ Observation $_2$ Observation $_3$ … Observation $_n$
Case $_n$	Observation $_1$ Observation $_2$ Observation $_3$ … Observation $_n$

This research has a formal case study structure (shown in appendix 2), this allowed the collection of similar data which enabled cross-case comparison and analysis. The case study structure does not intend to make the research design fixed; it has the purpose of standardising the collection of data. In fact, it was expected that the theoretical propositions would be refined and improved with the findings from each previous case study. Lessons learned were applied to subsequent case studies, where applicable; thus case studies vary slightly in their implementation. Further variation occurs due to differences in company quality culture, organisation size, type of industry and type of waste; however this variation is actually a desired condition for a varied sample and will not affect the cross-case analysis and comparison.

3.6.3 A case study research outline

The purpose of the research provided in this thesis is to generate sustainable manufacturing strategies for eliminating waste in industrial settings. Case study research allows for an increased understanding of a topic since it investigates a contemporary phenomenon in depth and within a real-life context (Yin 2009). The research strategy focuses on understanding the dynamics within a single setting and comparing a range of quantitative and qualitative descriptors, to organize data and identify patterns that will be developed into a coherent theory (Eisenhardt 1989), in this case a theory about waste management in manufacturing organisations.

Upon developing the "all seeing eye of business (All-SEB): a model for understanding the nature, impact and potential uses of waste" (see section 4.2) it became necessary to test the proposed model into a real world case scenario in order to observe the impact this model would have on managerial decisions regarding non-product output (waste, pollution, unsold product, etc.) Implementing the all seeing eye of business is the first phase of the case studies, the objective is to test hypothesis number one:

H1. The all seeing eye of business will trigger business instincts and prompt the elimination of non-product output once the impact of waste on profit (and the potential uses of it) is understood by decision makers.

The alternative (null hypothesis: N1) is formulated as the following outcome:

N1. The all seeing eye of business does not trigger business instincts or for some other reason companies are not prompted take action to eliminate non-product output even if the impact of waste on profit (and the potential uses of it) is realised.

If a company does decide to take further action to reduce non-product output after analysing their process through the all seeing eye of business, then the null hypothesis is rejected. It then becomes important to discern the factors leading the change and find out the degree of influence that the all seeing eye of business had on the decision making process, this issue could be further investigated by interviewing the decision makers. A company might take further action by choosing to implement a “lean” protocol, maintenance regimes or by implementing the ATM of waste (introduced in section 5.2).

If the null hypothesis is not refused; it means that a company that has taken part in the research measured the impact of waste on profits and may have even realized the potential uses of waste, but it still failed to take further action to reduce non-product output.

The second phase of the case studies will investigate companies that are willing to eliminate non-product output. The All-SEB helps companies identify and quantify unavoidable waste, waste caused by inefficiency and the waste cause by error. The second stage of this research is concerned about the potential uses of unavoidable waste. The objective is to test hypothesis number two:

H2. Unavoidable non-product output can be transmuted into profitable co-products.

The alternative (null hypothesis: N2) is formulated as follows.

N2. Unavoidable non-product output cannot be transformed into profitable co-products.

The ATM of waste is a methodology developed to help companies transform unavoidable waste into profitable co-products (it is introduced and described in detail in section 5.2). One of the strategies for waste elimination derived from the all seeing eye of business is that waste could be transformed into highly profitable co-products. It is thought that this strategy could contribute to solve the landfill challenge outlined in the research background (section 1.1); therefore, the third hypothesis will investigate the following proposition:

H3. Co-products generate different levels of profit; not only are low and medium margins possible (“salvage” and “upgrade”), but also highly profitable co-products (“alchemy”).

The alternative (null hypothesis: N3) could be formulated as follows:

N3. “Alchemy” co-products made from unavoidable remain a theoretical proposition; the proposed co-product has not shown potential for high profit margins (alchemy).

3.6.4 Case study selection

Eisenhardt & Graebner (2007) discusses the concerns of case selection for theory building. The main criticism put forward is: how can such theory be generalized if the cases are not representative of a population?—as is the case with large scale hypothesis testing research—(Eisenhardt & Graebner 2007). Their response to this criticism is that the purposed of case based research is

> “*to build theory, not to test it, and so theoretical (not random or stratified) sampling is appropriate.*” “*Theoretical sampling means that the cases are selected because they are particularly suitable for illuminating and extending relationships and logic among constructs*” (Eisenhardt & Graebner 2007).

Furthermore, multiple cases are considered more generalizable because comparisons can be made in order to test whether an emergent finding is “simply idiosyncratic to a single case or consistently replicated by several cases”. Yin (2009) suggests that multiple cases are chosen for theoretical reasons such as replication, extension of theory, contrary replication, and elimination of alternative explanations.

3.7 Case study research rigour

Four tests are commonly accepted to establish the quality of any social research.

3.7.1 Construct validity

For doing case study research, Yin (2009) advises that an operational set of measures needs to be in place in order to avoid 'subjective' judgements during the collection of data. The researcher must be sure to cover two steps:

- define the research issue in terms of specific concepts (and relate them to the original objectives of the study) and
- identify operational measures that match the concepts (preferably citing published studies that make the same matches)

The case studies presented in this thesis addresses these two steps in the following way:

- The case studies investigate the transformation of waste into profitable co-products; this theoretical proposition is derived from the all seeing eye of business model which in turn has been deduced from well-established concepts in the literature. This model is described in section 4.2, the model is also presented in a journal paper published in the Journal of Cleaner Production (Bautista-Lazo & Short 2013).
- In practice, the identification of projects to transform waste into a co-product is currently adhoc, making it difficult for firms to evaluate whether it is worthwhile to investigate the feasibility of projects (Lee 2012). The case studies on this research project will investigate what are the mechanisms that facilitate the

transformation of waste into a co-product [an area of future research suggested by Lee (2012)]. Lee also recommends that a firm could factor the fixed cost of implementing a waste transformation project (e.g. research and development or capital equipment) as it would do for any strategic project. For example, it could calculate the net present value of the investment cost and future cash flows (Lee 2012).

Yin also points out that construct validity can be increased during data collection by using multiple sources of evidence and by establishing a chain of evidence (Yin 2009). In this research, construct validity is ensured by collecting data from the following sources:

- Site visit observations
- External reports
- Company literature

3.7.2 Internal validity

Internal validity is a concern in the case studies presented in this thesis due to the explanatory focus during result analysis. With regard to internal validity, Yin warns that when a researcher is trying to explain how and why event x led to event y. If the researcher concludes that there is a causal relationship between x and y without knowing that some third factor (z) may actually have caused y, the research design has failed to deal with some threat to internal validity (Yin 2009).

To address internal validity concerns, this research three general strategies:

- The case study design is based on the theoretical propositions derived from the all seeing eye of business: a model for understanding the impact and potential uses of waste.

- Using a case study presentation structure, each case is described in detail and presented in sequential order following the ATM methodology.
- When waste transformations were not possible to implement, the research examined rival explanations and tried to find out the causes that inhibit the waste transformation.

The researcher will play particular attention to rival explanations before drawing any major conclusions. Table 3.4 shows different kinds of rival explanations and the way in which they may appear in the research findings.

Table 3.4 Different kinds of rival explanations

Type of rival explanation	Description or example	Specific examples
Craft rivals		
The null hypothesis	The observation is the result of chance circumstances only	A highly profitable co-product design is found serendipitously and not by following the ATM methodology guidelines
Threats to validity	e.g. history, maturation, instability, testing, instrumentation, regression, selection, experimental morality, and selection-maturation interaction	Maturation: a co-product transformation is eventually found not by following the ATM methodology but simply because a company has spent long enough time as to come up with a solution Selection: a chosen company was more likely to achieve a “waste transmutation” (see section 4.2.4) due to the nature of their waste
Investigator Bias	e.g. “experimenter effect”, reactivity in field research	The researcher might attribute all the credits to the “all seeing eye of business” model when in reality the model had a smaller effect in the decision making process

Real-life rivals		
Direct rival (practice or policy)	An intervention ("suspect 2") other than the target intervention ("suspect 1") accounts for the results.	The researcher might be unaware of parallel research being done about the waste stream, e.g. the work of other consultants
Comingled rival (practice or policy)	Other interventions and the target intervention both accounted for the results	The co-product transformation is the result of a combined effort from the implementation of the ATM methodology and from the use of other techniques
Implementation rival	The implementation process, not the substantive intervention accounts for the results	The increased attention to the issue prompted a solution to the waste problem but not because of the implementation of the all seeing eye of business or the ATM methodology
Rival theory	A theory different from the original theory explains the results better	In this scenario the all seeing eye of business fails to explain the nature of co-products with regards to profit. It could also happen that the ATM of waste is not an appropriate methodology to help companies transform unavoidable waste into co-products.
Super rival	A force larger than but including the intervention accounts for the results	It could be that the sheer force of regulation (e.g. landfill tax) alone has forced companies to look for ways to divert waste from landfill.
Societal rival	Social trends, not any particular force or intervention accounts for the results.	Some companies might be diverting waste from landfill because best practice in the industrial sector has adopted the zero waste ideal.

3.7.3 External validity

The test of external validity deals with the problem of knowing whether the study's findings are generalisable beyond the immediate case study (Yin 2009). As Yin points out, survey research relies on statistical generalisation, whereas case studies rely on analytical generalisation. The researcher will strive to generalise a particular set of results to some broader theory. A theory must be tested by replicating the findings in a second or even a third case study, where the theory has specified that the same results should occur. Once such direct replications have been made, the results might be accepted as providing strong support for the theory (Yin 2009). Eisenhardt (1989) also recommends such a purposeful sample selection for case study research; each case should contribute to meet the research aims and specific objectives. The researcher will provide ample details about the company and the research context, for example:

- Organization:
- Location:
- Production volume per year:
- Product:
- Brief description of the process:
- Process flow diagram:
- Market size: %

3.7.4 Reliability

The objective of the reliability test "*is to be sure that, if a later investigator followed the same procedures as described by an earlier investigator and conducted the **same** case study all over again, the later investigator should arrive at the same findings and conclusions*" (Yin 2009), the goal is to minimise errors and biases in a study.

The case study proposal document (see Appendix 1) was used to ensure reliability of the case study research. This document describes to the research subject what is the aim of the research, the background to the theoretical propositions, it provides guidelines on how to initialise an ATM case study project, explains the way in which the ATM methodology works and how to implement it in an industrial setting. The case study proposal is the case study protocol (appendix 1), it was named proposal because the way in which the ATM methodology itself is implemented will depend on a number of factors, such as, the organisational culture, the company size, time and resources allocated etc.

3.8 Analysis of case study results

"In case study analysis, as in all types of research, the choice of approach is determined by one's research questions and one's analytic purposes" (Vogt et al. 2011). Vogt et al. (2011) distinguish three broad purposes for undertaking case study research: theory building, refining and theory testing. When there are few theories to address one's question, the purposes is to discover causal relations among variables in the case(s) so as to begin to build a theory; when explanations of outcomes are interesting but underdeveloped, the research aims to refine existing theories; and finally, when the field and the theories have well-elaborated but competing explanations, one can aim to test one or more of these theories (Vogt et al. 2011). Because the current academic literature lacks a theory for the transformation of waste into profitable co-products, this research study has focused on revealing the causal mechanisms that enable such waste transformations. The case study research presented in this thesis also aims to generate a refined theory of "waste transmutation" (from unavoidable waste to profitable co-product, see section 4.2.4 for a formal definition).

"*The starting point of case-oriented theory testing is often a single, well studied case or a small number of comparable cases*" (Ragin & Schneider 2011); a qualitative outcome (i.e. a change that occurred over a specified period of time) of some sort is studied "*in order to identify the processes and mechanisms involved in the production of the outcome*" (Ragin & Schneider 2011). Under this research framework, four case studies were carried out in four different companies in the Northwest of the UK; these case studies were analysed within-case and in a cross-case manner as a way of generating theory.

3.8.1 Criteria for choosing cases and for analysing them

This case study research aimed to test and validate the theory and concepts, presented in Chapter 4Chapter 3 and Chapter 5, in a real world setting as a way of gaining knowledge about the manner in which they could be applied in industry. If this theory and concepts were to have a meaningful impact in solving the landfill issue (described in Chapter 1), they would need to be applicable to a wide range of industry sectors and readily adapted for small, medium and large scale organisations. From this perspective, it was decided to recruit companies from a wide range of industrial sectors and of different sizes.

Bearing the previous thought in mind, the companies taking part in this case study research were selected opportunistically, as is often done in ethnographic research and program evaluation (Vogt et al. 2011). In such instances, (Vogt et al. 2011) recommend the use of a combination of nine criteria for the analysis of a small number of cases: very similar cases (except for one outcome that is different), very different cases (except for one outcome that is the same), diverse or contrasting cases, typical or representative, extreme or unusual, deviant or unexpected, influential or emblematic, crucial or critical test case, and pathway or linking case. But before comparing the case studies in such a manner, it is important to analyse each case study separately in order to gain insight and to start building a theory of waste transmutation, the way in which this insight was generated is explained in the following section.

3.8.2 Analysing within-case data

"*Analysing data is at the heart of building theory from case studies, but it is both the most difficult and the least codified part of the process*" (Eisenhardt 1989), a key step to bridge the chasm between data and conclusions is to carry out within-case analysis (Eisenhardt 1989). According to Eisenhardt (1989) carrying out within-case analysis helps researchers coping with the deluge of data, within-case analysis typically involves detailed case study write ups for each case.

In this thesis, these write-ups are presented in Chapter 6, each provide a description of the implementation of the theoretical concepts developed in during the research. The case studies are presented according to a formal case study structure (shown in appendix 2) which was sent as a report to the companies. Generally, these write-ups are often simply pure description (Eisenhardt 1989), however; this thesis includes some analysis and insights that will be useful to the companies during their waste elimination quest. Further within-case analysis will be presented in chapter in Chapter 7 during the analysis of generative mechanisms in section 7.1.

3.8.3 Analysis of generative mechanisms

"*A generative mechanism is described as a trans-empirical but real existing entity, explaining why observable events occur. Mechanisms are mostly possible to grasp only indirectly by analytical work (theory building), based however on empirical observations*" (Blom & Morén 2011). Blom and Morén (2011) note that generative mechanisms are not real for not being directly observable; they actually exist in the social world. Generative mechanisms are contextually conditioned; auspicious conditions are necessary for them to occur, however, at a certain moment and under certain contextual circumstances, counteractions can entail that observable effects do not take place (Blom & Morén 2011).

Generative mechanisms will be analysed from a micro (waste stream), meso (organisational) and macro (legislative) social perspective in order to uncover the actual mechanisms that enable the transformation of unavoidable manufacturing waste into profitable co-products.

The analysis of generative mechanisms presented in Chapter 7 will use Blom and Morén (2011) methodology which consists in 5 steps:

1. Observation/description: observe and empirically describe the research object. This step is covered in the presentation of the case study results in Chapter 6.
2. Division and sorting: empirical information is analysed (dived up) into smaller entities. The insights gathered in each case study were classified and coded for further validation and comparison.
3. Abduction/redescription/theoretical reinterpretation: "*abduction means that single events or occurrences—by means of concepts theory and models—are described and interpreted as expressions of more general phenomena*" (Blom & Morén 2011).
4. Retroduction: is a form of inference/thought operation aiming to describe the generative mechanism that can explain a phenomenon.
5. Contextualization/concretization: explain events and processes in concrete situations (specific contexts) and how the mechanisms become manifest.

3.8.4 Cross-case analysis

(Eisenhardt 1989) suggests coupling within-case analysis with cross-case search for patterns as a way of counteracting people's poor information processing abilities. Cross-case analysis forces the researcher to look at the data in many divergent ways and can prevent the researcher from reaching premature, and even false conclusions, as a result of information processing biases (Eisenhardt 1989).

This research used two tactics for cross-case analysis suggested by (Eisenhardt 1989). First, the categories generated during the second step of the analysis of generative mechanisms' methodology (above) were analysed for within group similarities and then coupled with intergroup differences. The second tactic was to compare the cases and then to list the similarities and differences between each of them. "*Explicit comparison allows a wider range of research questions to be addressed than does the single case study*" (Vogt et al. 2011), cross-case comparison has been carried out as a way of building theory, as suggested by Vogt et al. (2011).

3.9 An overview of the PhD research project

The following text describes the different steps involved in producing and testing the contributions of my thesis. Showing the way in which the PhD project evolved will give an understanding of the research approach and the reasons for selecting the specific research methods.

1. **Literature review on general sustainability**

   This step provided the researcher with the key concepts about sustainability and the way in which companies are implementing it in the real world. The researcher proposes the "growth-ability" concept: the ability for companies to grow in the economy whilst contributing positively to the balancing of the ecosystem; in other words growth that restores the carrying capacity of the earth's life supporting systems.

2. **Ways to improve the sustainability of a company: state of the art review**

   The researcher learned about frameworks, methods, tools, techniques for sustainability. These ranged from the general, such as, eco-deign, biomimetics, product service systems, to the specific, e.g. DfS, DfX, PSS, eco-functional matrix.

3. **Resource efficiency and the landfill issue**

The researcher came to the realisation that in order to have a sustainable production and consumption systems, we need to have "truly sustainable" materials. The research was narrowed down to finding ways to divert more waste from landfill.

4. Literature review on waste in manufacturing

At this point it was necessary to revisit waste elimination strategies in the field of lean manufacturing and pollution prevention.

5. General theoretical propositions: the all seeing eye of business framework

From the literature I deduced a new framework to understand the nature and impact of waste on the profitability of a firm. It became evident that there was a need to upgrade “unavoidable waste” into value adding co-products.

6. Pilot case study

This pilot case study was started with the aim of testing the hypothesis that waste could actually be transformed into a co-product. It was also intended to give the researcher a first-hand experience of the necessary steps needed in order to transform waste into a valuable co-product.

7. Specific theoretical propositions: the ATM of waste

After some insights were gained in the field from the pilot case study, the ATM methodology was deduced in analogy to Shewart’s improvement cycle; its purposed is to guide engineers during the waste upgrading process.

8. Literature review on waste transformation technologies

This literature review covered journals related to waste management and waste recycling technologies, its purpose was to provide the researcher with an understanding of the advancements in the field and the know how knowledge that companies would need in order to transform waste into a co-product.

9. Tool development: the wheel of waste

From the literature review on waste technologies, the researcher induced a set of fundamental uses of waste which were incorporated into a design tool that uses a specific language used in the field of waste management.

10. Literature review on case study research

A literature review on case study research methods was conducted in order to gain the necessary knowledge to implement and test the theoretical propositions in a real industrial scenario. After this literature review, a case study protocol that was developed, this in turn, was later used to obtain research ethics approval.

11. Recruiting case study participants

Several large multinational companies were contacted through the industrial liaison board at the University of Liverpool, however none of them signed up to test theoretical propositions described to them in the case study protocol. Almost all the companies in the case studies were signed up through opportunistic sampling technique during networking sessions at NISP events.

12. ATM implementation

The ATM was implemented almost simultaneously in the case studies.

13. Literature review on qualitative analysis techniques

Given the number of case studies and the results collected, the researcher selected analytic analysis, mechanism analysis, and cross-case analysis as the most suitable methods.

14. Case study write up

All the observations and results were compiled and each case study was written up according to the case study structure format.

15. Analysis of case study results

Generative mechanism were identified and analysed in order to refine the ATM methodology. The results of the case study were also compared in cross-case analysis to draw generalizable knowledge.

16. Discussion

17. Conclusion

Chapter 4. Theoretical propositions

This chapter will introduce two frameworks to help in the reduction of waste at different stages of a product life cycle. As pointed out in section 2.1.5, waste should be prevented during the early design stage of product development, a framework dubbed “Fit Thinking” is proposed to be used during this stage. The other proposition introduced in this chapter is the “All Seeing Eye of Business” (ALL-SEB); this framework helps companies understand the nature, impact and potential uses of manufacturing waste. The understanding that the ALL-SEB provides is crucial in the deployment of management/corporate strategies to reduce manufacturing waste sent to landfill (as discussed in section 2.1.1).

This thesis proposes ways to remediate waste at the ‘end of the pipe’ but it also recognises the importance of waste prevention at the ‘front end of the pipe’. The development of a waste prevention framework is based on the premise that companies that realise the impacts of waste on profits might eventually look for long term strategies to prevent the waste in the first place. The theoretical propositions presented in this chapter are the findings to the research questions of the first stage of the research (see section 1.3). This findings have also been published on the Journal of Cleaner Production; for further reference and a more compact reading, see Bautista-Lazo and Short (2013).

4.1 Waste prevention through “Fit Thinking”

Elaborating on the idea of waste prevention, which is considered a higher aim than waste elimination (as discussed in section 2.1.5), the “fit thinking” framework is proposed as a way to integrate knowledge about product design and the insights from the Kano model in order to create a framework for the design of products that create customer satisfaction whilst using the optimal amount of material and energy.

As pointed out in section 2.1.5, it has been established that "*good design results from fit between the functionality of the product and user's needs and expectations*" (Ravasi & Stigliani 2012). The Kano model shown in Figure 2.2 provides insight about the way in which products create customer satisfaction given a balanced mix of must-be, one-dimensional and attractive requirements. The fit thinking framework will use two sets of three parameters to understand the interaction between product design and customer satisfaction. On the one hand, customers express a set of needs, requirements and expectations (NRE) for a given product experience. On the other hand, products need to fulfil such requirements providing function, features and wow factors (FFW) that create customer satisfaction in accordance to the three parameters of the Kano model. The interaction between customer's NRE and product's FFW determines the degree in which a product generates customer satisfaction (as explained by the Kano model described in section 2.1.3).

"Fit Thinking" is proposed as a framework to design products that use the exact amount of resources (material and energy) to satisfy a complex set of customer's NRE. This is achieved by providing products with FFW that "fit and meet" precisely the customers' NRE with effective cost and quality and in a timely manner. Elaborating on Ohno's diagram of Figure 2.1, Figure 4.1 is a representation of the Fit Thinking framework.

Scientists have come to the conclusion that reasoning by analogy is at the chore of human cognition (Gentner, Holyoak & Kokinov 2001; Hofstadter & Sander 2013; Schauer 2008) and "a key component of expert and professional decision making" (Schauer 2008). Hofstadter and Sander (2013) highlight that although analogical reasoning is not deductive, it constantly provides insightful inferences that lead to hypothesis generation on the basis of existing knowledge. The proposed fit thinking framework uses the analogy of a rotating shaft (representing a product's material and energy – M&E) that needs to mesh precisely with grooves in a mating piece (customer's NRE) in order to be able to transfer torque (value). Customer's NRE determine the amount of resources that a product should have in order to provide FFW that generate customer satisfaction; this level of resource intensity is represented by the size of the rotating shaft. The timeline arrow represents Ohno's original idea of waste elimination: from the time a company receives an order to the time they receive the cash. The double head of the arrow represents the interactive relationship between the product and the consumer: the customer shapes what FFW the product must have, but customers' NRE can also be shaped and created through marketing. Following the sufficiency strategy for cleaner production (Schaltegger et al. 2009), the Fit Thinking framework show how companies could persuade their customers to accept the loss of FFW that do not add significant value, thus reducing the cost and environmental burden of the product. The elimination of non-physical types of waste ultimately leads to the elimination of physical waste and vice versa. For example, eliminating unnecessary transportation and handling of materials reduces the consumption of energy and fuel. Eliminating non value adding FFW consequently eliminates the production steps and the energy and materials necessary to create them.

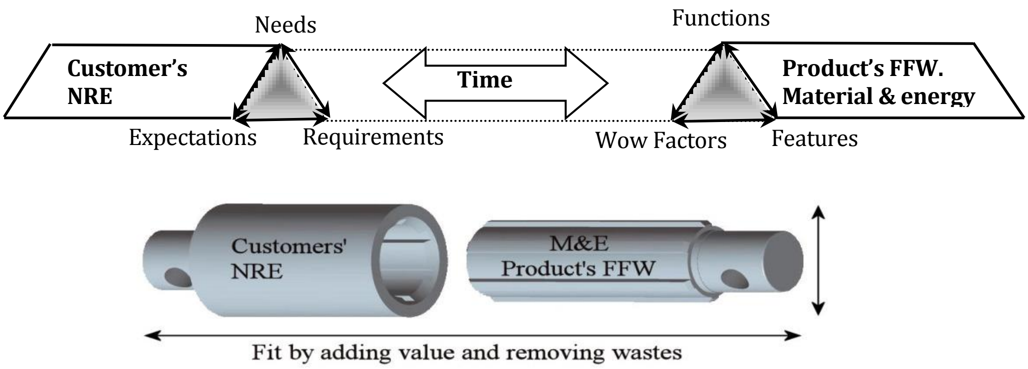

Figure 4.1 Graphical scheme of the Fit Thinking framework

Within the Fit Thinking framework two types of worst case scenarios can be considered:

- Designing products that "under meet" and therefore do not fit the customers' NRE leads to unsalable, underperforming products that rapidly become waste;
- Designing products that over meet the customers' NRE leads to high cost and high quality products that over use resources. In addition, if this second type of product cannot be sold due to the high cost it will probably enter the waste stream more rapidly.

These two worst case scenarios form the ground where the apparent dilemma of quality engineering against value engineering is raised. Fit Thinking is the balance of two seemingly counteracting strategies in product design: "lean thinking" against "robust thinking". These types of seemingly confronting concepts pursue the same goal: satisfy the customer while making a profit (van den Brekel 1974).

4.2 Introducing the "All Seeing Eye of Business" (ALL-SEB).

Whilst Fit Thinking aims to reduce waste through addressing the early stages of product design, some waste is often unavoidable, as discussed in section 2.1.2. This section therefore introduces the ALL-SEB, a new model for understanding the impact and potential uses of waste, built on an understanding of the concepts explained in Chapter 2.

In particular:

- Material flow cost accounting, providing the concepts of product output and non-product output (section 2.1.2);

- The Kano model for customer satisfaction, used as an analogy of the three different ways in which waste has an impact on profit (section 2.1.3);
- Kanthal's demonstration that different products have a different level of impact on profitability (section 2.1.3).

The ALL-SEB was built using critical theory following the research trends in management studies, this "school of thought" has been used to analyse accounting, information systems, marketing, operational research, and human resource management (Alvesson & Willmott 1992). In his introduction to critical theory and the management of change in organisations, Carr (2000) outlines what Critical theory is what it is and what is not—particularly in the field of management. For the purposes of this section it is only important to highlight that the purpose of the ALL-SEB model subscribes to this school of thought whilst aiming to produce knowledge that seeks to help companies divert waste from landfill (an emancipatory interest leading to praxis). Through a critical epistemology, critical theory rejects the self-evident nature of reality and acknowledges the different ways in which reality is distorted (Carr 2000). The focus of critical theory is not just to mirror "reality" as it is, but to change it, in the words of Carr (2000): "theory is only critical if it is explanatory, practical and normative at the same time" The All-SEB subscribes to the explanatory, practical and normative stance of critical theory .

The construction of the ALL-SEB based on the Cartesian plane facilitates the study of waste and it's relation to profit using the dialectical process of critical theory. The dialectic process begins with a thesis, reflection progresses and this thesis is seen is seen to encompass its "antithesis" as part of its very definition; in this dynamic relationship of interdependence, contradictions emerge which in turn promote the generation of a new totality (Carr 2000). Carr (2000) describes this process involving three "moments": thesis, antithesis and synthesis; it is also acknowledged that the synthesis becomes a "new working reality" and may, in turn, become a thesis. The triadic structure of Hegelian thought is not simply a series of building blocks but "*a process wherein the synthesis absorbs and completes the two prior terms, following which the next triad is absorbed into the next higher process*" (Carr 2000).

The ALL-SEB will be explained in three stages: firstly, the meaning of each of the four quadrants of the graph in relation to profit will be described (thesis-antithesis relationships); secondly, each quadrant will be discussed in detail (synthesis), explaining three degrees of profit per quadrant (in analogy to the Kano model); finally the model will be presented in its entirety.

The ALL-SEB was built in a similar way to the Kano model, but with the x-axis representing dialectic concepts of product/non-product output (PO/NPO) and the y-axis showing the dialectic concepts of profit/loss (P/L). The logic of the Cartesian plane dictates the nature of the relationship between these two oppositional planes: NPO generates loss whilst PO generates profit. Based on this logic, the first part of the model is shown in

Figure 4.2 shows **saleable product output** (a positive outcome for society, as opposed to waste) creates profit (a positive financial outcome) and is represented in the first quadrant (PO, P) of the Cartesian plane. The opposite third quadrant (NPO, L) shows non-product output (a negative outcome for society) in relation to the monetary losses associated with **waste**. In addition to non-product output, **unsold product output** is added to the third quadrant because resources were used without providing a service to society; therefore such products become waste and cause financial loss.

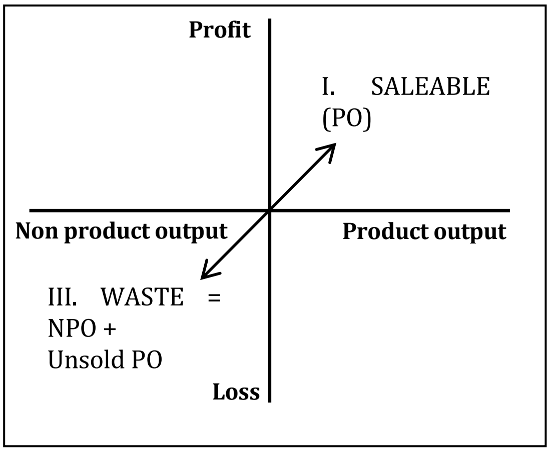

Figure 4.2 Product output and non-product output quadrants in relation to profit.

Synthesizing the dialectical relationship between these two planes; two further planes were conceived in a way that opposes and negates the first set of quadrants according to the logic of the Cartesian plane: NPO generates profit whilst PO generates loss. At this point it is important to take into account Nadler (1990)' observation that Descartes' deductions of the laws of nature did not constitute a confirmation or validation of the laws, "*these are to be confirmed empirically, a posteriori, by recourse to their agreement with the phenomena*".

Further analysis of the literature reveals the real existence of these two phenomena: PO could be priced at a loss and NPO can be used to generate profit.. Not all products being sold contribute to gross profit. The term "loss leader" pricing (also known simply as leader pricing) has been defined as a pricing strategy in which retailers set very low prices, sometimes below cost, in order to lure customers into stores (Hess & Gerstner 1987), therefore the name "**loss output**" for the fourth quadrant (PO, L). "Loss leader" products (positive as product output but negative with respect to the financial loss) are shown in Figure 4.3.

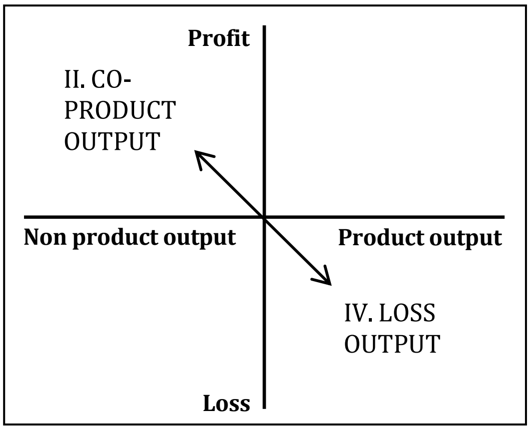

Figure 4.3 “Cash your waste” and “loss leader” quadrants

Figure 4.3 also depicts the second quadrant (NPO, P) named Co-Product Output where, theoretically, non-product outputs yield profit. An organization that transforms waste into saleable co-products is in fact moving NPO to the profit side of the y-axis; this could be considered a “cash your waste” strategy. Revision of the literature confirms that this strategy is not only theoretically sound but it has been proposed in the steel industry; Koros (2003) suggested that non-steel by-products (i.e. dusts, scale, slag, sludges) of the steel industry offer significant potential for costs savings or profits if reintroduced to the industrial metabolism. Subscribing to Clift’s (2004) views on waste, the term **co-product** was chosen because it implies a purposeful activity aiming to obtain profit, as opposed to unintended by-products that need to be addressed, as (Clift 2004) points out, the word co-product makes a difference.

In their simplest form, the diagrams presented above are tools to educate firms that eliminating NPO makes business sense. Jasch (2009b) exemplifies how businesses are indeed wasting up to 61% of the cash value of purchased materials by producing high levels of NPO. Progressive industries and companies are no longer losing profits as a result of waste generation; in the food sector, vegetable waste is being upgraded into value added co-products (Laufenberg, Kunz & Nystroem 2003).

4.2.1 Levels of profitability for product output

In this second level of design, the ALL-SEB model is refined by synthesising the relationship between the two concepts in each quadrant. This relationship is explored using the triad thinking of thesis, antithesis and synthesis. This thinking method is deemed important in business studies because it helps to take a self-critical view of the proposed solutions to a problem (Friedman 1995). Each quadrant of the ALL-SEB is similar in purpose and composition to the Boston Consulting Group's growth/share matrix and, as it is the case with the BCG model (Seeger 1984), the ALL-SEB only provides an easy to understand (and powerful) description of the quadrants.

The Kanthal effect provides evidence that different products have varying degrees of impact on profitability. Based on this understanding, the ALL-SEB framework is built, by plotting the amount of product output against profitability, a line which reflects the material intensity per unit of profit (MIPP) is created. The MIPP concept includes the effects of brand and profit mark-up on profitability and thus cannot be used to measure resource efficiency—as plotted by Nocera (2010)—or environmental impact [as shown by Clift and Wright (2000)]. Instead, MIPP provides a measurement of profitability efficiency in terms of material intensity, i.e. $£_{\text{(profit)}}/\text{kg}_{\text{(product)}}$. This proposed measurement would help managers identify and measure the sources of profit (or loss) in the firm's production output.

As outlined in the literature review, section 2.1.3, the firm's profitability objectives could be described in terms of maximizing and satisficing objectives (Hague 1971); customer's product satisfaction could be understand in terms of must-be, one dimensional and attractive attributes (Berger et al. 1993); consumer purchasing behaviour could too be studied in terms of maximizing and satisficing behaviour (Schwartz et al. 2002). By means of analogical reasoning, the ALL-SEB uses the dichotomy of the maximising VS satisficing behaviour explained by (Hague 1971) and (Schwartz et al. 2002) in order to generate two opposing MIPP concepts (maximizers and satisficers) for each of the quadrants in the model. In order to improve the accuracy of the ALL-SEB, a third concept is synthesised in order to transcend the dichotomy between the maximising and satisficing concepts; thus each quadrant of the ALL-SEB can be divided into three parts, as can be seen in Figure 4.4. This triadic thinking requires that the conditions and circumstances of the whole be taken into consideration in order to overcome the effect of the "lifeless diagram" criticised by Horkheimer (Carr 2000). Furthermore, "dialectic is a more supple form of thought than mathematical inference" (Carr 2000). The ALL-SEB model explains higher order relationships of the concept under scrutiny and opens the door to new possibilities by exploring unexamined assumptions and comparing these with the resonance of existing knowledge (Carr 2000).

There are infinitely many possible syllogisms (number of divisions) to be drawn in Figure 4.4, but there is only a finite number of logically distinct types, which we classify and enumerate below. These three types of categories serve to explain a product's role as part of a product mix and can be explained in analogy to the Kano attributes:

- Maximizers: require low amounts of product output to generate high levels of profit.
- Satisficers: provide linear contributions of profit in relation to amounts of product output.
- Enablers: generate low levels of profit and tend to have high levels of product output.

Hague (1971) noted that firms display maximizing or satisficing behaviours when setting profit objectives. It is natural to see these strategies reflected in the profit margins of their products. **Maximizers** are the ultimate expression of doing more with less, products that are effective in the generation of profit and efficient in the use of resources. **Satisficers** are competitive products that have not achieved the "star" status of the maximizers. Enablers on the other hand have a different function. In his analysis of advertisement strategies, Simbanegavi (2008) explains why goods could be sold at a loss (loss output) or simply at reduced margins but still at a profit (enablers). Equilibrium is characterized by loss leader pricing when differentiation is low, but when products are sufficiently differentiated firms may afford to make a small marginal profit by selling low margin leader goods. These low margin products enable and facilitate the sale of other items in the product family, hence the name "**enablers**".

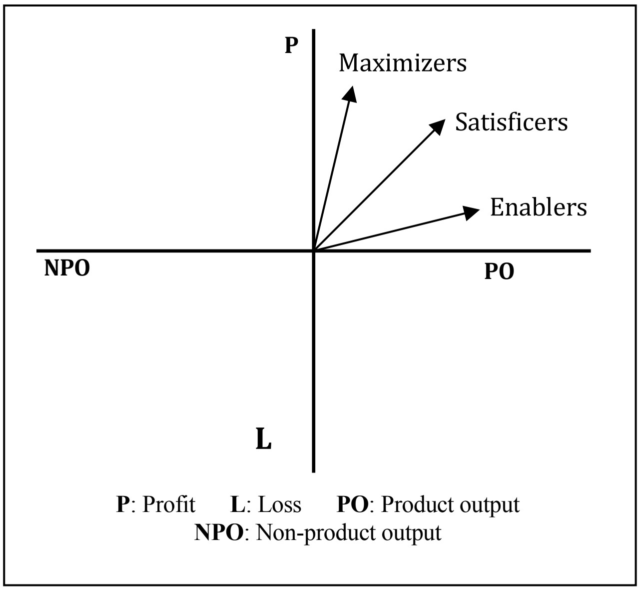

Figure 4.4 Profitability analysis of product output

4.2.2 Degrees of loss in product output

This quadrant comes from the propositions shown in Figure 4.3 which states that PO does not only generate profit but it could also become a source of loss. Using the dialectic process enables the synthesis of a triad of concepts that explain the nature and totality of products that belong to this quadrant:

- Strategic losses: product output that generates low levels of losses in spite of large output quantities.

- Loss leaders: product output that generates linear (controllable) levels of loss in proportion to output quantities.
- Critical losses: product output that generates large levels of loss in spite of small output quantities.

The literature on loss leader pricing was examined in order to test the proposed concepts with existing phenomena. A series of examples can be used to illustrate the "real world" existence of the above concepts (shown in Figure 4.5). DeGraba (2006) suggests that supermarkets selling turkey at a loss for Thanksgiving is an example of an effective "loss leader". This type of effective loss leader is herein dubbed a **Strategic loss** because it aims only to attract customers—in such strategies loss margins do not need to be big. Another example is the case of Gillette attaching free razors to a diverse range of targeted products in efforts to seed the market and collect profit from the replaceable blades they themselves distributed (Overfelt 2003). The Gillette case exemplifies a classical **Loss Leader** product output where the loss is considerable but controlled because it is in direct proportion to the quantity of razors produced and distributed. This model names **Critical loss** outputs products that have high margins of loss per unit of product. This can be exemplified in the aggressive strategy adopted by Microsoft towards the Xbox. Trying to enter the highly profitable video game market, the Xbox video game system was sold at a loss of more than $100 per unit in order to create greater potential for profit from the sale of higher-margin video games (BusinessWeek 2005).

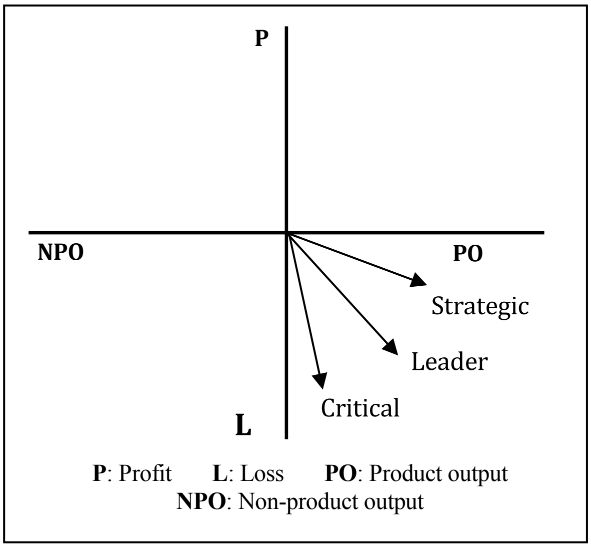

Figure 4.5 Degrees of loss in product output

4.2.3 Degrees of loss in non-product output

Understanding the nature of loss in non-product outputs proves more difficult because the generation of non-product output is caused by technological, organisational and economic variables at the same time. By means of dialectic reasoning it is possible to synthesize three concepts from quadrant III of Figure 4.2. The nature of this quadrant is described in terms of the following triad:

- Unavoidable waste: unavoidable waste due to limitations of physics or chemistry laws. The nature of this waste is such that even large amounts of NPO do not have significant impact on profits.
- Inefficiency waste: the generation of NPO is embedded in the current modus operandi of the production process and thus generates proportional amounts of loss.
- Error waste: Waste that in principle could have been prevented. Low amounts or sporadic generation of NPO generate significant levels of loss.

As discussed in section 2.1.1, it has been shown that there is waste that cannot be eliminated due to physics or chemistry principles. For example, the thermodynamic analysis of iron production by Baumgärtner and Arons (2003) exemplifies the magnitude of unavoidable and inefficiency waste. Losses due to **Unavoidable** waste could be considered a minor loss compared to the waste caused by inefficiency. In a way, some kind of unavoidable waste will always exist as background loss in production processes. Waste caused by **Inefficiency** has a higher impact in a company's profitability, but it could be reduced through continual improvement as proposed in the lean and six sigma literature for pollution prevention (Calia, Guerrini & de Castro 2009). Another type of waste represented in the model is that caused by a severe "nonconformity". This type of **Error** results in critical amounts of economic loss and may generate large quantities of waste in a short period of time. Accidents and system failures are included in this category because they are caused by errors that in principle could have been prevented. A clear example of waste caused by error is the "Deepwater Horizon" blowout, the largest offshore oil spill in history (Camilli et al. 2010). BP PLC has spent approximately $3.12 billion in response efforts (Dittrick 2010).

These three concepts are illustrated as degrees of economic loss per unit of non-product output in Figure 4.6.

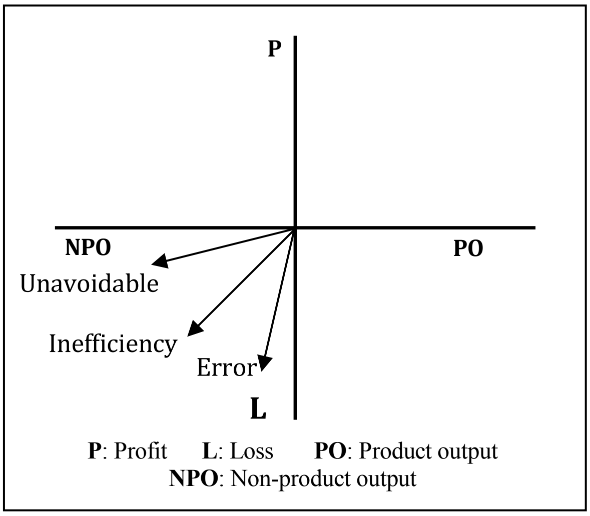

Figure 4.6 Analysis of loss in the non-product output

4.2.4 Degrees of profit in the "cash your waste" strategy

It was previously explained that waste output could be transformed into a co-product output (as depicted in Figure 4.3). Therefore, this quadrant can become subject of product output analysis—in analogy to 'enablers, satisficers and maximizers'. Three new concepts are proposed and shown in Figure 4.7; this triad describes the nature the cash your waste strategy and highlights the potential sources of profit.

- Salvage: NPO that is transformed into a co-product that adds low levels of profit.
- Upgrade: NPO that is transformed into a co-product that satisfies profit objectives.
- Alchemy: NPO that is transmuted into a co-product that adds high levels of profit.

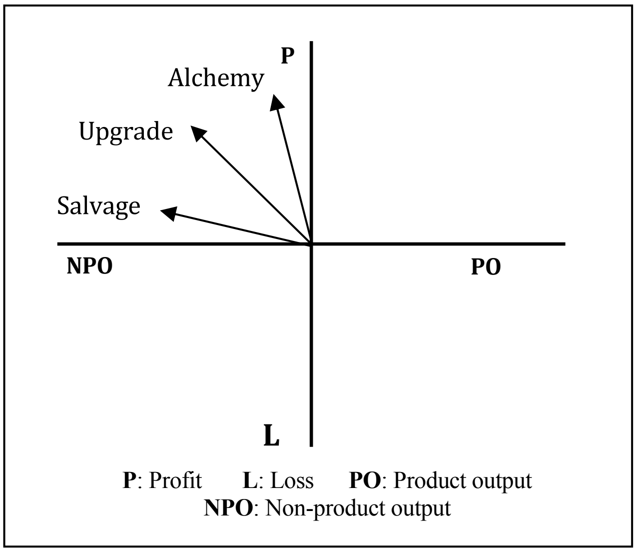

Figure 4.7 Analysis of 'cash your waste' strategies

At times given the level of technology, it may not prove feasible to eliminate waste completely; for example, reformulating an entire iron production process is neither practical nor economical. Thus there is a need to consider appropriate strategies for managing unavoidable NPO in production process. As proposed by Dyson (1941), the first option is to **Salvage** waste by transforming it into a low margin co-product; waste exchange symbiosis at scrap value illustrates this category. The second option is to **Upgrade** waste into a value adding co-product that increases profits and adds value to the customer—this concept taken from Friend and Cowan (1997). The ultimate option is the proposed concept of Alchemy: transmuting waste into a highly profitable co-product that adds value to the customer and becomes a stream of generous profit. This triad is aligned with previously proposed suggested by practitioners in times of material emergency: to salvage, reclaim and transform into by-products (Dyson 1941). Others have also classified waste exchanges in three types: direct match, waste upgrade and feedstock substitution (Friend & Cowan 1997).

In order to verify the existence of the deduced phenomena, the history of crude oil refining was reviewed. This industry provides some clear examples on the **alchemy** of waste. For instance, refineries used to treat gasoline as a useless by product that was left to run off into nearby rivers. Now central to some economies, natural gas was once fired as waste by-product. Also, petroleum jelly was discovered from a residue that had to be periodically removed from oil rig pumps. This historical alchemy of waste found in the oil industry could explain why modern petrochemical e-factor numbers (ratio of waste to desired product) are in the scale of 0.1, albeit this does not necessarily position them as environmentally friendly companies.

Cagno, Trucco and Tardini (2005) reported internal rates of return from Pollution Prevention projects; figures ranged from 1% to 433% with an average of 77%. Waste and cost reductions represented 60% of the primary objectives pursued by the companies in the study. In relative terms, in process recycling was identified as the most profitable type of project. This kind of recycling resembles the alchemic transmutation concept presented in this paper, from waste to a highly profitable co-product.

4.2.5 The All Seeing Eye of Business

It has now been shown that the outputs from a business consist of either product or waste, that product output can be sold at loss and that waste output can be transmuted into value adding co-products. These are the main four types of output that could be found at any profit seeking company. Each type of output has then been analysed in relation to profit levels, and represented on a graph, each quadrant of which can be further divided into three types of output. Each of the resulting twelve types of output has been described in detail, together with examples. The integration of these twelve types of output classified in four categories forms the All Seeing Eye of Business shown in Figure 4.8.

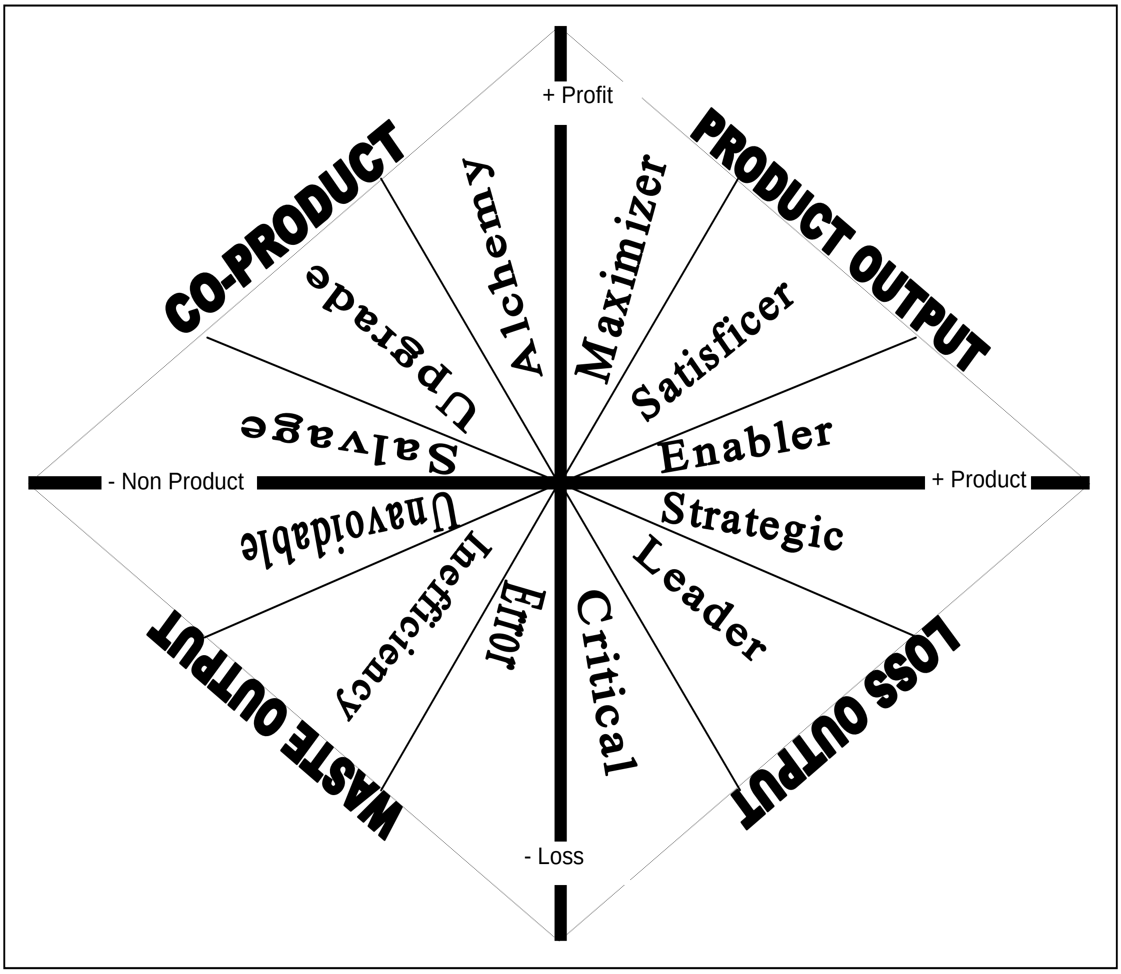

Figure 4.8 A tool for output analysis: the All Seeing Eye of Business

4.3 Theoretical validation

The model will be tested in industry as detailed in the methodology chapter of this thesis. However, the all seeing eye of business should be validated through examination of the waste management literature, to verify the existence of “waste transmutation” phenomenon in industry—or it may be just a theoretical construct produced by the model. The results of the literature search are shown in Table 4.1. This revision of the literature did not intend to carry out an exhaustive revision of the field; it merely seeks to find evidence of the proposed co-product output triad. The nature of the actual or potential profit is described in the column "driver" of transformation; the following examples were chosen in order to illustrate the potential for alchemic waste transmutations that could potentially generate high levels of profit.

Table 4.1 A selection of "waste transmutation" projects

Waste technology			
Original waste stream:	**Transformed into Co-product:**	**Driver**	**References**
Carbon slurry from the fertilizer industry	Adsorbent for the removal of anionic dyes	Low cost alternative to activated charcoal and 80% as efficient	(Jain et al. 2003)
$Ca(OH)_2$ and CaO from steel slag or concrete waste	Carbon sequestration in the form of carbonate minerals $CaCO_3$	Potential market for carbon credits valued at $ 70 million annually	(Stolaroff, Lowry & Keith 2005)
Fe(III)/Cr(III) hydroxide sludge	Adsorbent for waste water treatment	Reduces costs for treating waste water	(Prathap & Namasivayam 2009)
Road dust	Recovery of precious metals	There is approximately £60M of precious metals on the streets of Britain	(BBSRC 2009; Morgan 2010)
Leach waste from gold cyanidation	Cyanide recovery	Technology developed to prevent harmful environmental effects	(Gönen, Kabasakal & Özdil 2004)
Glycerol	Ethanol, hydrogen and formate	Adds value to an inevitable by-product in biodiesel production	(Hu & Wood 2010; Shams Yazdani & Gonzalez 2008)
Glycerol	Value added succinate	Could add value to glycerol waste producers and possibly future algae oil industries	(Blankschien, Clomburg & Gonzalez 2010)
Mussel shell waste	High purity calcium carbonate	Mussel shell roughly represents 31–33% of the mussel weight therefore raising high waste volumes and hygiene concerns.	(Barros et al. 2009)

Radioactive nuclear waste	Fuel for energy production	Technology in development: Nuclear hybrid, fast reactors and accelerator hybrids.	(Freidberg & Kadak 2009; Gerstner 2009)

The cases presented in Table 4.1 a waste stream have been identified as materials of interest because of their high value and/or hazardous to health. In all of the cases, there is the potential for high value co-products to be produced – for the waste "alchemy" suggested by the All Seeing Eye of Business. Ultimately the degree of profitability of such transformations will vary from company to company due to economies of scale, profit margin, efficiencies, type of customer and such other economic factors that were analysed in section 2.1.3 and will be further discussed in section 4.6.

It would therefore seem possible that combining the Fit Thinking framework for waste prevention (section 4.1) with the All Seeing Eye of Business may provide a means by which industry can understand, reduce and possibly profit from unavoidable waste whilst aiming to a zero waste to landfill status.

4.4 Discussion

It is proposed that the All Seeing Eye of Business illustrates the profitability analysis of a firm's output. It provides a clear picture of the sources of profit and loss. Break-even types of output have not been pointed out for the sake of elegance and simplicity, but their existence is acknowledged according to the logic of the Cartesian plane, these can be easily represented within the model as a line tracking along the x-axis.

Understanding that markets are diverse and complex, the model does not imply that all 12 categories of product are, or should be, present in every product mix. Not all companies operate in markets where there is a pressure for offering loss leader products. Neither do all companies operate in those profitable pools of the supply chain that allow for high profit margins: the

Maximizer products. Instead what is useful is a comparison amongst the family of products in the marketing mix.

When all products in a product mix are placed in the model, the resulting picture becomes useful to managers for the development of business strategies. The visual representation reveals where the efforts are being spent and where profits are coming from. By identifying the non-product outputs and quantifying the degree of loss (for example, by using the ISO/DIS 14051 standard for material flow cost accounting), firms will be able to make more informed decisions with regards to non-product outputs. Collecting all the information for each category will show a broad picture of the economic and environmental performance of the company. Combining information from profitability analysis and from material flow cost accounting makes a powerful analysis tool. For instance, consider the visual impact of seeing a loss leader product becoming a critical loss output, or consider plotting the amount of waste output caused during an accident (error). The lessons learned for the company will become a visual tool for change and improvement. As Bruce Henderson points out, in practice, consultants do not oversimplify their concepts when working with their clients (Seeger 1984). Consequently, the ALL-SEB should be used with a caveat; the model is useful to the extent that it can provide understanding about the sources of profit and loss in in relation to product and non-product output. At this stage of development it does not intend to constitute and exhaustive model for profitability analysis or product portfolio management. For instance, in order to apply the model to a "real world" scenario, the quadrants should be defined and dived with the rigour of Cartesian join operations in the feature space, as illustrated in (Ichino 1986) .

It is important at this point to highlight the Fit Thinking proposition; some features, functions and wow factors in the design of the product might be thought to be sources of waste. However, not having them may lead to products that cannot be sold, thus rapidly becoming waste.

The All Seeing Eye of Business is useful at illustrating waste types by origin, namely: unavoidable waste, inefficiency waste and waste caused by error. An important observation derived from the model is that unavoidable waste is the only type that should be reused and transformed into co-products, because it is the only type of waste that, due to technological and economic factors, cannot yet be eliminated. Waste caused by inefficiency and error should instead be eliminated and prevented by all means possible – particularly through Fit Thinking. Section 2.1.1 presents the way in which the framework for waste prevention and elimination has evolved from Ford's and Ohno's insights to the more academic concepts of lean thinking. Tools, methods and philosophies for the reduction of waste caused by inefficiency and error are abundant in the quality management literature, such as Total Quality Management and Total Productive Maintenance.

Given that loss outputs are not necessarily an undesired outcome, for example as part of a strategy to penetrate new markets, it may be appropriate to create co-products even if at a loss. For instance, a co-product could improve the environmental performance of a company and become part of the social corporate responsibility program. Transforming unavoidable waste into a co-product could represent a big challenge and might not always prove feasible, but in some cases, it might be the last step needed before achieving—and publicising—a zero waste status for the production process.

4.5 Limitations

Examples from existing literature have been provided across a variety of industries in order to demonstrate the concepts but, at this stage, no new case studies are presented. Therefore no proper comparisons can be made between the levels of profit or loss described in each of the four categories. Chapter 6 will provide specific examples using case studies in order to show evidence about the feasibility of transmuting waste into co-products. This transmutation is achieved using the “ATM (Analyse, Transform and Market) of waste”, a methodology that was developed to guide companies in the transmutation process—this methodology is introduced in the next chapter.

4.6 Implications for industry

Improving the sustainability of a company’s operations is not an easy task and some will agree that changing the mindset is even harder. Companies are in a constant struggle to survive, expand and grow in the midst of a “hot, flat and crowded” world as Thomas Friedman (2008) describes it. In fact some companies find themselves immersed in a vicious cycle of day to day operations that leaves little or no resources for improvement and innovation, thus becoming stuck in a situation of “short termism” (Repenning & Henderson 2010a). In the context of such operation environment, companies will struggle to change from a compliance approach to a strategic way of eliminating industrial waste in the way described by (Cagno, Trucco & Tardini 2005). The short termism scenario highlights the need to integrate environmental improvement measures (i.e. the elimination of waste) with the core of the business strategy (i.e. product portfolio management) and the pursuit of profits. This is the ultimate purpose of the All Seeing Eye of Business: to illustrate the current and potential sources of profit (and loss).

Transforming waste into co-products and seeking for alchemic transformations has some caveats. True environmental improvements would only be achieved if the transformation process is more efficient than using virgin raw materials. Therefore there is a need for a thorough life cycle assessment for each waste transmutation. The capital investment in order to achieve waste transmutations could be a deterrent for the projects to go forward and so the need is to find alchemic transformations that yield high profit margin products. As mentioned earlier, future technological advances could enable the complete elimination of waste thereby eliminating the need to upgrade waste at all; this factor could limit the amount of capital investment needed for such waste transmutation projects. So companies should always consider the case of redesigning the production process and adopting new technology or methods that prevent waste.

Beyond individual companies, waste transmutations present potential to the entire waste management industry. There are market opportunities for companies that specialize in waste transformations, mimicking scavengers in the food chain. For instance, waste collectors, skip hires and waste transfer stations, could position themselves to take an active role in waste transmutations and ensuring that waste stays inside the “industrial metabolism” in the form of co-products. Some waste transmutations could lead to the wastes returning safely to the “natural metabolism”. It is noted that by actively seeking to transform non-product output into profitable co-products, industry will become greener because ultimately all environmental impacts are caused by non-product output, dubbed waste in the broad sense.

The All Seeing Eye of Business could also be applied to the product itself, highlighting areas for improvement. Where products are identified to yield waste during their functioning, engineers may be in a position to analyse the economic and technical feasibility of recovering such wastes. For example, the fact that an engine requires a cold sink in order to function does not mean that the heat needs to be wasted; instead wasted energy could be recovered and put to use—for example Talom and Beyene (2009) provide a technological overview of heat recovery in automotive engines. It would be contradictory to have a zero waste plant producing wasteful products.

4.7 Summary and conclusions

This chapter introduced the All Seeing Eye of Business (ALL-SEB), a novel construct to focus business attention on output analysis and to create awareness about the true cost of waste and potential sources of profit (or loss). The model is based on concepts from environmental management accounting (material flow cost accounting), profitability analysis (the "Kanthal effect"), and customer satisfaction (Kano model). The model suggests that there are four categories of possible outputs from a production process: Product, Loss, Waste and Co-product. Each output can be broken into three possible degrees of impact on profit or loss, to give 12 output types in total. The role of each type of output was described and exemplified. It is important to understand each output type in order to effectively manage the product mix and design appropriate business strategies.

The research provides useful insights into the nature of waste. First of all, it is crucially important to eliminate waste at the design stage of production. Fit Thinking was introduced as a framework to illustrate the importance of dematerializing production, as long as it does not compromise the product's performance in the eyes of the customer. Where waste is unavoidable the All Seeing Eye of Business shows that it should be upgraded into value-adding co-products, in order to maximize profit. This approach suggests that an output is considered waste only as long as it does not provide a useful service to society, the environment or the economy.

The ultimate aim of the research is to show business the current and potential sources of profit and loss. It is hoped that such awareness will trigger business instincts and prompt appropriate actions to eliminate non-product output. Such business-driven actions have the greatest potential to solve the landfill challenge faced by many societies around the world. Keeping non-product output confined to the "technical metabolism" of industry prevents harmful interactions with the ecosystem. In this way, raw material consumption could be reduced, contributing to the creation of cleaner and more sustainable production systems.

Chapter 5. New methods for waste elimination

The ALL-SEB model presented in the previous chapter proves that companies could transmute NPO (non-product output) into profitable co-products as a strategy to divert waste from landfill. Based that theoretical proposition, this second stage of research provides answers to the 'how' question posed in section 1.3: how to help industry improve resource efficiency and divert waste from landfill? In line with the functionalist paradigm of business research described in section 3.4, this chapter presents the practical solutions that could help companies divert waste from landfill. The pragmatic approach of this research project called for the development of a method that could provide answers to the 'how' question; this research strategy resulted in the development of ATM methodology, a method that aims to help companies transform NPO into profitable co-products.

The proposed ATM methodology is constructed under an objectivist ontological position; objectivism assumes that companies have a reality of their own (compliance with industry legislation and internal standard procedures). From this position the research did not take into account the input of the social actors (employees) in order to solve the waste generation issues within the company. Instead, the research proposed solutions deduced from the existing body of knowledge (the ALL-SEB) and used independently developed solutions (i.e. the ATM of waste) in order to solve the waste problem.

The first step to solve the generation of waste within a production process is to understand the nature and impact of waste using the ALL-SEB. In order to achieve this understanding waste should be analysed in a systematic way. The Deming cycle (PDCA) and the DMAIC (define-measure-analyse-improve-control) methodologies for continuous and performance improvement provide the basis for the general framework and the ATM of waste methodology.

This chapter proposes a bottom up approach for tackling the waste problem in industry. Starting at the "end of the pipe"—identifying physical waste; then, asking questions about the nature and characteristic of waste in order to implement a combination of remediation, minimisation and prevention strategies as a way of achieving the ultimate ideal: zero waste status.

5.1 A general framework for waste elimination in industry:

This framework adapts the steps of two quality improvement methodologies: The PDCA (plan-do-check-act) and the DMAIC (define-measure-analyse-improve-control) described in (Snee 2007) and analysed by Sokovic, Pavletic and Pipan (2010) in terms of main characteristics, strengths and limitations. The general framework for waste elimination uses a pragmatic approach to propose a series of steps that help companies eliminate waste in a holistic manner.

1. **Waste identification**

The objective here is to quantify the amount of waste generated and to calculate the true cost of waste in order to have information to select an operation to be improved. A useful guide for achieving this objective is the international standard ISO 14051; it provides a framework for implementing material flow cost accounting.

2. **Waste analysis**

2.1 Analyse the origins of waste: cause and type.

Analyse the nature of waste, determine the root cause of waste. Thermodynamic and exergy analysis are means to discern to what extent waste is caused by inefficiency and the extent in which waste is an unavoidable outcome. Another less common type of waste is the waste caused by error. The all seeing eye of business is a model that can be used to understand the impact of these types of waste on profitability.

2.2 Description and characterization of waste.

It is important to understand the composition of waste, to do this, laboratory test are sometimes required.

2.3 Analyse the implications of generating waste.

As proposed in section 4.1, the lean thinking framework shows to what extent waste could be embedded in the product design. Having unnecessary functions, features and wow factors will generate excess use of materials which in turn affects the environmental and economic performance of the product in the next stages of the life cycle and across the supply chain. These considerations should be analysed at this stage in order to choose the best course of action for waste elimination.

3. Waste elimination strategies

3.1 Design a waste elimination strategy for each level of action.

PREVENTION: waste must be prevented at the design stage; methods such as design for six sigma (Yang & Basem 2008), dematerialization strategies (Van Der Voet, Van Oers & Nikolic 2004) and design of product service systems (Baines et al. 2007) provide guidelines for achieving this goal.

MINIMISATION: The literature on quality and productivity provides a wide range of tools and methodologies for the minimisation and elimination of waste during production lean manufacturing and total quality management are good examples.

REMEDIATION: Only if waste is unavoidable or if it has already been produced it should be remediated at the "end of the pipe". The concept of industrial symbiosis proves useful for the reuse of waste within an industrial network. The ATM methodology presented in this chapter (below) is designed to upgrade this type of unavoidable waste into co-products. If a company is still analysing the technical and economic feasibility of eliminating waste, then, temporal corrective actions should be put in place in order to recover the lost value from waste.

3.2 Devise and implement an action plan to eliminate waste

3.3 Implement waste elimination measures

4. Waste monitoring

4.1 Monitor resource efficiency in the organization

4.2 Measure the efficacy, efficiency and effectiveness of the implemented actions.

5. Continuous improvement

5.1 Identify and assess improvement opportunities.

5.2 Introducing the ATM of waste: a new methodology to Analyse, Transform and Market unavoidable industrial waste

Unavoidable waste remains waste only as long as the beholder treats it as a non-product output, as shown in Figure 4.8, unavoidable waste has the potential to become useful to society in the form of a co-product, if that is not possible, it should be returned safely to the ecosystem. Ideally, the transformation should contribute positively to the economic system as a whole.

Designing a co-product requires a different approach compared to conventional product design methods. A co-product's design brief contains initial conditions that affect the entire design process; the material's characteristics and properties are given, not chosen. It is important to, first, analyse and fully understand the nature and origins of the waste before proceeding to describe and characterize it in terms of its physical and chemical properties. Based on a deep understanding of the nature of waste and its characteristics, it becomes possible to develop sound ideas for potential co-products. Key questions must be answered in a systematic way; the following paragraphs describe the steps in the proposed ATM methodology (Figure 5.1):

Analyse:

- Analyse the waste in order to identify a value adding capability as a co-product.
- What purpose or function can the waste provide given its state and structure?
- What would be the performance of this function, given the waste's state and structure?
- Can the waste's state/structure be improved?

Transform:

- Design a production process to transform waste input into the desired co-product output.
- Is the transformation process (waste to co-product) technically and economically feasible?
- Is the estimated production price competitive in the market place?
- Is there a business case for investment?

Market:

- Identify and analyse the market potential for the desired co-product.
- Is there a market need for a co-product with such function?
- Who are the customers and possible competitors?

- What are the customer needs, requirement and expectations?
- Is there a market opportunity for such a co-product?

The three design stages are closely intertwined and interdependent as illustrated in Figure 5.1.

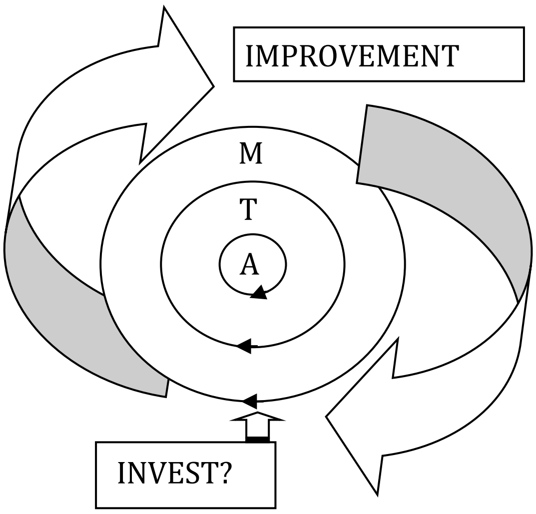

Figure 5.1 The ATM of waste (Analyse, Transform and Market)

Whilst analysing the potential uses of waste one needs to consider if there are customers willing to buy the co-product, therefore market research becomes important, but only up to a certain level of detail. Whilst designing waste transformations, sometimes, technically feasible solutions do not exist; thus, co-product ideas should be abandoned. The opposite is also possible; technically feasible solutions that are uneconomic to implement. An iterative design cycle integrates these three stages of the methodology as a way to address such issues in increasing levels of detail.

5.3 The wheel of waste: a tool for idea generation

To aid companies in the analysis of waste transformation opportunities, a tool for idea generation was developed, see Figure 5.2. This tool is based on a review of the literature on waste remediation projects; six fundamental uses of waste were induced from the analysis of waste transformation technologies published in the literature. The tool was developed from a pragmatic approach; a classification table was built in order to keep track of the research papers. The idea for a tool was conceived when concept saturation occurred; all further papers could fit into any of the 6 categories. This fundamental uses of waste are described an exemplified as follows:

1. **Store**: Storing waste is the least desirable option; it is what landfills do in an unsystematic way. Nuclear waste is stored for safety concerns. If there is no alternative, waste could be stored in a systematic way in order to facilitate its recovery when that becomes viable, for instance: mining landfills is becoming a profitable proposal (van der Zee, Achterkamp & de Visser 2004); nuclear waste could be reused in hybrid nuclear power plants (Freidberg & Kadak 2009).
2. **Combine**: Wastes could be combined to obtain new properties suitable for useful products. For example, unrecyclable thermoplastic rejects and foundry sand are combined with a steel mesh to manufacture manhole covers (El Haggar & El Hatow 2009).
3. **Extract**: Valuable substances could be extracted from waste streams, this is a common approach in the food and metal industry, see for example (Gönen, Kabasakal & Özdil 2004; Mokrejs, Langmaier & Mladek 2009).
4. **Replace**: Waste output could become a substitute material; up to 80% of fly ash can replace clay in bricks with properties superior to conventional red clay bricks (Sarkar, Singh & Kumar Das 2007)
5. **Function**: A waste output has the potential to perform useful functions; for example, activated carbon from coconut coir pith is

an effective and economical adsorbent for the removal of Cd(II) from wastewater (Kadirvelu & Namasivayam 2003).

6. **Incorporate**: Waste could be incorporated to other processes as feedstock. An example is the use of red mud aluminium waste as a basic component for new high strength construction materials (Mymrin & Vazquez-Vaamonde 2001).

This fundamental uses of waste are combined with the PSSP (purpose, structure, state and performance) language introduced in the theory of waste management (Pohjola & Pongrácz 2002); PSSP are the four universal properties that objects can have. Changing one of the properties would alter the nature of waste; as a consequence, new uses for the waste would become available, such is the basic mechanism for multiple combinations and idea inspiration.

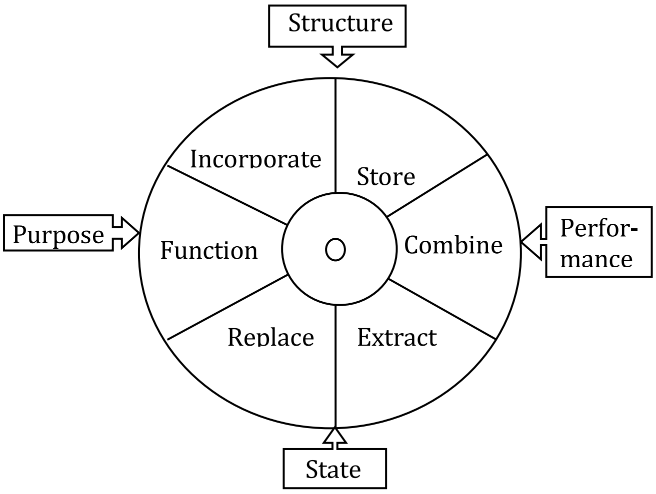

Figure 5.2 The wheel of waste

5.4 Discussion

The ATM methodology is based on the premise that waste output has the potential to become a useful co-product that adds value to the customer; a serious limitation is that this is not always technically or economically feasible. For that matter, the “all seeing eye of business” points out to other approaches that do not add high levels of profit. Salvaging materials and exchanging it at scrap value is always a last option. Even if transforming waste into co-products does not prove to be an economically feasible option, companies should consider doing it for other strategic reasons, such as improving the environmental credentials and corporate responsibility. In that case companies will treat waste as a strategic co-product with a relatively small economic loss.

The general framework does suggest analysing the thermodynamic nature of waste in order to determine to what extent waste is unavoidable, although a necessary step, it is not an easy calculation; the same case applies to material flow cost accounting. Small companies might struggle to find the expertise to make those calculations.

In spite of the above mentioned weaknesses, the general framework for waste elimination and the ATM of waste is simple enough to understand and implement if an organization has a culture for quality and improvement. It is perceived that the major limitation is the research capability of the company when it finds itself trying to device a waste transformation processes that goes beyond the area of expertise.

Chapter 6. Case study results

This chapter presents the case study results of implementing the theoretical propositions presented in Chapter 3. These theoretical propositions were implemented within the proposed methods for waste elimination described in Chapter 5. Each case study is presented according to a standard case study structure that was sent as a report to the companies taking part in the research. As explained in the methodology chapter (section 3.8.2), the case studies presented in this chapter also contain a degree of within-case analysis and insights that are considered useful to the company.

Four companies located in the Northwest of the UK took part in this case study research. The first case study served the purpose of a pilot case study and allowed an understanding of the implications of implementing the ATM methodology in a real industrial scenario. The results of the first case study (described in section 6.1) demonstrated that the ATM methodology had the potential to transform unavoidable waste into co-products. Case studies are presented in a chronological order; each case provided further insight into how to improve the theoretical propositions, thus cases vary slightly as the research progressed. The three other companies were contacted at several industrial symbiosis networking events organised by the National Industrial Symbiosis Program (NISP). Table 6.1summarises the case studies and the implementation stage reached in the ATM methodology. The following case studies were also sent to companies as case study reports, so they should be read as separate entities.

Table 6.1 Summary of ATM case studies

Case studies/Stage	A	T	M	Findings
1. 1st Choice concrete and skip hire	X	X	X	The project diverted to a generic co-product already in the market.
2. Senior Aerospace BWT	X	X	X	Waiting for implementation
3. James Dewhurst	X	X	X	Waiting for implementation
4. Yorkshire copper tube	X	X	X	Waste minimisation strategy

The three last case studies were all selected opportunistically as suggested by (Eisenhardt 1989) on the grounds of unique features and theoretical sampling. This three companies attended a NISP event entitled “Waste not, want not – your trading place for manufacturing waste”, at the Suites Hotel, Knowsley, on Thursday 3rd November 2011 from 8:30 am to 1:30 pm. Each company presented a resource form that contained the following sections:

- Resource Haves: in this section please provide full details of any resources you have that someone else may want. Please provide a full description, quantity / volume, location of resource and availability (e.g. available now, or available in May 2012)

- Resource Wants: in this section please provide full details of any resources you want that someone else might have. Please provide a full description, quantity / volume, final destination of resource and supply requirements (e.g. 1 tonne required per month)

- Ideas to explore: Please use this space to detail any ideas you would like to explore with other companies, and the types of relationships you would like to build with other organisations. For example: Company X would like to work with other category 3 food waste producers in Merseyside to invest in a “community” anaerobic digester.

The event was run in a networking type of environment where members were moved systematically across different tables in order to provide opportunity for interaction. Each member in the table would read out loud the resource haves/wants or ideas to explore. If a match was made, information was exchanged for further discussion. These were the circumstance under which the companies were formally contacted during the NISP event.

The NISP event provided with a selection of companies actively looking to divert waste from landfill by means of industrial symbiosis. This situation provided the opportunity to compare the performance of the ATM methodology with the solutions from the NISP program; in other words, this setting could allow the comparison of industrial symbiosis solutions with alchemic transformations and analyse which approach generates larger cost savings or profits.

6.1 Case study one. 1st Choice concrete and skip hire

6.1.1 Company introduction

Based in Kirkby, Liverpool, 1st Choice concrete and skip hire limited (1st CCSH) are proprietors of a large licensed waste transfer station; the company operates in several market segments: large construction sites, medium size projects and domestic work.

6.1.1.1 Products and production process

1st CCSH offers a number of products and services, including: skip hire, concrete (with recycled content), waste management, site clearance, recycling, demolition and just recently SMR (structural material for reinstatement).

6.1.1.2 Rationale for case study selection

Testing the methods and concepts proposed in the theoretical research required running a pilot case study, ideally in a simple and small scale setting with a friendly environment. At this stage of the research it was needed to verify hypothesis number one in order to gain an understanding of industry's reactions towards "the all seeing eye of business", thus initiating the first iteration to improve the model. This first case study also provides the learning ground for case study research methods, therefore, it was required that it takes place in a local small firm, ideally with a simple production process. A contact that was readily available was chosen for the purpose of this first case study.

1st CCSH's operations as a recycling centre and waste transfer station proved to be a good ground to test the theoretical propositions of the research, firstly because they already deal with different types of waste streams from the construction industry and secondly because they operate on small and medium size projects. Being a small family owned company, first choice also provided a friendly environment to implement the first version of the ATM methodology. Initial introduction to the company was made through their IT consultant.

6.1.2 Implementation of the Methodology: context

During the first site visit to 1st CCSH, the all seeing eye of business (All-SEB) model was introduced and explained to the site manager and to the company proprietor. Using the understanding provided by the All-SEB, the company immediately identified their critical loss output and major source of profit loss: construction and demolition soil waste (C&DSW).

The C&DSW is collected as part of the waste management and skip hire operations, construction and demolition waste is screened out to separate recyclable material to be used as aggregate in the concrete manufacturing; the residue from this operation is the C&DSW which is being stockpiled for further cleaning and treatment. If sent to land fill, the C&DSW would need to be transported which would incur in additional costs; landfill gate fees and penalty taxes should also be added. Given the large volumes of the waste (an approximate estimate is 20,000 tonnes) the land fill alternative is clearly not a viable option, just based on future cost projections.

6.1.2.1 Initial conditions

1st CCSH initially suggested the idea of producing top soil from the C&DSW. The company had been receiving requests for topsoil from their customer base; so, on those grounds the top soil idea was chosen as the ATM project objective.

6.1.2.2 Special circumstances

This case study was selected opportunistically as it is recommended by (Eisenhardt 1989) in order to take advantage of unique case features. A talk about the PhD project was given at the rotary club in Formby. After the event, two persons from industry approached to ask further questions and to provide valuable contacts from their networks. This is how the IT consultant of 1st FCCSH was first met. From this meeting a site visit was arranged and the waste transformation project was promptly started—after agreement with the company proprietor. It should be noted that an initial eagerness to collaborate might have been built on the grounds of the introduction made by the company's IT consultant (providing confidence on the method due to his position of authority as a consultant); this situation could have made it easier for the company to admit that the C&DSW was a source of profit losses and that corrective action was needed. This situation, however, has no direct impact on the implementation of the ATM methodology.

6.1.2.3 Analysis of the company's operations using "the all seeing eye of business"

The All-SEB helped the company realize that the C&DSW was not only a waste stream with high disposal costs; but that it was actually a source of profit losses, and as such, the waste stream could also be transformed into a profitable co-product. Given the known demand for topsoil from their customer base and the understanding provided by the All-SEB, the company decided to undertake further research to investigate how to transform the C&DSW into different grades of top soil. Additionally, being in the waste management sector, the company would like to improve their recycling targets, so transforming the C&DSW into a useful co-product was deemed to be the most favourable alternative not only because it would add potential profits but because it would also improve their green credentials.

6.1.3 Implementing the ATM methodology

6.1.3.1 Analyse

The Analyse phase of the ATM methodology was unnecessary because the company was pursuing a specific co-product output (top soil). However, in spite of this, additional ideas were generated during the analysis phase as secondary alternative.

a) Gardening topsoil

Turning C&D soil into top soil was suggested by management; however this waste upgrade alternative seems more competitive because top soil produced from farms has a natural advantage in terms of quality and cost. In this light, other alternatives must be explored before committing to this solution.

b) Brownfield regeneration

There is potential to manufacture topsoil and subsoil from C&D soils for use in brown field regeneration projects, such as the Lambton Cokeworks reclamation scheme; now part of National Coalfields Regeneration Programme. Dr Robin Davies of Soil Environment Services Ltd. was appointed the soil scientist and might be able to provide advice in soil remediation techniques; the brown field regeneration project is explained in detail in the following links:

1. http://www.soilenvironmentservices.co.uk/
2. http://www.englishpartnerships.co.uk/coalfields.htm

There are 7 coalfield sites listed in the northwest region, these are overseen by National programmes, Arpley house, 110 Birchwood, Warrington WA3 7QH Tel: 01925 651 114 email: coalfields@englishpartnerships.co.uk

Working with English partnerships might facilitate access to funding from the Northwest Regional Development Agency (NRDA) in order to develop a technology to transform C&DSW into topsoil designed specifically for brown field regeneration sites.

c) Alternative strategy: The magic pot.

To develop a soil remediating nursery pot, using tree and plant species known for their soil remediation qualities. The remediation system in the pot may include bio-char (derived from recycled wood) and a thin layer of activated carbon. This remediation system will benefit cities, bringing life back to the city whilst remediating the soil. The use of the magic pot in the cities will ensure that if leachate occurs, it will be directed to the sewage system for further treatment. The business benefit will be the reduction of costs and processing time, compared to the manufacture of topsoil, the magic pot will take less time to assemble and less time to bring revenue. An example of innovation in this market sector is the air-pot for super-roots http://www.superoots.com/. It might be interesting to seek for joint venture or partnership.

d) Use as filling material

Other suggested uses for C&DSW include its use as material for landscape and golf course construction, filling material for road works and other construction projects. The main challenge is to ensure that the soil has an adequate environmental performance, in order to achieve that, a cost effective soil remediation system for large soil quantities would need to be developed.

e) The landfill irony

Construction and demolition soil is actually a useful product as a landfill daily cover (assuming that the soil's environmental performance is acceptable); thus, in principle, a landfill tax credit should be obtained when C&DWS soil is deposited in landfills.

6.1.3.2 Transform

Current soil remediation techniques are expensive and energy intensive. It was proposed that further research and development should be carried out to design a soil remediation method specific for C&DSW, however, it was not possible to find a research program that could fund this project. In order to produce high quality top soil it was suggested that better segregation methods must be implemented at collection point and that this higher value C&DSW is kept aside for further treatment. A soil remediation company will provide the quote for the clean-up of the segregated waste stream.

6.1.3.3 Market

If top soil made from C&DWS is to be a competitive product, it must be match or surpass the quality and cost of competing products. Two companies were identified as the benchmark in the regional market.

a) The compost shop

Contact information: Orrell Lane, Liverpool, Merseyside L38 5DA. Telephone: 0151 929 2003. www.thecompostshop.co.uk. This company sells screened top soil (10mm) at a price of £41 per tonne. A larger delivery of 10 tonnes is sold for £204. The quotes include VAT and delivery to the L69 post code area in July 2010. [5]

b) Country garden supplies

Contact information: Little Ferny Knoll Farm, Ferny Knoll Road. Rainford. St Helens, Merseyside WA11 7TQ. http://www.turfsoilgravel.co.uk Telephone: 01695 50792.

This company has two products that will be competing directly against First Choice Ship hire's propositions, these are the following:

- Topsoil grade one (2 tonne): mixed and blended to the clients requirements, with a pH of 6.5. This company provides daily deliveries around the northwest of the UK and nationwide. The quoted price for delivering to the L69 area was £65 including VAT and delivery.
- Topsoil grade two (10 tonne): is suitable for turfing and for building up levels. Tipped loose is a very cost effective way of bringing large amounts of topsoil. A quote for the Liverpool area is £165 including VAT and delivery.

6.1.4 Results

Existing soil remediation techniques are expensive and energy intensive. It was decided that a passive soil remediation technique must be developed and tested, this was the main challenge for upgrading the C&DSW into a co-product; the company lacked the research capability to move the project forward and desk research did not discover additional contacts either.

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[5] At the time of writing the thesis, the company had closed its operations.

Throughout the project an alternative solution to making top soil emerged. In October 2008, the joint Government –Industry Strategy for Sustainable Construction committed to halve the amount of construction, demolition and excavation waste going to landfill by 2012; reaching 2011 the commitment had been signed by 602 companies from across the supply chain (WRAP 2011a). 1st Choice concrete and skip hire ltd., saw this as an opportunity to move into the structural material for reinstatement (SMR) market, thus abandoning the project to upgrade C&DSW into top soil.

As a waste prevention measure, the researcher suggested finding ways to prevent further contamination of the C&DSW at the collection point. The proprietor and site manager pointed out that it was possible to allocate a special bay for unloading high quality top soil removed from selected sites.

6.1.4.1 Impact of ATM analysis

The all seeing eye of business model highlighted that C&DSW is not only a cost but a source of profit losses; the framework showed the potential to make profit from C&DSW. The proprietor agreed with these observations and in a way it echoed what the company already knew and what they wanted to achieve.

6.1.4.2 Steps taken as a result of ATM analysis

- Sources of funding to research and develop cost effective methods for passive soil remediation were sought.
- The company committed to taking preventive measures to prevent further contamination of the C&DSW.
- The company entered the SMR market using the C&DSW as a raw material input.

6.1.4.3 Description of the co-product

1st Choice concrete and skip hire describes the co-product as following:

"SMR (Structural material for reinstatement) has proven repeatedly that it can be used to encapsulate contaminants in contaminated soil. This enables the client to re-use the existing contaminated spoil on-site by reducing the leach-ability of the contaminants in the spoil to safe levels. The contaminated spoil can then be used as a structural material that will actually outperform traditional backfill materials. With the small number of non-hazardous landfill sites remaining and even fewer hazardous landfills available, the SMR solution cuts out huge transport distances and even larger disposal costs. As an example, SMR has been used on the following contaminants and constantly proved successful in encapsulating these contaminants: heavy metals, PAH, TPH, asbestos and diesel. Use of SMR on remediation projects has resulted in significant savings being achieved compared to other methods."

"On-Site Machine Mixing: the SMR solution can be adopted by the use of our mobile mixing plant. The plant can easily be transported to site where it will process up to 30 tonnes of excavated spoil per hour. This processed material can then be placed back into the road in place of Type 1 granular sub-base (GBS) material. The benefits that customers gain from this are: no landfill costs, no quarried aggregate costs, no transport costs, decreased carbon foot print, significant cost savings, and the benefits of using a backfill material (SMR Premixed) that outperforms Type1 GS".

The Highway Authority and Utilities Committee (HAUC) publishes the specification for the reinstatement of openings in highways (SROH) in which it recognizes SMRs as alternative reinstatement materials that may offer significant environmental or practical advantages, and/or cost benefits, compared with conventional materials. The SROH defines SMRs as a generic group intended to include proprietary or alternative bound reinstatement materials that include a cementitious, chemical or hydraulic binder or are inherently self-cementing (HAUC 2010). The SROH recognises four types of SMRs:

- Foamed concretes for reinstatements
- Flowable SMRs
- Non-flowable SMRs
- Hydraulically bound mixtures

The waste and resources action programme (WRAP) also carried out a study to determine the carbon impacts and cost benefit analysis of trench reinstatement options. Overall, the study demonstrated that recycling trench arising material resulted in a reduction of CO_2 emissions, estimated to be up to 40%, whilst indicative costs were up to 35% lower than the landfill scenario (WRAP 2011b).

6.1.4.4 Process

A machine was purchased to process the C&DSW (spoil).

6.1.4.5 Cost

The associated capital investment with regards to the SMR process is not known.

6.1.4.6 Profit

Since the last phone call, the company was still building a customer base and getting the necessary permits to initiate operations, so, the company was not in a position to report profits at that point in time.

6.1.5 Discussion: review of the methodology

From the beginning of the project, the implementation of the ATM methodology was directed towards the production of top-soil; hence the Analyse phase of the methodology was not very substantial. Although the analysis phase was not a major part of the project at 1st CCSH, it was realised that a systematic approach was needed to search for potential co-product transformations. Initial ideas were generated after reading the literature on construction and demolition waste, others emerged after talking with construction experts; it was observed that without a system and without in-depth knowledge of a field it was not possible to generate more ideas.

6.1.5.1 Attributable benefits to the company

Using the all seeing eye of business, the company was prompted to embark in a research project to transform the C&DSW into a profitable co-product. Throughout the course of the project, the company has found a readily available technology that transforms C&DSW into a profitable product on site, SMR.

6.1.5.2 Impact of the methodology in the decision making process

The ATM methodology revealed the need to design a large scale and cost effective remediation treatment for the large quantities of contaminated soil generated as result of 1st CCSH's operations. Overcoming this technological barrier would enable 1st CCSH to transform C&DSW into a range of co-products.

6.1.5.3 Interaction with the company

The ATM of waste was implemented in the setting of an external consultant. In this setting, the company's role was limited to providing all the necessary information and support to enable the researcher generate and propose solutions. The main contact was the company general manager who oversees all operations at the Kirkby site. The "short termism" described by (Repenning & Henderson 2010b) was observed, the general manager was very busy attending the day to day requirements of the business. This situation left the waste transmutation project in the low priority agenda.

6.1.6 Lessons learned

Implementing the All-SEB in a real world scenario highlights three important factors to consider during the implementation of the ATM methodology. First, it was noted that a formal method was needed in order to calculate the loss from the waste output and the profit from co-products. Second, as discussed in section 6.1.5, it was observed that companies would benefit from using a systematic approach during idea generation during the Analyse phase. A tool is needed to help problem solvers to systematically generate potential waste transformation ideas to be tested for feasibility. Lastly, although the theoretical concepts were implemented according to a case study protocol, it was observed that the theoretical concepts would be easier to implement if they were part of a coherent framework for waste elimination; on that basis, a "grand scheme" for waste elimination in manufacturing is needed.

6.1.7 Improvement of the ATM methodology

It was after this first case study where the adoption of the ISO 14051 standard for material flow cost accounting (MFCA) was included in the general framework for waste elimination described in Chapter 5, section 5.1. The need for a tool for idea generation also stems from this case study, the "wheel of waste" tool described in section 5.3, helps companies generate theoretical waste transformations for further feasibility analysis. The proposed "grand scheme" for waste elimination is the general framework for waste elimination described in section 5.1; the framework aims to eliminate waste at three strategic levels and brings together the theoretical propositions generated during the development of the research project.

6.2 Case study 2 - Senior Aerospace BWT

Senior Aerospace BWT (BWT) designs and manufactures ultra-lightweight low pressure air distribution and insulation systems. The company is part of Senior plc - a group of international manufacturing companies - with operations in 11 countries manufacturing and marketing components and systems (i.e. thin-walled flexible tubing and related high performance products) for principal OEMs in the worldwide aerospace, automotive and specialised industrial markets. BWT is located in an 85,000 sq. ft. purpose-built facility in Adlington, Macclesfield. Today BWT employs around 400 staff. Senior Aerospace BWT's product family includes:

- Flexible ducting
- Rigid ducting
- Silencer ducting
- Ducting insulation
- Fuselage insulation

The production process is based on the hand lay-up of composite materials; the company manufactures gypsum mouldings required during the hand lay-up step. Once the product has cured, the product is retrieved by breaking the gypsum moulding; this manufacturing step is the origin of the waste stream in this particular case study. The company produces around 8 tonnes of broken gypsum per month which incurs in disposal costs of around £4,000 annually.

Gypsum moulds are prepared by adding water to the casting plaster and preparing a paste with a specific consistency. The paste is then poured into wooden master moulds and left to dry and harden.

6.2.1 Implementation of the ATM methodology: context

BWT was first contacted at a NISP (National Industrial symbiosis programme) event. The company presented a list of “resource haves” which became the starting point for the case study project. The company was contacted from this first meeting at the event using the case study proposal to explain the aims of the case study. Once approval was received from the Health and Safety Co-ordinator, a site visit was arranged.

The Health and safety officer lead a walking tour of the production process and pointed out where the waste was being generated. During the site visit, it was decided that the gypsum waste could be a good starting point because it accounted for the higher volume of waste output (8 tonnes per month). The health and safety officer (HSO) provided further information about the gypsum waste (material safety data sheets). During the site visit the HSO also pointed out that the gypsum had already been sent in an industrial symbiosis reuse in agricultural land application. However, for reasons unknown to the HSO the industrial symbiosis was terminated.

The moulds are currently the best available production method for BTW’s requirements and thus gypsum waste seems to be an unavoidable waste stream that cannot be prevented or minimised. Additionally, the perceived degree of complexity for transforming unavoidable gypsum waste into a co-product was relatively simpler than transforming any of the chemical wastes into a co-product. So, given the early stages of development of the ATM methodology, this waste stream seemed to be a good candidate.

The gypsum waste is generated as a result of breaking the gypsum moulds during product retrieval. Product retrieval is carried out with care and skill in order to prevent product damage. The gypsum waste collected from the product retrieval is kept segregated; this waste stream consists only of broken gypsum moulds of varying shapes, and sizes. The size ranges from flakes and dust to large gypsum mould parts up to 50cm. It should be noted that the gypsum mould parts are relatively fragile and easy to break with a hammer, but because there are no size requirements for waste disposal, the gypsum waste stream is put into an outside skip without further size reduction processing.

6.2.1.1 Initial conditions

The case study starts with an interest of the company in diverting waste from landfill; this interest is expressed by attending the NISP event and the willingness to collaborate in a research project to produce potential co-products from their waste stream.

6.2.1.2 Special circumstances

The implementation of the ATM methodology was carried out by the researcher in coordination with a team of two Health and Safety Officers that attended the NISP event. The health and safety officer had the responsibility of managing the waste stream and thus was in charge of overseeing the ATM project. During the course of the case study, one of the health and safety officers took a leave of absence and transferred the case study project to the Health and Safety Co-ordinator who was mostly overwhelmed with work and had this project in the low priority category. This situation caused some delays in the provision of information (e.g. section 3.4 of Appendix 3) and more importantly, it delayed the implementation of the proposed solutions.

6.2.2 Waste elimination strategies

The all seeing eye of business (All-SEB) postulates that there are three types of waste according to its origin: unavoidable, inefficiency and error (see section 4.2.2). The understanding provided by the All-SEB suggests that only unavoidable should be transformed into co-products; manufacturing waste should be prevented during process design and minimised during operation. Three waste elimination strategies were analysed in order to verify that the gypsum waste was actually an unavoidable waste stream under the given current conditions and circumstances.

6.2.2.1 Prevention

The moulds are a tool necessary for the hand lay-up of composite materials. Unless the entire production method changes, i.e. using 3D printing techniques can be adapted for printing moulds, gypsum moulds remain the best available technology and will generate unavoidable waste as a result of product retrieval.

6.2.2.2 Minimisation

The amount of waste could be minimized by optimizing the thickness of the moulds; however, the room for improvement is minimal since the company already considers this when optimising drying time: the thicker the mould the longer it takes to dry.

6.2.2.3 Remediation

It was concluded that the gypsum moulds are a type of unavoidable waste; a necessary auxiliary material in the manufacturing process. The last alternative is to upgrade the broken gypsum moulds into a high value co-product using the ATM of waste.

6.2.3 Waste transformation strategies

Waste transformation strategies have been identified in four areas of the industrial system. Exploring waste transformation strategies in each area provided an understanding on how to best integrate the quantity and quality of gypsum waste into the industrial ecosystem.

6.2.3.1 Intra-process reuse

Theoretically, the gypsum could be recycled onsite for its reuse in the moulding process again and again until performance drops to undesirable levels. However, in practical terms setting up such a process would be very complex and would require significant investment; the process would require crushing the gypsum moulds and then milling it to a powder, mostly before calcining, though occasionally calcining may precede grinding (Karni and Karni 1995). Given the volume of gypsum produced (8 tonnes per month) and due to a lack of economies of scale, recycling this waste stream onsite would be impractical and not very efficient using conventional machines; although, the possibility exist for entrepreneurial companies to design small scale gypsum recycling machinery for this potential niche market. Another barrier is with regards to the quality control of the recycled gypsum; the company lacks the necessary metrology equipment and expertise for this task. It is also not known the number of times that plaster can be recycled (due to the accumulation of impurities) whilst maintaining the required level of quality. So, for those reasons the intra-process reuse of gypsum is discarded.

6.2.3.2 Inter-process reuse

No other processes in the plant could make use of gypsum.

6.2.3.3 Reuse in the regional metabolism

Recycling gypsum: broken gypsum moulds could easily be reprocessed by the manufacturer, because no other additives are added during the moulding process. However, the company does put a coat of wax on the moulds in order to ease the retrieval of the finished composite product, but this should not be an issue because wax traces would be minimal and would burn during the calcining step of gypsum hemihydrate production.

There are various plasterboard and gypsum recyclers e.g. Tadrebe premier waste management, Saint Gobain, Mid UK Recycling, Speedilinerecycling, Roy Hatfield Plasterboard Recycling. However, none of these companies could offer a viable recycling alternative; some of them would not take gypsum moulds because they specialize in plasterboard recycling and others were too far away from Macclesfield to make transportation costs affordable.

Other uses within the region might be possible, e.g. animal bedding; however, for this to happen, the gypsum will need to be further processed, this alternative would be analysed with the ATM methodology in section 6.2.5.

6.2.3.4 Reuse in the market place

The ATM methodology was used to generate a proposal for transforming the gypsum waste into a co-product that could be sold in the market place at a profit. For example, recycled plaster could be used to fabricate reinforced plaster using the other waste streams in the factory: fibreglass blanket, aramid fibre, glass fibre scrim trimmings, etc.

6.2.4 A general framework for waste elimination

6.2.4.1 Waste identification

Create a waste map of the production process. This step was already complete by the company, the health and safety office had produced a list of waste streams generated at the manufacturing site (Table 6.2). A site visit was arranged in order to see the production process at work. Figure 6.1 illustrates the steps in of the production process.

Table 6.2 BWT's resource haves presented at the NISP event

Resource Have (Description)	**Quantity / Volume**	**Availability (frequency / duration)**
Aramid fibre fabric (Kevlar)waste Product made from continuous filament aramid fibres with a nominal diameter of 10-14 µm	100 kg	Every month
Casting plasters waste Mix of the Crystal R and water (gypsum based plaster)	8 tonnes	Every month
Lagging material waste Ultra core aircraft insulation (fibreglass blanket)	100kg	Every month
Glass cloth / scrim waste Loom state glass fabric finish	100 kg	Every month
Chemical waste Mix of Dichloromethane >95% & plastic granules	800 kg	Every month
Chemical waste Silicone/polyurethane sludge c/w solvent 90% mixed PU/Silicone, 10% cyclohexane	300 kg	Every month
Wood waste Scrap timber, pallets	1 tonne	Every month
Cardboard waste Packaging	1.5 tonne	Every month
Food waste Food waste from the company canteen (400 employees)	800 litres	Weekly
WEEE Computers, monitors, cables etc.	300 kg	Every quarter
Plastic wheels For cables/ wires – new (white and black) 8" x 8"	720 (4 pallets)	One off

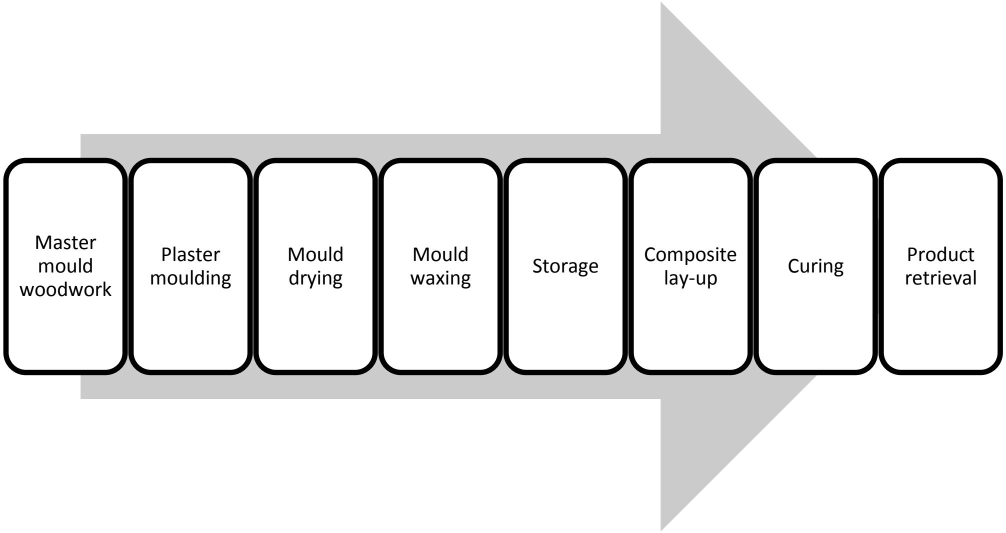


Figure 6.1 Senior Aerospace BWT's production process

6.2.4.2 Select a production step for waste reduction activities

The Health and Safety Officer is in charge of the waste management of the site; it was agreed with her to start working on the gypsum waste stream because it represents the largest output in terms of volume (8 tonnes) and because of the perceived degree of simplicity in transforming the gypsum waste stream into a co-product.

6.2.4.3 Understand the current and potential sources of profit (or loss)

Senior Aerospace BWT did not need to implement the All-SEB because the company already had identified specific sources of waste where the ATM methodology was needed. However the company was briefed about the All-SEB and were advised to undertake calculations to find out the true cost of waste using the general framework for material flow cost accounting outlined in the ISO standard 14051:2011.

6.2.4.4 Identify and quantify the three types of waste (Unavoidable, Inefficiency and error)

Table 6.3 shows the manufacturing waste generated by Senior Aerospace BTW's production processes.

Table 6.3 Classification of manufacturing waste at Senior Aerospace BWT

Waste stream	**Quantity**	**Availability** *(frequency / duration)*	**Waste type**
Aramid fibre fabric	*100 kg*	*Every month*	*Unavoidable:* trimmings are necessary to shape the fabric to the mould.
Casting plaster moulds	*8 tonnes*	*Every month*	*Unavoidable:* casting plasters are moulded to provide the shape for laying up the composite materials; the moulds have to be broken for product retrieval.
Lagging material	*100kg*	*Every month*	*Unavoidable:* trimmings are necessary to shape the fibre glass blanket to the mould.
Glass cloth / scrim waste	*100 kg*	*Every month*	*Unavoidable: t*rimmings are necessary to shape the fabric to the mould.
Mix of Dichloromethane	*800 kg*	*Every month*	*Inefficiency:* the dichloromethane mix consists of left over resin which becomes useless after a period of time due to exposure.
Silicone/polyurethane sludge	*300 kg*	*Every month*	*Inefficiency:* the sludge mix consists of left over resin which becomes useless after a period of time due to exposure.
Wood waste (timber and pallets)	*1 tonne*	*Every month*	*Unavoidable: o*ffcuts are necessary to shape the timber wood into master moulds. Wooden pallets are classified as waste caused by *inefficiency*.

6.2.4.5 Calculate the true cost of waste in order to determine its impact on profit

A material flow cost accounting spreadsheet was prepared to calculate the true cost of waste. All cost were identified and classified, however due to confidentiality issues the cost data could not be provided for this project.

6.2.4.6 *Design an action plan for the elimination of the types of waste identified*

It was out of the scope of the case study research project to eliminate waste caused by inefficiency and error, so no action plan was proposed. The target relevant to the research project is to transform unavoidable waste into a profitable co-product.

6.2.4.7 *Set up measures to eliminate waste caused by inefficiency and error*

An idea for waste minimisation was suggested for consideration in further improvement projects within the quality management system. This is an idea for the minimisation of chemical resins (mix of dichloromethane and mix of silicone/polyurethane).

Problem: The resin mix is contained in open top plastic containers and applied using a brush. This situation permits the evaporation of the resin and the concentration of high amounts of VOC (volatile organic compounds).

Proposed solution: Design a self-contained resin dispenser that works like the Dishmatic™ dish brush, as seen on http://www.dishmatic.com. This resin dispenser could provide a number of benefits, for example:

- Improve health and safety by reducing work exposure, due to the fact that the resin is contained in an enclosed environment.
- Improve efficiency resin of application. Due to the elimination of time and motion steps necessary when the brush has to be dipped into the resin container and carried to the working piece.
- Prevent resin waste. The dispenser could preserve the life of the resin for a longer period of time.

6.2.5 Implement the ATM methodology for the selected unavoidable waste stream

As pointed out previously, this case study focusses on the 8 tonnes of gypsum waste because it is the largest quantity of waste and also a relatively safe material to reuse or recycle.

6.2.5.1 Analyse

Naturally occurring calcium sulphate is commonly known as natural gypsum, it is found in nature in different forms, mainly as dihydrate ($CaSO_4$ x 2 H_20) and anhydrite ($CaSO_4$). They are products of partial or total evaporation of inland seas and lakes (Karni & Karni 1995).

Shortly after mixing the casting plaster with water, setting begins, dihydrate ($CaSO_4$ x 2 H_2O) is formed and the material hardens. Karni and Karni also point out that the strength of hardened gypsum derives directly from crystallisation of the gypsum. Growth and interlocking of contacting crystals impart strength to the gypsum paste. Himsworth (1947), as cited by Karny and Karni (1995) , classifies calcium sulphate in three hydration states: anhydrite, which contains no water of crystallization; gypsum, which contains two water molecules; and hemihydrate (or semihydrate), which contains less water than the gypsum. So, in this light, the casting plaster used in BWT becomes gypsum when the water is added and the paste is formed into moulds.

The next step was to study the physical and chemical characteristics of the casting plaster used in the manufacturing of the moulds; a good starting point to gather information was the technical data and the safety data sheet provided by the plaster manufacturer. The plaster used in BWT is identified as Crystacal R, manufactured by BPB formula this document describes the casting plaster as an off white odourless powder with neutral pH, chemically stable and unreactive. The chemical composition of the casting plaster is principally calcium sulphate hemihydrates and natural constituents, which may include clay, limestone, and trace amounts of quartz. Minor amounts (less than 1.0%) of other additives may be included. The chemical formula is: $CaSO_4 \times 0.5\ H_2O$

The CAS registry number assigned by the chemical abstract service is 26499-65-0. The EINECS number (for European inventory of existing chemical substances) is: 231-900-3. The casting material is commonly known as Plaster of Paris.

The manufacturer publishes an A-Z list of gypsum properties and applications. Using this information as a starting point, it was easy to generate ideas for potential waste transformation using “the wheel of waste” tool described in section 5.3. This idea generation tool was used to generate 25 ideas for waste transformation (Table 6.4); this table describes potential co-products and lists its potential customers. The co-products are described in four columns using the PSSP (Purpose, Structure, State and Performance) language: Table 6.4 states the new *purpose* for the waste stream, it shows the level of change required in order to make the product useful (*structure*), it lists the required transformation process to make the product useful (*state*) and, lastly, when information is available, it lists the performance of the described co-product (*performance*).

Table 6.4 Waste transformation ideas for gypsum waste

	Waste transformation	Description	Potential Customers	Purpose	Structure	State	Performance
1	Ceramic material	Plaster's absorption properties are key to producing quality ceramic pieces.	Producers of Fibrous Plasterwork, Glass Reinforced Gypsum (GRG) and GRG column casings as well as creating technically challenging dry-lined suspended ceilings and linings. http://www.ryedaleinteriors.co.uk/about.asp (Leeds. LS11 5XA) Cornice mouldings. http://www.ossettmouldings.com/gesimse.html (DEWSBURY WF12 7RQ) Producers of Fibrous Plaster Cornice & Mouldings http://www.ukplaster.com/ (BOLTON BL6 5QE) GRG Mouldings, drywalls. http://www.ceilingandpartitions.com/grg-mouldings.php (Warwickshire. B80 7BW)	Building material	Pulverized	Ground	-
2	Aggregate for concrete	Plaster is used in construction materials for its capacity to adhere to a variety of surface backgrounds.	Concrete mixed onsite. http://www.aardvarkconcrete.co.uk/ (Stockport, SK4 2BE) Bagged and loose aggregates. http://www.bradshawaggregates.co.uk/aggregates.php (STOCKPORT, SK3 8LF) Pre-cast and ready mixed concrete. http://www.welslot.co.uk/concrete_recycling.html (Carrington M31 4QJ)	Strength	Broken gypsum	Crushed	-
3	Aggregate for concrete	Plaster is used in construction materials for its capacity to adhere to a variety of surface backgrounds.	Concrete recycling company. http://www.welslot.co.uk/concrete_recycling.html (Carrington M31 4QJ)	Adhesive	Pulverized	Ground	-

Table 6.4 Waste transformation ideas for gypsum waste

	Waste transformation	**Description**	**Potential Customers**	**Purpose**	**Structure**	**State**	**Performance**
4	Cement manufacturing	Cementitous binder.	Leading supplier of heavy building materials to the construction industry, clay brick manufacturer, solvent recycling and waste processing. http://www.heidelbergcement.com/uk/en/hanson/products/cements/index.htm (national)	Adhesive	Pulverized	Ground	-
5	Cement Manufacturing	Gypsum is added to clinker (raw cement) to prevent cement from setting too quickly when used, this replaces naturally mined gypsum.	**http://www.tradebe.co.uk/business-areas/73-tradebe-minerals-recycling** (Kirkby, Liverpool, L33 7UF) Hanson Cement - alternative fuels and raw materials. Padeswood Works. Mold, Flintshire. CH7 4HB	Retardant	Crushed	Ground	Proven
6	Sound barrier	Plaster is used in interior construction applications due to its capacity to absorb air-borne sounds.	Innovative supplier of acoustic products, i.e. acoustic plaster systems. http://www.quietstone.co.uk/Products/Noise-barriers (Macclesfield, SK10 5SD)	Sound absorption	Pulverized	Ground	-
7	Insulating material	Plaster has low conductivity making it an energy saving, insulating material in construction applications	Manufacturer of a range of range of interior finishing products (durable gypsum drywall interiors). http://uk.usg.com/service/contact/address.html (Durham, SR8 2HS)	Insulation	Pulverized	Ground	-
8	Bulking agent	Gypsum is used as an extender or filler to give bulk to products, i.e. Compost	Suppliers of horticultural and landscape supplies. http://www.leesgrowerssupply.co.uk/building_materials.html (Cheshire, WA16 8TA)	Filler	Pulverized	Ground	Proven
9	Mixtures	Gypsum is a chemically inert mineral which makes it compatible in a wide range of formulations.	No contacts	Inertness	Pulverized	Ground	-
10	Additive	Controlled expansion, required for dimensional accuracy in moulding applications.	No contacts	Expansion material	Pulverized	Ground	-

Table 6.4 Waste transformation ideas for gypsum waste

	Waste transformation	**Description**	**Potential Customers**	**Purpose**	**Structure**	**State**	**Performance**
11	Portable source of heat, self-heating products.	Plaster produces heat on setting. It could be a portable source of heat.	No contacts	Heat releaser	Pulverized	Dehydrated	-
12	Fire resistant material	Gypsum is an A1 material (not contributing to fire)	Manufacturer and supplier of fire protection and high temperature insulation materials. http://www.promat.co.uk/manufacturing/default.aspx (Berkshire RG12 2TD) Foam concrete (fire resistant properties) specialist. http://www.gsfoamconcrete.co.uk/ (Cheshire SK8 4BE) Fire protection and interior services: http://www.ga-fireprotection.co.uk/dry_board_encasement.html (Head office: Suffolk CB9 7AA) Merseyside WA10 3NS http://www.knaufinsulation.co.uk/products/fire_protection/knauf_fireboard.aspx	Fire resistance	Pulverized	Ground	-
13	Flocculate	Flocculating aid	Used as a flocculating aid in agricultural and water treatment applications. http://www.veoliawaterst.co.uk/en/expertise/technologies-solutions/Actiflo/ (Head office, Birmingham, B37 7YE) Macclesfield Water Water Treatment Plant SK104DS Waste water treatment specialists. http://www.atana.co.uk/contact.php (Leicestershire, LE67 1TX)	Water treatment	Pulverized	Ground	-
14	Additive	Plaster is relatively stable under “normal” air humidity conditions, and will not be subject to mould or fungus growth.	Manufacturer of a range of range of interior finishing products (durable gypsum drywall interiors). http://uk.usg.com/service/contact/address.html (Durham, SR8 2HS)	Mould resistance	Pulverized	Ground	-

Table 6.4 Waste transformation ideas for gypsum waste

	Waste transformation	**Description**	**Potential Customers**	**Purpose**	**Structure**	**State**	**Performance**
15	Particle size distribution	Particle size distribution is controlled during gypsum manufacturing to adapt and to meet application requirements	No contacts.	Granularity	Various particle sizes	Ground	-
16	Reused in paints formulations	Gypsum is used in paints to increase opacity and adjust gloss level	Independent British paint manufacturer. http://www.littlegreene.com/about-us/ (Manchester, M11 2FB) Floor paint manufacturer. http://www.paintmaster.co.uk/aboutus.html (Derbyshire, SK23 7LY)	Additive	Pulverized	Ground	-
17	Soil improver.	Gypsum is a source of nutrients, i.e. S, Ca, K. It is a pH Buffer and promotes growth,	Root - Gyp Natural Highly Soluble Calcium Sulphate Fertiliser. http://www.rootwise.co.uk/gypsum-root-gyp.htm (Durham, DL12 8PQ) Envar analyses your waste product to identify what properties it contains. http://www.envar.co.uk/?page_id=435 (Huntingdon, PE28 3BS) Applying recycled gypsum can improve crop quality. http://www.needhamchalks.co.uk/products/gypsum/ Fertilizers and spreading. http://www.rmafertilizer.co.uk/our-product-list.html (Cheshire, CW2 5NT)	Agricultural treatment.	Pulverized	Ground	-

Table 6.4 Waste transformation ideas for gypsum waste

	Waste transformation	**Description**	**Potential Customers**	**Purpose**	**Structure**	**State**	**Performance**
18	Radiation protection of buildings	Gypsum has a capacity to absorb neutrons, and is therefore useful in the radiation protection of buildings containing medical linear accelerators, used for cancer treatment. Info: http://www.british-gypsum.com/pdf/DS-105-01%20Thistle%20X-Ray.pdf	Knauf's new Safeboard takes the lead in X-ray protection. http://www.knaufdrywall.co.uk/news/page_241.html (Kent, ME10 3HW)	Radiation Shielding	Pulverized	Ground	-
19	Wet spot drainage	Gypsum opens up hard soils allowing better drainage.	Gravel/sand limestone. (Macclesfield) http://www.shentongardensupplies.com/gravel-and-sand (Macclesfield, SK10 4RS)	Drainage	Crushed	Crushed	-
20	To clean muddy ponds fast.	Gypsum is a flocculate material	Aqualife Water Plants & Landscapes Ltd Sedimentation/flocculation technologies. http://www.remediation.com/technologies.html (Wigan, WN3 6PR)	Clearing of ponds	Pulverized	Ground	-
20	Used for sealing ponds slowly	Calcifying agent	Aqualife Water Plants & Landscapes Ltd	Rock formation	Crushed	Crushed	-
21	Ceramic block production	Substitute for clay	Decoration and building products. http://www.ceramica.co.uk/ (Stockport, SK7 4PL) Mouldmaking http://www.brunswickceramics.com/page1.htm (Staffordshire, ST6 5QF)	Building material	Pulverized	Ground	-

Table 6.4 Waste transformation ideas for gypsum waste

	Waste transformation	**Description**	**Potential Customers**	**Purpose**	**Structure**	**State**	**Performance**
22	Soil stabiliser	A mix of Phosphogypsum, cement and fly ash is used to provide soil stabilisation.	Expert soil stabilisation http://www.combined-stabilisation.co.uk/ (Bolton, BL6 4SB) Soil remediation and recycled aggregates, Poynton, Cheshire SK12 1LQ http://www.armconenvironmental.com/lev1/pages/arm-env-intro-1.php	Soil stabilisation	Crushed	Crushed	-
23	Animal bedding	Why gypsum animal bedding? **http://www.usagypsum.com/animalbedding.aspx**	Derbyshire DE6 1JF http://www.rwn.org.uk/rwn_Cow_Cubicle_Bedding_Dairy_Gypsum.htm (Derbyshire, DE6 1JF) Exeter, Plymouth and Cornwall. http://www.wood-yew-waste.com/index.php/farm-animal-bedding Southport PR8 5EF http://www.shredbed.co.uk/	Bedding	Crushed	Crushed	-
24	Geopolymer Concretes	Exploring the idea of using waste gypsum as a material for making sustainable construction products. http://www.liv.ac.uk/concrete/sustainable-construction-products/geopolymer-concretes/	University of Liverpool http://www.liv.ac.uk/concrete/sustainable-construction-products/geopolymer-concretes/	Filler	Pulverised	Ground	-
25	Road stone, i.e. drive ways, temporal roads in construction sites.	Using the broken moulds as road stone material. It allows better drainage, white surface.	Quarried road stone materials, Stockport, Cheshire, SK2 6DG. http://www.tyronestone.co.uk/ Soil remediation and recycled aggregates, Poynton, Cheshire SK12 1LQ http://www.armconenvironmental.com/lev1/pages/arm-env-intro-1.php	Soil surface structure	Minimal crushing	Broken ceramic	-

6.2.5.2 Transform

The required structure would dictate the state that the material needed to reach, thus pointing out the required machinery to perform the transformation. From the analysis it becomes evident that the gypsum needs to be either crushed to small particle sizes or ground to a fine powder of less than 3mm in particle size distribution.

Quotes for suitable machines were obtained.

- Firstmining Machinery (Shangai) Co. Ltd. quoted (in USD) a small hammer crusher mill at $1,500 with an estimated $2,500 for shipping cost to the port of Liverpool. The total cost amounts to $4,000 USD, equivalent to £2,555 GBP (calculated on 4 July 2012 with http://www.xe.com). The machine capacity ranges from 20 to 80 kg/h. The output size ranges from 3 mm to dust texture.
- Greg Shipley, a British supplier at www.crushers-uk.com, quoted a minicone crusher at £14,490 ex works, with a 600 kg/h capacity when set at 3 mm output size. This crusher is suitable for processing gypsum for animal bedding which requires particle sizes of around 3mm.
- Glen Creston Ltd. quoted a single jaw roll crusher mill (Model SRC 20/27/CS) at £11,252 including stand and feed hopper (quote excludes packaging, transit charges and value added tax). The output size ranges from 15-19 mm and the throughput rate for gypsum is up to 2 ton/h approximately. This machine is suitable for crushing gypsum for agricultural use as soil improver because agricultural gypsum doesn’t require a fine particle size distribution.

Importing machinery from Chinese suppliers was ruled out due to the lack of experience in the importing processes, as well as the high risk associated with sourcing from new suppliers from abroad. Additionally, the financial analysis of the project showed that smaller and cheaper machinery would actually make the waste transformation process unprofitable (calculations are shown in appendix

3), this is due to the high labour cost required with feeding a small machine for a longer period of time. The economic feasibility analysis shown in section 6.2.6 proves that it makes better economic sense to buy a big machine and crush the gypsum in a shorter time using less labour.

6.2.5.3 Market

Market research was carried out in order to gauge interest from potential customers and to obtain knowledge about the specific product requirements. This knowledge helped discard ideas that were not feasible to implement. The co-product idea was marketed through a “cold contact” approach; meaning that one reached the company with no previous introduction thus relying purely on the formal channels of communication either by phone or email.

The form of contact used the following procedure.

1. Contact the main line, generic enquiry form or email.
2. Introduction as a researcher from the University of Liverpool working in the area of Sustainable manufacturing.
3. Introduce Senior Aerospace BWT and explain how the waste stream in the case study will benefit the potential customer, i.e. economic savings, waste avoidance and better product/process performance (if applicable).
4. Request a direct contact with someone in the technical/engineering/production department to further discuss the feasibility of the proposition.
5. Follow up on the conversation and provide the necessary information to help the decision making process of the potential customer.
6. Outline a proposal to engage the potential customer into a collaboration project with Senior Aerospace BWT to develop a co-product that meets their requirements, needs and expectations.
7. Initiate a co-product development project.

The findings of the initial Market research were that potential customers were unwilling to uptake the waste stream as a co-product due to low volume issues. For example, one potential customer was a supplier of specialist building materials, for this application, crushing the gypsum waste stream to a specified particle size distribution would have rendered the gypsum waste into a usable raw material for some of their products, i.e. as soil stabilisation material for driveways or as decorative aggregates. It was later found, through a follow-up phone, that the volume issue was the main detractor; Tyrone Stone deals with large volumes of raw material, so, 8 tonnes was not enough to develop and market a new product that incorporated recycled gypsum. The gypsum was also offered as a raw material for animal bedding applications to Richard Webster Nutrition, an independent supplier of quality feed and associated products for the high yielding dairy cow industry, the potential customer was also not interested in low volumes of gypsum and highlighted that gypsum from waste plasterboard is available in large quantities and at a very low cost.

The market research revealed that Senior BWT had companies that could incorporate the crushed gypsum into their product lines For that reason, it was decided to explore the idea of transform the broken plaster moulds into gypsum for animal bedding and sell it directly to farms; the transformation process is simple and as such would require minimal investment, so, on those grounds, the project was analysed for economic feasibility.

6.2.5.4 Further market research for gypsum for animal bedding

Using business search engines, several dairy farms in the Macclesfield area where identified and contacted to build a database of potential customers. Although unfamiliar with gypsum as a material for animal bedding two farms showed interest in the product: Alan Eardley and R J & J Venables. Another farm that showed interest in the gypsum was King Feeders UK, in fact this farm turned out to be a farm machinery supplier and knew about the use of gypsum for animal bedding, so an industrial symbiosis between these two companies was foreseen. Even if the gypsum were to be given away free of charge, the financial savings for the industrial symbiosis would be higher than doing the transformation in house, and the company would not need to bother with an additional processing step. A trial run was proposed in order to test if King Feeders crushing machines could grind the gypsum to a suitable particle size for animal bedding.

Unfortunately, later in the year the Environment agency (Environment Agency 2012) issued a position statement to ban the use of gypsum and plasterboard as a material for animal bedding, this due to lack of scientific evidence to demonstrate that gypsum does not poses risks to animals, humans and the environment from hydrogen sulphide generation. The Environment Agency (EA) states that it is currently waiting on an application request for a trial regulatory position to study the use of waste gypsum in different bedding systems, the EA clearly states that: "*this trial will be examining whether hydrogen sulphide (H_2S) is generated when waste gypsum is used as animal bedding and under what conditions. If as a result of further research there is stronger evidence to show that gypsum waste is a suitable replacement bedding we will review this position.*"

6.2.6 Economic feasibility analysis

This section presents the economic feasibility analysis for transforming gypsum waste into an animal bedding material using machinery from British suppliers (option 2). The analysis uses data gathered during the transform and market phase of the ATM methodology, this is shown on Table 6.5. The following list explains the origin of the data and the assumptions that have to be made for calculation purposes:

1. The machine chosen for crushing gypsum for animal bedding is the minicone crusher from Greg Shipley; it was estimated that shipping

and installation costs would be around £500, so the total machinery cost adds up to £15,000.

2. Assuming a service life of 15 years for the machinery, the monthly depreciation is calculated by spreading the total cost of machinery over the entire 15 years.
3. Machine processing capacity is 600 kg/h; so, processing 8000 kg of gypsum would require approximately 14 h per month.
4. Electricity consumption is calculated based using the formula kWh/month x electricity price. Under load and overload conditions can't be taken into account until actual operation measurements; hence, the electricity consumption is based on the motor's maximum power rate: 14kW.
5. The labour required consists in loading the gypsum waste, overseeing correct functioning of the machine and unloading the processed gypsum into the shipping vessel. The required level of skill for this operation calls for a worker on minimal wage compensation.
6. Transportation cost for the processed gypsum would require a single one day skip hire and delivery to nearby farms quoted at £70.00 from Blockerhurst skip hire.
7. Taking a conservative stand, the economic feasibility analysis will take into account the worst case scenario. Richard Webster Nutrition (RWN) is a is an independent specialist supplier of dairy feeds and associated farm inputs. RWN quotes gypsum for animal bedding at £18 to £28 per ton delivered on site on 20 – 29 tonne loads. Given the small volumes of processed gypsum, it could be safely assumed that local customers (e.g. surrounding dairy farms) would be willing to pay £18 per tonne for the processed gypsum.

Market prices for gypsum for animal bedding had a wide range of prices, from £18 up to £35 per tonne.

8. Waste disposal costs reflect the cost in the current scenario (no waste transformation).

Using the data in Table 6.5 it was possible to project a profit and loss statement for annual operations (Table 6.6), this calculations project £3,401.12 in annual profit. This profit is the combined cost saving from waste disposal and the profit generated from the sale of the co-product (gypsum based animal bedding).

Table 6.5 Financial data for the animal bedding project, option 2.

Costs			**Revenue/Savings**			
Machinery:	Mini cone crusher	£ 15,000.00	Animal bedding	Animal bedding £/ton	£ 18.00	
	Service life (yr)	15		8 ton skip of gypsum (month)	£ 144.00	
	Monthly depreciation	£ 83.33	Waste disposal	Monthly waste disposal	£ 400.00	
Labour:	h per month	14				
	Wage/h	£ 6.19	Animal bedding quotes:		Min	Max
	Monthly wages	£ 86.66	RWN		£ 18.00	£ 28.00
Transport:	Single delivery	£ 70.00	Wood Yew Waste		£ 35.00	
Energy	kWh/month	196				
	Electricity price/KWh	£ 0.11				
	Monthly electricity consumption	£ 21.58				

Table 6.6 Estimated profit/loss for the animal bedding project, option 2

Costs	**Monthly cost**	**Annual cost**	**Revenue/Savings**	**Monthly**	**Annual**
Machinery depreciation	£ 83.33	£ 1,000.00	Crushed gypsum (revenue)	£ 144.00	£ 1,728.00
Labour	£ 86.66	£ 1,039.92	Disposal costs (savings)	£ 400.00	£ 4,800.00
Electricity	£ 20.58	£ 246.96			
Transport	£ 70.00	£ 840.00			
Totals	£ 60.57	£ 3,126.88	**Totals**	£ 544.00	£ 6,528.00
		Annual Profit	£ 3,401.12		

In order to calculate the payback period it is necessary to consider the annual profit contribution from the given investment: Table 6.7 shows the profit contribution, year by year. The project is expected to last at least 7 years, at that point, the production process might be able to change to additive manufacturing methods. So, in that light the machine will be expected to reach a resale value of around £ 5,000 to £8,000 (according to current market prices for used machinery and considering the depreciation rate). Considering the machine low usage rate, it is expected that it will remain in good condition and could reach a high market value, estimated to be £7,000.

Table 6.7 Annual profit contribution, animal bedding project – option 2.

Initial cost of machinery	£ 15,000.00
Service time (yr)	7
Year 1	£ 3,401.12
Year 2	£ 3,401.12
Year 3	£ 3,401.12
Year 4	£ 3,401.12
Year 5	£ 3,401.12
Year 6	£ 3,401.12
Year 7	£ 3,401.12
Resale value at year 7	£ 7,000.00

The annual net cash inflow is calculated by adding annual depreciation costs to the annual profit contribution (shown in Table 6.8).

Using data from the net cash flow projection the payback period can be calculated by locating the year which has the cumulative net cash inflow closest to the machinery investment, in this case 3 years. The remaining investment is £1,796.64; this is expressed as a percentage of the annual net cash flow for the following year, equal to 40%. So the payback period is equal to 3.4 years.

The payback period could reduce by almost a year if the price of gypsum for animal bedding could reach the maximum price.

Table 6.8 Annual net cash inflow for animal bedding project, option 2

Year	**Net cash inflow**	**Cumulative**
1	£ 4,401.12	£ 4,401.12
2	£ 4,401.12	£ 8,802.24
3	£ 4,401.12	£ 13,203.36
4	£ 4,401.12	£ 17,604.48
5	£ 4,401.12	£ 22,005.60
6	£ 4,401.12	£ 26,406.72
7	£ 11,401.12	£ 37,807.84

In order to take into account the time value of money throughout the entire project, the net present value of the project is calculated as show in Table 6.9. This project assumes a discount factor of 8% (as an average estimate for manufacturing projects in the UK); the discount factor values were drawn from discount factor tables.

Table 6.9 Net present value for the animal bedding project, option 2

Year	**Cash Flow**	**Discount factor 8%**	**Present value**
0	-£ 15,000.00	1	-£ 15,000.00
1	£ 3,401.12	0.926	£ 3,149.44
2	£ 3,401.12	0.857	£ 2,914.76
3	£ 3,401.12	0.794	£ 2,700.49
4	£ 3,401.12	0.735	£ 2,499.82
5	£ 3,401.12	0.681	£ 2,316.16
6	£ 3,401.12	0.63	£ 2,142.71
7	£ 10,401.12	0.623	£ 6,479.90
Project earnings			£ 15,807.84
		Net present value:	£ 7,203.28

The net present value is positive, which means that the discounted cash inflows exceed the discounted cash outflows even when taking into account the time value of money, thus making the proposal for transforming gypsum waste into an animal bedding co-product an economically viable project.

The downside for the project is that the net present value is relatively low to compete with other investment projects during budget allocation. In order to test the resilience of the business proposition, the net present value was calculated for a worse scenario: assume that the machine breaks down to irreparable condition or that it just cannot be sold at the end of the seventh year. In such scenario, the net present value would still be positive: £2,842.28 (shown in Table 6.10).

Table 6.10 Net present value for the animal bedding project, option 2 (no machinery resale).

Year	**Cash Flow**	**Discount factor 8%**	**Present value**
0	-£ 15,000.00	1	-£ 15,000.00
1	£ 3,401.12	0.926	£ 3,149.44
2	£ 3,401.12	0.857	£ 2,914.76
3	£ 3,401.12	0.794	£ 2,700.49
4	£ 3,401.12	0.735	£ 2,499.82
5	£ 3,401.12	0.681	£ 2,316.16
6	£ 3,401.12	0.63	£ 2,142.71
7	£ 3,401.12	0.623	£ 2,118.90
Machinery resale value	£ -		
Project earnings			£ 8,807.84
		Net present value:	£ 2,842.28

6.2.6.1 *Sensitivity analysis*

An excel spreadsheet simulation was ran based on the data and assumptions shown in Table 6.5. The best and worst case scenario for the proposed solution was analysed by varying the price per ton of animal bedding from £28 to £35 pounds per tonne (as quoted by competitors); this resulted in pay back periods of 2.8 and 2.5 years respectively and net present values of £12,239.44 and £15,764.75 respectively.

In order to analyse the economic risks of the project, a wider range of price scenarios were analysed for the co-product. The results of the wide scenario analysis is shown in Table 6.11 where five price scenarios were analysed using the same data and assumptions in Table 6.5 but only varying the price per tonne of gypsum and analysing the scenario with no machine resale value (column NPV-2) as is the case presented in Table 6.10.

Table 6.11 Wide price scenario analysis for gypsum waste for animal bedding

Price	Profit	Payback	NPV	NPV-2
£ 10.00	£ 2,633.12	4.13	£ 3,174.35	-£ 1,186.65
£ 15.00	£ 3,113.12	3.65	£ 5,692.43	£ 1,331.43
£ 18.00	£ 3,401.12	3.4	£ 7,203.28	£ 2,842.28
£ 28.00	£ 4,361.12	2.8	£ 12,239.44	£ 7,878.44
£ 35.00	£ 5,033.12	2.49	£ 15,764.75	£ 11,403.75

6.2.7 Second iteration of the ATM methodology

Due to the environmental regulatory uncertainty surrounding the implementation of the first solution, alternatives projects were explored for the transformation of gypsum waste into a co-product. It was found that Hanson Cements has a division for Alternative Fuels and Raw materials in the Northwest of the UK and that they are able to take the gypsum for cement manufacturing. Generally, Hanson Cements has a gate fee for every gypsum waste delivered to their plant; however, if gypsum could be supplied according to specification for virgin gypsum, i.e. crushed to less than 63mm and ensuring a consistent product in terms of chemistry and particle size, then a price premium of £10 per tonne of gypsum would be paid.

Due to the high degree of similarity (assumptions and calculations) with the previous project, the economic feasibility analysis for the Hanson Cement project is presented in appendix 3, section 3.2. The calculations showed an estimated payback period of 4.7 years and a very low net present value: £25.72; based on this measurement it was considered an economically risky option. The price of crushed gypsum would have needed to reach £19 per tonne to get a net present value immune to a loss in the resale re-sale of the machine and a payback of 3.6 years (close to the gypsum for animal bedding project). Analysing the cost structure, it is noticed that transportation is the second highest cost contributor (64%) and that if eliminated or reduced the project would look slightly more economically attractive.

An alternative scenario involving no transportation costs would be one where gypsum is crushed to a particle size suitable for use as a soil improver in agricultural applications, a reuse option approved by the Environment Agency. The economic feasibility analysis is also presented in appendix 3, section 3.3. Analysing the cost structure of this project, in this scenario, it makes sense to give away the crushed gypsum for free and let the word spread so that local farmers could collect the crushed gypsum at their own cost; implementing this strategy would lead to a 78% reduction in current waste disposal costs. But if the gypsum is sold at a modest £5 per tonne, the project would contribute £2,838.89 in annual profits, with a payback period of 3.7 and a NPV of £4,544.55. This alternative scenario is a route to return gypsum waste to the local ecosphere, and benefit the local farmers.

No other potential customers identified in the wheel of waste expressed interest in the gypsum waste stream as a potential co-product. However during the market research for the sale of gypsum for animal bedding, a potential industrial symbiosis was identified with King Feeders UK (http://www.ecogreencomposting.co.uk), the company specialises in the supply of green waste composting machinery. King Feeders has a machine able to process plasterboard, on that basis a trial run was proposed to test the gypsum waste. The industrial symbiosis proposal would require no investment and would save 4,800 in waste disposal costs. Computing these savings for a period of seven years, using a discount factor of 8%, results in a net present value of £25,180.80 as shown in Table 6.12.

Table 6.12 Net present value for the industrial symbiosis project

Year	Cash Flow	Discount factor 8%	Present value
0	£ -	1	£ -
1	£ 4,800.00	0.926	£ 4,444.80
2	£ 4,800.00	0.857	£ 4,113.60
3	£ 4,800.00	0.794	£ 3,811.20
4	£ 4,800.00	0.735	£ 3,528.00
5	£ 4,800.00	0.681	£ 3,268.80
6	£ 4,800.00	0.63	£ 3,024.00
7	£ 4,800.00	0.623	£ 2,990.40
Project earnings			£ 33,600.00
Net present value:			£ 25,180.80

6.2.8 Results

Firstly, this section presents the secondary benefits that the implementation of the ATM methodology had in the company. This case study shows how focusing on waste streams could lead a company to improve not only their environmental performance but also its competitive advantage by means of processes improvements that seek resource efficiency and waste prevention. This section summarises the viable co-products that could be manufactured from Senior Aerospace BWT's gypsum waste stream, it has been found that waste transformations need to make utmost use of the waste properties as a way to gain value with minimal processing. The economic analysis of the possible waste transformations is summarised in this section, noting that due to the low volume of waste generated at BTW's manufacturing process, none of the waste transformations surpassed the economic gains of entering an industrial symbiosis. Lastly, this section presents further steps to take into account in the waste legislation arena, a possible waste exemption route is outlined for the gypsum waste stream from BWT.

6.2.8.1 Impact of ATM methodology

During the implementation of the ATM methodology, Senior Aerospace BWT was introduced to material flow cost accounting techniques, it was noted that cost management practices play an important role in the implementation of the all seeing eye of business (All-SEB). All the costs were for the MFCA calculation were identified and listed in an excel spreadsheet (Table 8.16, appendix 3, section 3.4), but BWT could not provide detailed cost estimates at the time of the project so the task of carrying out a material flow cost accounting was left to the health and safety officer for future calculations once the accounting team supplies the data. A spreadsheet of the mould production process was prepared for the value stream mapping of the manufacturing process (Table 8.17—in appendix 3, section 3.5). It was noted that only two production steps in the manufacturing process are value adding activities: composite layup and curing. Calculating the cost of each production step will be useful during cost benefit analysis for the implementation of 3D printing technology to substitute the mould making steps in the production process.

Senior Aerospace BWT showed interest in the prevention of waste; additive manufacturing was explored as a technology that could have an immediate role in preventing the generation of gypsum waste. In theory, 3D printing resins could be reprocessed and reuse on site. However, after further investigations it was found that the technology is not mature enough for the mould production throughput required by Senior Aerospace BWT - around 500 moulds of different shapes and sizes per each eight hour shift. Stratasys has developed an additive manufacturing technology that produces soluble washout mandrels and tooling (e.g. moulds) for the composite industry, but the substrates they use for the tooling cannot be reprocessed for further reuse within the production system.

6.2.8.2 Description of the co-product

Two different co-products could be produced from the waste stream of Senior Aerospace BWT: gypsum for animal bedding and soil conditioning gypsum. The use of gypsum for animal bedding requires the gypsum waste to be crushed to a particle size distribution of less than 3mm. At the moment, the Environment Agency has issued a position statement to ban the use of waste gypsum in animal bedding due to concerns about hydrogen sulphide generation in anaerobic conditions. From a product development perspective this only means this product has not been fully developed yet and that whoever wants to commercialize gypsum for animal bedding needs to do more research and development to determine that the product is safe to use under certain conditions. The second product is soil improver gypsum; standard practise requires the mould waste stream to be crushed to less than 10mm to make spreadable gypsum suitable for agricultural machinery and soil uptake.

6.2.8.3 Process

Crushing gypsum is the only extra step needed for the transformation of waste into a co-product.

6.2.8.4 Summary of the economic feasibility analysis

Table 6.13 summarises the results of the economic feasibility analysis of all propositions analysed for technical and market feasibility (includes the first and second iteration of the ATM methodology) No waste transformation surpassed the economic gains of embarking in an industrial symbiosis with King Feeders UK. But this is due to the conservative price estimates used for the calculations; the minimum co-product price was taken. The price sensitivity analysis shows how each waste transformation option would perform in other price scenarios.

Table 6.13 Summary of economic analysis for all waste transformation options

Waste transformation	Investment	Price	Annual profit/loss	Payback	NPV	NPV-2
Animal bedding option 1	£ 2,555.00	£18.00	-£5,444.30	-	£ -	£ -
Animal bedding option 2	£15,000.00	£18.00	£3,401.12	3.4	£ 7,203.28	£ 2,842.28
Hanson Cement raw material	£14,000.00	£10.00	£2,032.87	4.7	£ 25.42	-£ 4,335.58
Soil improver	£14,000.00	£ 5.00	£2,838.89	3.7	£ 4,544.55	£ 3,007.82
Industrial symbiosis	£ -	£ -	£4,800.00	0	£25,180.80	£ -

6.2.8.5 Sensitivity analysis of the proposed solutions

The following tables are taken from Appendix 3, where the economic feasibility for the alternative options is presented. The animal bedding project option 1 (using overseas machinery) is ruled out due to obvious import risks and high operating cost (see Appendix 3, section3.1). The sensitivity analysis for the animal bedding option is presented in Table 6.11.

So far, the Hanson Cement option has been analysed from a conservative price scenario, assuming that Hanson Cement is willing to negotiate the gate price of crushed gypsum, to match the typical price of gypsum for animal bedding then a better scenario could emerge (see Table 8.9 of Appendix 3). Just with a price of £15 per tonne of crushed gypsum, the NPV improves from £25.42 to £2,543.50 for this alternative scenario.

The option of using waste gypsum as a soil improver was also analysed for a wide range of prices (see Table 8.15 of Appendix 3). The sensitivity analysis revealed that this option outperforms (in all economic measures) the production of gypsum for animal bedding when compared in terms of price (£15 per tonne).

The worst case scenario identified during the sensitivity analysis is the inability to recover the cost of the machinery after at the end of the project. In that scenario, NPV is significantly reduced (as shown in the column NPV-2 of Table 6.13) but it never falls below zero, except for the Hanson Cement option (see Table 8.9), in which case, the price must reach £19 per tonne in order for the NPV to be positive (also from Table 8.9).

6.2.8.6 Steps taken as a result of the ATM methodology

Senior Aerospace BWT is yet to implement any of the suggested gypsum waste upgrade suggestions.

6.2.8.7 Future steps: environmental permits

Even though no formal decision had been made about a waste transformation, for the purposes of this case study, the waste legislation was explored to gain insight about the way in which co-products are legislated. For the proposed uses of gypsum waste at BWT, special environmental permits or waste exemptions are needed in order to transport and sell a co-product made from waste. It was found that gypsum is not explicitly listed in the approved uses of waste by the Environment Agency: U10 - spreading waste to agricultural land to confer benefit, and U8 - use of waste for a specified purpose. However, gypsum is listed in U9, use of waste to manufacture finished goods, so, with further processing (crushing) gypsum broken moulds can be turned into any of the co-products mentioned in this case study.

The case for a waste exemption could be made by recurring to the quality protocol for recycled gypsum from waste plasterboard (Environment Agency & WRAP 2011); this protocol designates the use of recycled gypsum in three applications:

- *"as a raw material in the manufacture of new gypsum-based products, e.g. plasterboard and coving;*
- *as a soil treatment agent for agricultural benefit; and*
- *as a raw material in the manufacture of cement."*

But as the name suggests, this quality protocol only permits input materials from waste plasterboard. However, having a quality protocol that permits the use of waste gypsum for agricultural benefit should provide enough legal commonality for a successful waste exemption application. The case could be made to allow the use of other sources of gypsum waste for the proven and legislated applications. On these grounds, an application for waste exemption status should be successful under U9 of the EA waste exemption permits. Ultimately, BWT would need to demonstrate that it could manufacture of a co-product for these applications in compliance with the publicly available standard specification for the production of recycled gypsum from waste plasterboard (PAS 109:2008) published by the British Standards Institute.

6.2.9 Discussion: review of the ATM methodology

This section analyses the benefits for Senior Aerospace BWT attributable to the implementation of the theoretical propositions of this thesis. BWT has not implemented the proposed waste transformations thus no net benefits (profits) could be measured. There are however intangible benefits for the company; Senior aerospace BWT was introduced to material flow cost accounting techniques, which would give them better understanding of their own cost structures and highlight opportunities for improvements. One of these improvements was revisiting the feasibility of implementing additive manufacturing technologies for the reduction of the waste generated due to the use of gypsum moulds; although Senior Aerospace BWT already knew about Stratasys' 3D printing capabilities, it was unaware of the new technology to make soluble tooling for laying up composites. Senior Aerospace BWT was interested in additive manufacturing mainly from a quality and productivity perspective, for example: improving cycle times, consistency and reducing manufacturing costs. Senior Aerospace BWT was also introduced to contacts in the additive manufacturing research group at the University of Liverpool to explore the development of the technology further.

Senior aerospace was presented with four profitable waste transformation alternatives for their gypsum waste stream. It was found that none of the waste transformation processes was more profitable than an industrial symbiosis between BWT and King Feeders UK; this is due to the relatively low volumes of gypsum waste generated in the manufacturing process when compared to gypsum volumes traded in the agricultural soil improver and animal bedding market segments. The most profitable waste transformation has to make use of the high purity if the gypsum waste stream, instead of trying to compete with low cost plaster board gypsum. In that light, option 24 and 25 from Table 6.4 are examples of waste transformation ideas that are worth pursuing as more profitable waste transformation alternatives.

6.2.10 Additional findings from the implementation of the ATM methodology

6.2.10.1 Theoretical high value co-products

This case study provides a point of comparison for the ATM approach against an industrial symbiosis interchange. As shown in the economic feasibility analysis (summarised in Table 6.13) the expected profit and savings from crushing gypsum into animal bedding would be significantly less than the proposed industrial symbiosis between King Feeders and Senior Aerospace, even if the gypsum was to be given to them free of charge. This is due to the fact that the added value in this ATM option is not very high and due to the low volumes of waste gypsum generated.

Theoretically higher value adding co-products could be derived from waste. Using Pothmann's hierarchy for the use of waste, as cited by Weenen (1990), we can classify some of the proposed uses for the gypsum waste stream.

This hierarchy intends to maximise the resource potential of a waste stream as shown in Table 6.14.

Table 6.14 Resource potential of a waste stream

Reuse waste hierarchy	**Broken gypsum moulds uses**
1. Use of the total characteristics	The total characteristics of the moulds have been lost due to product retrieval. Retrieval method is very difficult to change, but if removal is carried out with a better technique valuable pieces of gypsum moulds could be retrieved for reuse as ornamental or artistic pieces; only a small portion of the gypsum waste could be reused in this way.
2. Use of the physical components	1. The next available physical component in the hierarchy is the broken gypsum as it comes out from the current product retrieval. This structure is of little use as a co-product. 2. After further processing the gypsum could be turned into gypsum gravel to be used as road stone for drive ways, and temporal roads in construction sites. This use could have a higher price value because the structure of the gypsum moulds is preserved. 3. Crush the moulds to produce gypsum chips. 4. Crushed gypsum for animal bedding
3. Use of the chemical components	1. Crush gypsum to use it as soil improver in agricultural and non-agricultural land. 2. Use gypsum for flocculating applications. 3. Calcining of gypsum to turn it back into calcium sulphate hemihydrate or anhydrite. 4. Extract calcium and sulphur from the gypsum
4. Use of the chemical bonding	-

5. Returning the original elementary constituents to nature	Use gypsum to replenish quarries in an environmentally safe manner.

Pothmann notes that each lower level in the waste hierarchy is linked to increasing disorder, which means an increase in entropy and energy required to produce the subsequent material. This observation holds true for the gypsum waste stream in this case study; but we also notice that the resource potential does not always decrease as we move down the hierarchy. For example, calcining the gypsum would make the waste stream more usable and would enable to retain its value as a high purity gypsum material; this option would be economically feasible if the quantities were high enough or if a third party could consolidate a reliable supply chain of high purity gypsum waste streams. In the current system most waste transfer stations crush the high purity gypsum and mix it with plasterboard waste which has a more consolidated supply chain for its recycling.

Another theoretical proposition would be the transformation of Senior Aerospace BWT's waste streams into a unique co-product, in this case, biomimetic composite plasterboards. The idea takes inspiration from the structural hierarchy of the sea urchin spine as described by Seto et al. (2012); the hierarchical structure is described in four levels: the sea urchin spine is a complex porous material in which the crystalline composites are made of even smaller mesocrystalline structures in which amorphous calcium carbonate and biomolecule inclusions are found. Seto et al. (2012) argue that the crystal growth mechanism observed in the sea urchin spine can be used to form composite materials with highly controllable structures and properties. Using a biomimetic approach, an "UrchinBoard" gypsum plasterboard product concept is proposed as a way to combine several waste streams to fabricate a value adding co-product; the fibreglass cloth and scrims could be ground to appropriate sized fibres and could deliver the function of the biomolecule inclusions mixed in the virgin gypsum slurry, whilst the amorphous gypsum chips forms a composite structure in the plasterboard gypsum.

This proposition makes better use of the resource potential of the waste streams. The gypsum chips still preserve the mechanical properties of the casting plaster and the same is true for the reinforcing fibres (glass cloth, glass scrim and aramid); the fibres retain the reinforcing properties and minimal processing steps are required (crushing and chopping). The limitation in this proposition would be that Senior Aerospace BWT does not produce the volumes of waste required to make the co-product feasible to manufacture. For instance, even if the reinforcing fibres were to be added at rate of only 1% of the plasterboard weight, the manufacturer would need 800kg/month of reinforcing fibres (Senior Aerospace BWT only produces 200kg per month).

6.2.10.2 The waste alchemist: a new role in the industrial ecosystem

A solution to the volume issues in the proposed waste upgrade projects is the creation of a new role in the industrial ecosystem, here named "the waste alchemist". A company with this new role will have to consolidate a consistent and reliable supply of high purity gypsum and transform it into value adding products in a way that maximizes the resource potential of the waste streams. The waste alchemist would need to create a diversified portfolio of co-products in order to create a resilient business model so that in the event where any of the waste stream producers stops generating waste the waste alchemist is not put out of business, this idea is illustrated in figure 6.2. Consolidating a supply chain of specific waste streams will enable the waste alchemist to reach waste volumes high enough make the waste transformations economically feasible, i.e pay for the machinery investment and co-product development costs. It might be necessary for the waste alchemist to make joint ventures with waste transfer stations and waste management companies as a way to build these supply chain and reduce transportation costs.

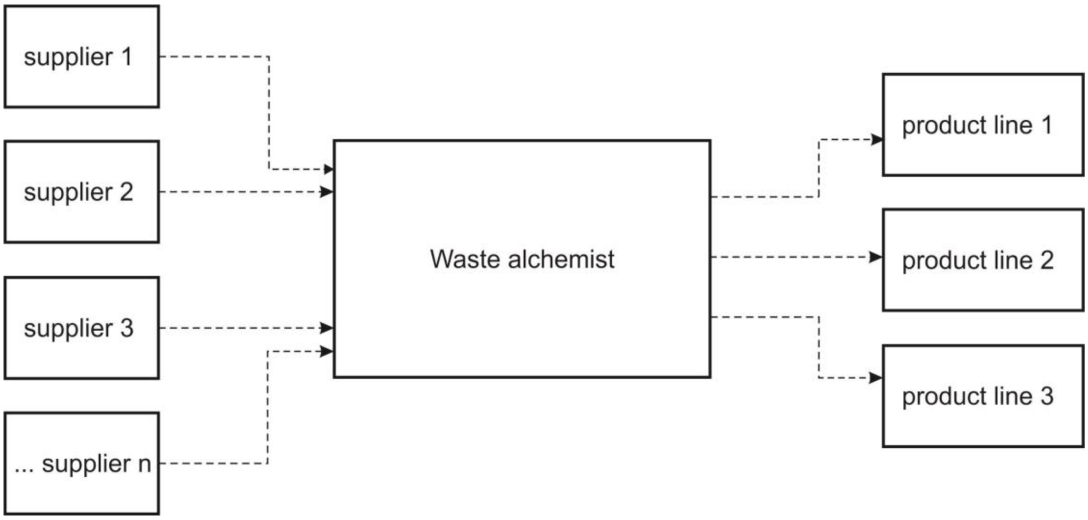


Figure 6.2 Business model for a waste alchemist

6.2.10.3 Additive manufacturing

The finding with regards to additive manufacturing is in line with the preliminary results of the analysis of additive manufacturing technologies by Hague (2010) which shows that most of the environmental benefits from implementing additive manufacturing technologies come from the high efficiency and performance of the products that this technology enables, and not so much from the additive manufacturing process itself.

6.2.10.4 Findings in the industrial ecosystem

During the course of the market research it was found that several companies selling gypsum for animal bedding were affected by legislation and were lobbying at the Environment Agency to make the case for a trial regulatory position. They expressed their interest in presenting this case study as evidence of the benefits of upgrading waste into a valuable co-product whilst diverting waste to landfill.

6.2.11 Lessons learned

With the insights and understanding gained in this particular case study it is possible to suggest ways to improve the original theoretical propositions presented in Chapter 4. This learning should be taken into account in future research projects aiming to refine these theoretical propositions.

Waste volume issue is a critical factor in determining the best waste management strategy for a given waste stream. A company looking to cash the embedded value of their unavoidable waste stream should analyse the available alternatives given the waste output, this analysis shall be incorporated in the first stage of the ATM method as a way to screen the most viable solutions.

Higher value adding co-products could be produced once volumes reach a high enough level to pay for the development cost and necessary investment to bring the product to market. It was found that the waste producer is too busy dealing with day to day activities of the business chore; hence, it was difficult for them to carry out the waste transformations. Supporting the development of high value adding co-products will benefit waste generators because higher than scrap value prices will be paid for their waste.

The case study highlights the importance of waste segregation in the industrial ecosystem. A high quality waste stream would be put to better use and will maximize resource potential if it makes use of the current state and structure of the waste material by investing little energy in further transformations. Waste management companies and waste transfer stations should put in place measures to ensure better classification and segregation of waste. For instance, gypsum waste from plaster board should be kept separate from higher purity gypsum waste. In a way this is already happening due to the fact that plasterboard manufacturers have set up their own take back schemes for plasterboard waste, so they usually do not accept gypsum waste from unknown sources or from manufacturers that are not part of their recycling scheme. Other gypsum recycling companies were also unable to accept the gypsum waste stream from Senior Aerospace BWT because they were producing gypsum from plasterboard waste only. This is due to the fact that these recyclers were producing gypsum for agricultural applications under a publicly available specification (PAS 109:2008) which only allows the use of gypsum from waste plasterboard.

6.2.12 Improvement of the ATM methodology

Future research projects should include the following steps in order to improve the Analyse phase of the ATM methodology:

1. Add a volume analysis step immediately after using the wheel of waste in order to select the most technically and economically feasible waste transformations.
2. Add an environmental legislation step to screen out the waste transformations that are not approved under current environmental legislation, or at least point out the legal barriers that the project will need to overcome if the waste transformation is deemed to be environmentally safe.

6.3 Case study 3 - James Dewhurst

6.3.1 Company introduction

James Dewhurst (JD), a high performance textile manufacturer, is a large global manufacturer of flexible textile reinforcement materials. Reinforcement solutions include:

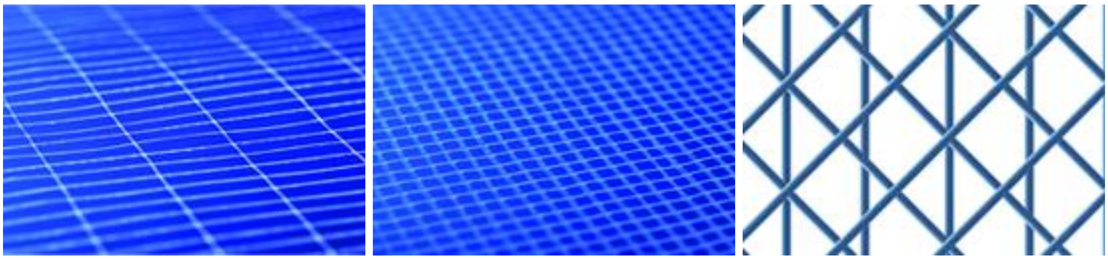
- Reinforcement scrims
- Laminated scrims
- Woven textiles
- Industrial textiles solutions

James Dewhurst is essentially a component manufacturer; it develops materials which, when incorporated into the customer's product or process, delivers the required and specified performance criteria. James Dewhurst has experienced strong growth in the last ten years, with sales reaching over one billion m^2 of fabric (sold in 48 countries in the last two years) it now serves a large variety of markets on a world-wide basis. Commitment to becoming centres of excellence in the products and services they provide has been recognised in recent years with the Queen's award for export and the Queen's award for technology.

6.3.1.1 Products

This case study will deal with the glass fibre waste from three of JD's product lines: reinforcement scrims, laminated scrims and woven textiles.

a) Reinforcement scrims or meshes: these are often the most effective solution for flexible reinforcement. Their properties can be adapted in both the machine and across the directions to offer optimum solutions. Their open construction and chemical coatings allow them to be fully bonded and incorporated into a wide range of materials in a variety of applications, such as, construction, flooring, filtration, packaging, insulation and a myriad of other demanding applications. The product line is formed of three different products: Dewtex™, Triatex™ and Dewlock™; all coated with adhesive and adhesive weights tailored to customer application (Figure 6.3).



Dewtex™
Offers low profile and low crimp performance

- 100mm to 5300mm wide
- 76 Dtex Polyester to 6000 Dtex Glass
- 1 thread per 5cm to 5 threads per cm
- Roll Lengths up to 150.000 linear metres

Triatex™
Suited for ducting applications

- 100mm to 5300mm wide
- 167 Dtex polyester to 2720 Dtex Glass
- 1 Thread per cm to 10 threads per cm
- Roll Lengths up to 5000 linear metres

Dewlock™
Offers superior geometry and tearing resistance

- 1500mm to 3300mm wide
- 76 Dtex Polyester to 2720 Dtex Glass
- Up to 5 thread per cm
- Roll lengths up to 100.000 linear metres

Images source: **www.jamesdewhurst.com**

Figure 6.3 Reinforcement scrims product line

b) Laminated scrims: James Dewhurst has developed a wide range of proprietary adhesive technologies used to lock the scrims together. Combining this technology with the laminating and curing systems, JD offers flexible solutions to meet coating substrate requirements. The laminated scrim technology is marketed under the Omnitex™ brand and is used in

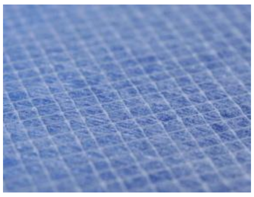


Image source: **www.jamesdewhurst.com**

Figure 6.4 Laminated scrims

roofing, flooring, composites and many other applications, a sample is shown in Figure 6.4.

c) Woven textiles: using a flexible loom technology glass fibre yarns are woven into a variety of high performance industrial woven materials. Uses range from textiles for heavy truck tarpaulins to the latest performance fabric for the manufacturing of wind turbines.

6.3.1.2 Processes

The manufacturing divisions are based in England and the United States. The manufacturing division that took part in this case study is located in Altham, Lancashire, in the northwest of England.

In the Altham division, James Dewhurst has two production sites: the main site for Dewtex and woven production and the second site for Omnitex lamination and trading vision.

a) Woven production: uses flexible rapier and projectile looms.

b) Dewtex™ process: unlike weaving, yarns are laid over one another, using a patented process, and then bonded together by a range of chemical adhesives. This process produces fabric ten times faster than weaving, from materials including glass fibre, polyester and nylon.

c) Omnitex™ system: is an extremely versatile process which enables JD to offer accurate fabric impregnation and lamination for woven, Dewtex and non-woven materials, either individually or in combination. The system is built around a variety of processing options including several impregnation units, multiple unwinds, contact and non-contact drying units.

The main site has 11 machines producing various geometries of textile. Glass fibre products represent about 38% of the production output. As a percentage of production output, the company generates approximately 12% of waste from trimmings and offcuts in the Dewtex process and 5-6% in the weaving process. The waste in the Omnitex lamination process is about 2.5% of production output.

6.3.2 Implementation of the ATM methodology: context

James Dewhurst was first contacted at a NISP event “Waste not, want not – your trading place for manufacturing waste”. The company’s health and safety co-ordinator (HSC) presented a list of “resource haves” which became the starting point for the case study project. The company was later contacted for a potential case study project. The case study proposal was sent to the Operations Director for approval. Upon confirmation of approval, a site visit was scheduled with the HSC, this visit started with a walk tour of the manufacturing site to describe the production process and to explain why and how the generation of waste occurs. The HSC informed about previous attempts to reuse the glass fibre waste as reinforcement material for a race course, and the way in which that solution failed to divert waste from landfill[6]. The visit ended with provision of samples of the targeted “non-product output” (fibre glass). It was decided to focus on the glass fibre waste because there were no existing recycling routes for this type of material. The Health and Safety Officer remained the main contact within the company.

6.3.2.1 Initial conditions

James Dewhurst had an interest in diverting waste from landfill; this is the reason why the company attended the NISP event in the first place. The company was not expecting to make profit from their waste stream; in fact,

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[6] An industrial symbiosis was tested with an unnamed company, this company chopped the glass fibre waste and mixed it with aggregates to create a race course material, but the solution failed because during production process the glass fibre broke into finer fibres that could cause health and safety concerns amongst workers. It is noted that this problem could be overcome if the machinery was equipped with a vacuum sealed environment.

management would have been so satisfied that if someone could recycle the glass fibre waste they would offer it free of charge. They would even incentivise the recycler by giving away all their other waste streams (waste streams such as polyester had a market value of £60 per tonne). In their view, this would simplify the waste handling process and would build a long term relationship with the waste recycler. James Dewhurst is aware that the price of waste materials fluctuates significantly and would be willing to invest in a long term and sustainable waste management strategy. Glass fibre waste could be shipped to China for recycling, but this recycling option could have several drawbacks in the long term future, for instance, shipping costs are likely to increase, concerns about the greenhouse gas emissions caused from overseas transportation is also an issue, as well as the future changes in waste legislation with regards to exporting waste abroad. So, for this reasons, management would rather have the glass fibre waste recycled in the UK.

One of the ideas that James Dewhurst was keen on exploring was the possibility of using the reinforcement fibres to fabricate composite sheet or board for the construction industry.

6.3.2.2 Special circumstances

The implementation of the ATM methodology was carried out by the researcher in coordination with the health and safety co-ordinator (HSC) who attended the NISP event. Actually the HSC was met by chance whilst networking prior to the start of the event, this situation contributed to an initial interest in the research proposed in this thesis and later on this person became a valuable source of insight and an informant about the waste situation in the company. The Health and Safety co-ordinator had the role of overseeing the waste management and environmental aspects in the company and reported results directly to the Operations Director. During the course of the case study research the company showed signs of work overload; but nonetheless the waste transformation project was not relegated to a low priority category. For example, the HSC dedicated time to provide information promptly and even assisted to an industry-academia meeting to explore potential solutions to the glass fibre waste issue.

6.3.2.3 Analysis of the company's operations using "the all seeing eye of business"

Implementing the all seeing eye of business was not undertaken because the company had already identified specific sources of waste where the attention was focused. It was suggested to the company to calculate the true cost of waste using MFCA. The true cost of the waste in focus was relatively straight forward to calculate; it was calculated as the proportion of production costs that represent the percentage of waste produced plus the disposal costs. This calculation was deemed sufficient and in accordance with MFCA principles.

6.3.3 Waste elimination strategies

The all seeing eye of business (All-SEB) postulates that there are three types of waste according to its origin: unavoidable, inefficiency and error (see section 4.2.2). The understanding provided by the All-SEB suggests that only unavoidable should be transformed into co-products; manufacturing waste should be prevented during process design and minimised during operation. Three waste elimination strategies were analysed in order to verify that the gypsum waste was actually an unavoidable waste stream under the given current conditions and circumstances.

6.3.3.1 Prevention

Waste caused from the trimming of fabric could be prevented by developing SMED (single-minute exchange of die) techniques from lean manufacturing. This would enable the change of the loom width setting to the appropriate size and in that way reduce the necessary trimmings of the product. In practice it is accepted that product changeovers and production start-up should take less than 10 minutes (single digit minute); however, given the high production costs and the high volume of production, James Dewhurst cannot afford machine idling. So, unless OTED (one-touch exchange of die) techniques could be developed to achieve machine change over in less than 100 seconds, James Dewhurst is unlikely to stop the machinery in order to reset the loom to the right width.

Even if OTED techniques would ensure that changeovers take less than 100 seconds, the trade-off between cost of downtime and the savings from waste reduction activities should be weighed. An additional observation is that the company does not have the in-house expertise in lean manufacturing; this is one of the deterrents for waste prevention activities.

It was also noticed that due to the high growth period that the company experienced, the work force is overloaded and is unlikely to turn attention to waste prevention activities. This situation will require the intervention of professional consultants (or University collaboration projects) to implement waste prevention measures, so, consulting fees and other development expensed would be added to waste prevention projects.

6.3.3.2 Minimisation

Waste minimisation is achieved in production planning and control. Waste is reduced by taking into account the textile width and minimising the width difference in between product successions throughout the production schedule. Further waste reduction could be obtained by reducing the width of the *selvedge*[7] to the theoretical minimum.

6.3.3.3 Remediation

The glass fibre waste is currently sent to landfill, there are no viable routes to return the waste to the industrial metabolism. Waste remediation strategies

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[7] Selvedge is an edge produced on woven fabric during manufacture that prevents it from unravelling (Oxford dictionary online).

would be explored in this case study with a view to transform the waste into a profit adding co-product.

6.3.3.4 Intra-process reuse

The glass fibre (GF) trimmings and offcuts cannot be reused within the same process unless it is recycled back to yarn form.

6.3.3.5 Inter-process reuse

There are no other processes within James's Dewhurst operations that could reuse the glass fibre waste.

6.3.3.6 Reuse within the regional metabolism

There are no well-established reuse channels in the regional metabolism for this glass fibre waste, given its current state and structure. James Dewhurst would like to find someone that could use all their waste streams to produce composite boards for the construction industry.

6.3.3.7 Reuse in the market place

The ATM methodology will be used to find value adding transformations for the GF waste stream in the market place.

6.3.4 A general framework for waste elimination

6.3.4.1 Waste identification

At the NISP event, James Dewhurst provided a list of manufacturing waste streams generated at the site (Table 6.15).

Table 6.15 James Dewhurst "resource haves" presented at the NISP event

Non-product output	Quantity	Process
Glass fibre Scrim with PVOH coating	17 ton/month – all year	Altham-Dewtex
Glass fibre scrim with PVA coating	0.5 ton/month – all year	Altham-Dewtex
Glass fibre scrim with PVC coating	2.5 tonne/month – all year	Altham-Dewtex
Glass fibre scrim with glass fibre tissue	10 ton/month – all year	Altham-Omnitex
Glass fibre extraction waste	7.2 ton/month – all year	Altham trading
Polyester/Nylon woven selvedge	12 ton/month – all year	Altham weaving
Polyester extraction waste	7.2 ton/month – all year	Altham Dewtex
Polyester with PVOH coating	8 ton/month – all year	Altham-Dewtex
Polyester with PVA coating	3 ton/month – all year	Altham Dewtex
Polyester with PVC coating	1 ton/month – all year	Altham Dewtex
Polypropylene	0.5 ton/month – all year	Altham trading
Spun bonded polyester	0.5 ton/month – all year	Altham trading
HDPE plastic cores	0.25 ton/month – all year	Altham trading
Hessian	0.5 – 1 ton/month (1 ton peak in winter)	Altham trading
Wooden pallets	2 ton/month – all year	Altham trading

6.3.4.2 Select a specific waste stream for waste transformation

All waste streams have an available recycling route apart from GF waste. It was therefore of prime importance to find a way to divert the waste stream from landfill safely. The combined total of glass fibre waste is 37.2 ton per month approximately.

6.3.4.3 Identify the nature of waste and quantify the types of waste

The glass fibre waste stream could be classified according to the cause of the waste.

a) Waste caused by error: it was observed that some cut offs are caused due to imperfections in the weaving. Waste arising in this way could be prevented by finding the root cause of the problem and implementing the necessary changes to the production system. Quality improvement methods such as Kaizen and Six Sigma should eliminate this type of waste.

b) Waste caused by inefficiency: waste caused due to trimming to size could be prevented by implementing OTED techniques in the loom configuration.

c) Unavoidable waste: if waste caused by error and inefficiency could be eliminated, the waste output will be significantly reduced; however, there will be some unavoidable waste due to the need of having to have a selvedge in the weaving process.

For the purposes of this case study, all the waste would be considered for waste upgrade, so there was no need to differentiate and quantify the individual waste types.

6.3.4.4 Calculate the true cost of waste in order to determine its impact on profits

The company was made aware of the true cost of waste expressed as a proportion of the production costs relative to waste levels plus the cost of disposal.

6.3.4.5 Set up measures to eliminate waste caused by inefficiency and error

It is out of the scope of this research case study to eliminate waste caused by inefficiency and error; however waste preventing and minimisation strategies were identified and discussed in section 6.3.3.1 and 6.3.3.2 respectively.

6.3.5 Implement the ATM methodology for the selected unavoidable waste stream

6.3.5.1 Analyse

The waste stream is composed of glass fibre waste (GFW) with various types of coatings; the following section describes the physical and chemical properties in detail.

1. Dewtex glass scrim impregnated with a polyvinyl acetate (PVA)/ethylene vinyl (EVA) acetate blend.
    - Appearance: scrim type product bound together with adhesive
    - Odour: under ambient conditions there is no apparent odour
    - Flash point: coating, 79°C (closed cup)/400°C (open cup). Glass, non-burning.
    - Solubility in water: product is insoluble
    - Specific gravity: 2-2.5 g/cc
    - Colour: yellow to white depending on the original glass fibre shade and coating level
2. Di-Octyl phthalate based PVC plastisol coated glass scrim
    - Appearance: scrim type product bound together with adhesive
    - Odour: under ambient conditions there is no apparent odour
    - Flash Point: n/a
    - Solubility in water: Insoluble
    - Specific gravity: 1.5-2.5 g/cc
    - Colour: yellow to white depending on the original glass fibre shade and coating level
3. Medium hydrolysis polyvinyl alcohol (PVOH) coated glass fibre scrim
    - Appearance: scrim type product bound together with adhesive
    - Odour: under ambient conditions there is no apparent odour
    - Flash point: coating, 79°C (closed cup)/400°C (open cup). Glass, non-burning.

- Solubility in water: coating is completely soluble at 90°C. Glass is insoluble
- Specific gravity: 2-2.5 g/cc
- Colour: yellow to white depending on the original glass fibre shade and coating level

4. Dewtex woven glass scrim laminated to cellulose tissue impregnated with Polyvinyl Acetate (PVA)
    - Appearance: scrim type product bound together with adhesive, adhered to tissue
    - Odour: under ambient conditions there is no apparent odour
    - Flash point: coating: 79°C (closed cup)/400°C (open cup). Glass, non-burning.
    - Solubility in water: the tissue is soluble, but the scrim and binder is insoluble
    - Specific gravity: 2 - 2.5 g/cc
    - Colour: yellow to white depending on the original glass fibre shade and coating level.

The next step was to find out who are the potential customers of glass fibre. First, manufacturers of glass fibre products were contacted based on the assumption that James Dewhurst's glass fibre waste could be further processed and made into a usable form for other manufacturing processes. Then the supply chain was explored in search for end users of glass fibre reinforcement who could incorporate the glass fibre waste into their products. Finally, innovative uses of glass fibre waste were considered; there has been some research into the reutilisation of glass fibre waste from the composite industry, although the waste is different in its state and structure, the physical and chemical properties of the “clean” glass fibre waste from JD were considered to be of higher quality than that from the composite industry, so the same potential uses were considered. Table 6.16 of the fundamental uses of wastes shows the potential uses of GF waste and the results of the queries with the potential customers.

Table 6.16 Waste transformation ideas for fibre glass waste at JDH

	Reuse	Description	Potential Customers	Purpose	Structure	State	Performance	Response
1	Fire resistant rope Insulating rope Glass rope lagging	BS Definitions: a) A loosely braided sleeve of mineral fibre yarn packed with mineral fibre. b) A twisted rope of man-made mineral fibre. The scrim trimmings could be twisted into various rope thicknesses.	Example: http://www.ibhs.co.uk/Plain-Webbing-Tape--Ladder-Tape-&-Rope-Lagging/Glass-&-Ceramic-Round-Rope-Lagging/p-71-126/ Fibre glass rope Manufacturer. Cheshire SK14 2BZ. http://www.cheshireribbon.co.uk/products_01_g.asp	Fire resistance	Long Scrim trimmings	Spun, bundled and coated.	-	eddy.ashworth@textilestechnologies.com from Cheshire ribbon said it will be difficult to use the material as glass rope lagging because the rope needs to create air gaps and have good surface quality.
2	Glass fibre rope for wrapping of pipes etc. or as a conformable flange seal on boilers, stoves etc.	A soft, compressible, glass fibre core over braided with an open mesh of glass yarn.	Distributor: http://www.arco.co.uk/products/3500013/25709/Fortaglas+GFR1+Glass+Fibre+Rope#altproductsholder E glass webbing manufacturer. Cheshire SK14 2BZ. http://www.cheshireribbon.co.uk/products_01_j.asp	General insulation	Long scrim trimmings	Braided	-	

Table 6.16 Waste transformation ideas for fibre glass waste at JDH

	Reuse	Description	Potential Customers	Purpose	Structure	State	Performance	Response
3	Chopped strand mat (Filler)	Chopped strand mat is made from fibreglass chopped strands bonded with powder binder or emulsion binder. Chopped strand mat is used primarily for hand lay- up process, filament winding process and press moulding of FRP products. Typical products include bathroom accessories, pipe, building material, automobile, furniture and other FRP products.	Distributor based in Bristol BS4 3EH. £ 1.80 /kghttp://www.mcmc-uk.com/products-re-chopped-strand-mat.html Distributor: Tyne and Wear NE33 5BY http://www.ecfibreglasssupplies.co.uk/c-921-chopped-strand-matting.aspx Distributor: Newry, BT34 3FN http://www.fibreglassdirect.co.uk/fibreglass-mat-fabrics-chopped-strand-mat-c-38_45.html Needle felts producer, using dedicated punch machinery. Lancashire, OL12 7EQ. http://www.tbatextiles.co.uk/wovenandnonewovenfabrics.php	Moulding filler	Strand mat	Chopped and matted	-	TBA textiles seemed interested but they were moving site and were not be able to undertake any further projects until June/July. Fibreglass direct are not interested in taking waste as raw material but might be interested in buying chopped strand mat from recycled materials.
4	Glass fibre Surface tissue	Thin mats for hand lay-up process and press moulding of FRP products. A sheet of randomly orientated textile glass fibre.	Distributor: Newry, BT34 3FN http://www.fibreglassdirect.co.uk/contact_us.php Needle felts producer, using dedicated punch machinery. Lancashire, OL12 7EQ. http://www.tbatextiles.co.uk/wovenandnonewovenfabrics.php	Moulding	Matted	Chopped and matted	-	

Table 6.16 Waste transformation ideas for fibre glass waste at JDH

	Reuse	**Description**	**Potential Customers**	**Purpose**	**Structure**	**State**	**Performance**	**Response**
5	Chopped strand for general reinforcement	A product that can be used to produce mouldable dough for the reinforcement of complex mouldings where short fibre chopped strand reinforcement is required (Not suitable for DMC formulations)	Distributor. Various lengths available 3 to 25mm. Newry BT34 3FN http://www.fibreglassdirect.co.uk/fibreglass-chopped-strands-c-153.html Distributor. Cornwall TR16 5HY http://www.cfsnet.co.uk/acatalog/Chopped_Strand_Mat_Bandage.html	Moulding	Chopped	Loose strands	-	
6	Non woven needle felts	Produced using dedicated needle punch machinery	Needle felts manufacturer, using dedicated punch machinery. Lancashire, OL12 7EQ http://www.tbatextiles.co.uk/wovenandnonewovenfabrics.php Could be used as a filler for passive fire protection and Marine insulation filler. Lancashire, OL12 7EQ. http://www.tbafirefly.co.uk/index.asp Needle matt manufacturer. Cheshire SK14 2BZ. http://www.cheshireribbon.co.uk/products_01_j.asp	Thermal and acoustic insulation	Chopped	Punched	-	
7	Chopped Roving	Assembled roving with high strand integrity and a silane-coupling agent e.g. http://www.indiamart.com/rksales/fibre-glass-material.html	Distributor, Newry, BT34 3FN http://www.fibreglassdirect.co.uk/contact_us.php Specialist distributor of insulation. Sheffield S6 2LW http://www.sheffins.co.uk/		Chopped	Roving	-	
8	Black polythene enclosed glass fibre ceiling pad	Designed for additional thermal insulation of suspended ceiling systems. www.mayplas.co.uk/product_pdfs/563.pdf	Manufacturer. Bury BL9 0LU http://www.mayplas.co.uk/ceiling_ins.htm Specialist distributor of insulation. Sheffield S6 2LW http://www.sheffins.co.uk/	Acoustic and Thermal Insulation	Chopped and padded	Enclosed pad	-	Mayplas would require the fibreglass to be chopped to specific sizes, but they were not keen on taking a waste streams as raw material input.

Table 6.16 Waste transformation ideas for fibre glass waste at JDH

	Reuse	Description	Potential Customers	Purpose	Structure	State	Performance	Response
9	Foil wrapped /black tissue faced acoustic pad	Designed for use as a sound insulation in metal tray suspended ceiling systems. It helps reduce "room to room" sound transmission over ceiling voids and helps dampen sound within the room http://www.mayplas.co.uk/product_pdfs/562.pdf	Manufacturer. Bury BL9 0LU http://www.mayplas.co.uk/ceiling_ins.htm Specialist distributor of insulation. Sheffield, S6 2LW http://www.sheffins.co.uk/	Sound insulation	Chopped and padded	Foil wrapped	-	
10	Polythene enclosed glass fibre roll	Designed for use in thermal and acoustic applications, http://www.mayplas.co.uk/product_pdfs/541.pdf	Manufacturer. Bury BL9 0LU http://www.mayplas.co.uk/ceiling_ins.htm Specialist distributor of insulation. Sheffield, S6 2LW http://www.sheffins.co.uk/ Distributor. Based in Hants SO50 4NT http://www.solentinsulation.co.uk/Acoustic-Insulation-for-Ceilings/Coustifoam.html	Acoustic and thermal insulation	Chopped and padded in rolls	Enclosed	-	
11	Foil Faced Glass fibre duct wrap	20 kg/m^3 density glass fibre roll http://www.mayplas.co.uk/product_pdfs/611.pdf	Manufacturer. Bury BL9 0LU. http://www.mayplas.co.uk/heating_ventilating.htm Specialist distributor of insulation. Sheffield, S6 2LW. http://www.sheffins.co.uk/ Manufacturer based near Bridgend, South Wales: http://guide.rockwool.co.uk/products/industrial-%28rti%29/ductslab-and-ductwrap.aspx	Thermal insulation	Felt	Chopped and padded		
12	Mineral wool thermal and acoustic insulation	Glass and rock mineral insulation wool range.	Manufacturer based in St Helens, Merseyside WA10 3NS. http://www.knaufinsulation.co.uk/products.aspx Commercial centre, Nottinghamshire NG11 0LB http://www.isover.co.uk/Product-Solutions	Acoustic and thermal insulation	Felt	Roll panel or loose fibre	-	Knauff reuses its own waste glass fibre waste in ceramic production and did not express interest in taking glass fibre waste from other streams.

Table 6.16 Waste transformation ideas for fibre glass waste at JDH

	Reuse	**Description**	**Potential Customers**	**Purpose**	**Structure**	**State**	**Performance**	**Response**
13	Refractory Ceramic fibre additive	Aluminosilicate glass wools for high temperature use http://www.kitsonsthermal.co.uk/COSHH/Cerablanket.pdf	Manufacturer. Wirral, Merseyside CH62 3NL http://www.morganthermalceramics.com/our-locations/europe/	Thermal insulation	Chopped	-	-	
14	Coated Batt	Inert mineral wool with thermosetting phenolic resin, coated on one or two faces (according to specification) with a DFT of 600 microns of 1W coating. http://www.firestem.co.uk/downloads/firestem_firestop_barrier.pdf	Manufacturer. Dunfermline KY11 9JE http://www.kitsonsthermal.co.uk/manufacturers/firestem/default.htm Glass matt manufacturer. http://www.sg-adfors.com/Applications/IndustrialFabrics/Insulation/AcousticInsulation/GlassMat	Fire resistance	Chopped	Mixed fibres in batt	-	
15	Fire pillows	Could extraction glass waste be added to the non-hazardous exfoliating fillers-	Manufacturer. Dunfermline KY11 9JE http://www.kitsonsthermal.co.uk/manufacturers/firestem/default.htm	Fire resistance filler	Chopped	Filler	-	
16	Crimp Wrap	A flexible glass mineral wool roll, designed to provide thermal and acoustic insulation for ductwork. http://www.solentinsulation.co.uk/Insulation%3A-Industrial-Lining/Isover-Crimp-Wrap.html	Manufacturer. Runcorn, Cheshire WA7 3DP http://www.isover.co.uk/ Specialist distributor of insulation. Sheffield, S6 2LW. http://www.sheffins.co.uk/COSHH/Isover%20Health%20and%20Safety%20data%20sheet.pdf	Acoustic and thermal insulation	Chopped	Rolls, Slabs, Sections & Blowing Wool	-	

Table 6.16 Waste transformation ideas for fibre glass waste at JDH

	Reuse	Description	Potential Customers	Purpose	Structure	State	Performance	Response
17	Blown cavity wall insulation	Granulated Rockwool blown into an external wall cavity to a predetermined density. http://guide.rockwool.co.uk/products/building-insulation/energysaver-blown-cavity-wall-insulation.aspx	Manufacturer based near Bridgend, South Wales: http://guide.rockwool.co.uk/products/industrial-%28rti%29/ductslab-and-ductwrap.aspx	Thermal insulation	Granulated	Loose	-	
18	Rocksilk Firetech Slab	High density rock mineral wool slab faced with a Bright Class O reinforced aluminium foil. http://www.solentinsulation.co.uk/Product.asp-ProdID=1359&CatID=22&SubCatID=42	Manufacturer. St Helens, Merseyside WA10 3NS. http://www.knaufinsulation.co.uk/products.aspx http://www.sheffins.co.uk/COSHH/MSD1%20rev%20Dec%202005.pdf Manufacturer, Scotland, FK7 7QQ. Tel: 01786 451 170 http://www.superglass.co.uk/about_us/contacts/					
19	Glass Webbing Tape	Woven tapes for insulation and protection can be produced from core fibres i.e. glass, silica, aramid and ceramic http://www.kitsonsthermal.co.uk/show_prod.asp-ProdID=2263&CatID=44&SubCatID=100	Manufacturer. Lancashire, OL12 7EQ http://www.tbatextiles.co.uk/wovenandnonewovenfabrics.php Manufacture and distribution. Cheshire SK14 2BZ http://www.glasswebbing.co.uk/contact-us/	Strength	Woven fibre trimmings	Rolls	-	

Table 6.16 Waste transformation ideas for fibre glass waste at JDH

	Reuse	Description	Potential Customers	Purpose	Structure	State	Performance	Response
20	Round section glass fibre seals	Compression / density can be varied to suit the application. http://www.pyroglass.com/products.htm	Manufacturer based in Preston, PR2 5AP http://www.pyroglass.com/production.htm Based on high quality bulked 'E' glass fibre yarns.	Thermal insulation	Twisted	Round Rope	-	
21	Wire reinforced seals and clip seals.	Keep their dimensions under the most arduous conditions. http://www.pyroglass.com/products.htm	Manufacturer based in Preston, PR2 5AP http://www.pyroglass.com/production.htm Based on high quality bulked 'E' glass fibre yarns	Thermal insulation	Filler	Loose	-	
22	Glass rope lagging	For insulating hot pipe work and has also been adopted for flue sealing / caulking, and special exhaust systems. http://www.pyroglass.com/products.htm	Manufacturer based in Preston, PR2 5AP http://www.pyroglass.com/production.htm Manufacturer based in Cheshire, SK14 2BZ. http://www.cheshireribbon.co.uk/products_01_g.asp Supplier based in Northamptonshire, NN17 9RS, UK http://uk.rs-online.com/web/p/thermal-insulations/5364040/ Supplier based in Hampshire, PO15 5SF http://www.ibhs.co.uk/product.asp-strParents=71&CAT_ID=71&P_ID=126 Manufacture and supply, Chorley, Lancashire, PR6 7BX http://www.par-group.co.uk/high-temp-insulation/Ceramic-Glass-Fibre-Rope-Lagging.aspx Distribution: http://www.shastidenergy.co.uk/products.asp-categoryID=2398	Thermal insulation	Twisted	Rope	-	
23	'P' section (Tadpole) glass seals	Custom built: http://www.pyroglass.com/products.htm	Manufacturer based in Preston, PR2 5AP http://www.pyroglass.com/production.htm Based on high quality bulked 'E' glass fibre yarns	Thermal insulation	Twisted Woven fabric	Rope Fabric sections	-	

Table 6.16 Waste transformation ideas for fibre glass waste at JDH

	Reuse	**Description**	**Potential Customers**	**Purpose**	**Structure**	**State**	**Performance**	**Response**
24	Plain glass and silicone coated sleeving	Thick wall glass fibre sleeving is available as a plain knitted white glass sleeve or with a red oxide silicone coating. http://www.pyroglass.com/products.htm	Manufacturer based in Preston, PR2 5AP http://www.pyroglass.com/production.htm	Thermal insulation	Felt	Loose	-	
25	'O' rings	O ring seals: **http://www.pyroglass.com/custom-made-products.htm**	Manufacturer based in Preston, PR2 5AP **http://www.pyroglass.com/production.htm**	Thermal insulation	Twisted	Rope	-	
26	Glass Yarn and Twine	Space filling properties: http://www.cheshireribbon.co.uk/products_01_k_v.asp	Manufacturer. Cheshire SK14 2BZ. http://www.cheshireribbon.co.uk/products_01_j.asp Angus, Scotland, DD8 4BJ http://jdwilkie.co.uk/index.php	Filler	Twine	Rope	-	
27	Glass packing	Seals for boiler and furnace doors, provides a high volume of entrapped air and consequent good thermal insulation	Manufacturer. Cheshire SK14 2BZ. http://www.cheshireribbon.co.uk/products_01_j.asp	Sealer	Twisted	Packing	-	
28	Glass reinforced gypsum	manufactured with hard casting plasters reinforced with glass fibre matting and metal or timber sections http://www.ryedaleinteriors.co.uk/product.asp-productid=1	Specialist manufacturer and installer. Leeds. LS11 5XA http://www.ryedaleinteriors.co.uk/product.asp-productid=1	Strength	Chopped	Loose	-	
29	Energy	Fuel gases from gasification (Saetiaw et al. 2011)		Fuel	Gasified	Fuel	-	

Table 6.16 Waste transformation ideas for fibre glass waste at JDH

	Reuse	**Description**	**Potential Customers**	**Purpose**	**Structure**	**State**	**Performance**	**Response**
30	Concrete reinforcement	Glass fibre reinforced polymer is incorporated in low proportions in concrete mixtures, (Correia, Almeida & Figueira 2011)		Reinforcement	Trimmed	Layered-	-	
31	Glass fibre composite	Glass fibre was also treated by (3-Aminopropil) triethoxysilane as a coupling agent (Hisham et al. 2011)	West Auckland, County Durham DL14 9PD http://www.aptecproducts.co.uk/home/ GRP moulding, prototyping, manufacturing and support. Burnley, Lancashire, BB11 5TY http://www.allscope.co.uk/contact.php	Reinforcement	Trimmed	Layered-	-	
32	Short glass fibre composites	short GFs were irradiated with electron beam separately and the composites were prepared with Waste PE, HDPE (Satapathy, Nando & Nag 2011)		Reinforcement	Short fibres	Irradiated	-	
33	NOx Filter	NOx absorption in water using glass fibre filter (Yasuda et al. 2011)		NOx Filter	Chopped	High surface area	-	
34	Composite material based on recycled thermoplastics and glass fibres	Chopped Glass fibres can lead to material systems with more favourable and consistent sets of mechanical properties (Scelsi et al. 2011)	GRP moulding, prototyping, manufacturing and support. Burnley, Lancashire, BB11 5TY http://www.allscope.co.uk/contact.php	Reinforcement	Chopped	Fibres	Favourable	

Table 6.16 Waste transformation ideas for fibre glass waste at JDH

	Reuse	Description	Potential Customers	Purpose	Structure	State	Performance	Response
35	Polypropylene/Waste Tyre Dust/Short Glass Fibre (PP/WTD/SGF) Composites.	Composites were improved with the presence of γ-APS (Zainal & Ismail 2011)	GRP moulding, prototyping, manufacturing and support. Burnley, Lancashire, BB11 5TY http://www.allscope.co.uk/contact.php	Reinforcement	Short fibres	Keep long fibres	-	
36	Foam glass composites toughened by glass fibre	High silica glass fibre with the length–diameter ratio of 100–300 was cut into the length of 10–30 mm (Guo et al. 2010)	Glass fibre toughened foam glasses can be used with Portland cement, steel, concrete, and polymers in the exterior and interior wall of buildings to absorb the shock waves generated by explosions and earthquakes. GRP moulding, prototyping, manufacturing and support. Burnley, Lancashire, BB11 5TY http://www.allscope.co.uk/contact.php	Reinforcement	Chopped	Loose	Positive	
37	Composite materials from waste	Polypropylene composite materials with fillers such as 25 wt% talc and 20 wt% glass fibre made from injection moulding showed higher fatigue strengths (Hiraba et al. 2010)	West Auckland, County Durham DL14 9PD http://www.aptecproducts.co.uk/home/	Reinforcement	Chopped	Loose	-	
38	High strength porous tile	Mixing the clay and the waste GFRP and sintering the mixture (Kinoshita et al. 2010)		Reinforcement	Chopped	Loose	-	
39	Filler in styrene butadiene rubber	The waste powder was a thermoset polyester resin (Ansarifar et al. 2010)	West Auckland, County Durham DL14 9PD http://www.aptecproducts.co.uk/home/	Reinforcement	Powder	Ground	-	

Table 6.16 Waste transformation ideas for fibre glass waste at JDH

	Reuse	Description	Potential Customers	Purpose	Structure	State	Performance	Response
40	Recycle glass fibres	A one-step thermal-treatment process to remove all organic contaminants from the glass-fibre waste (Jody et al. 2003)		Recycling	Shredded	Cleaned	Similar to raw material	
41	Glazes for table ware ceramics	Different amounts of glassy waste processed as ground frit or ground fibres waste (Dima et al. 2008)	Ceiling tiles. Twickenham, Middlesex, TW1 3NJ. 020 8892 3216 **http://www.amfceilings.co.uk/contact.asp** Ceiling tiles, Acoustic pad. Uxbridge UB8 1NG. 0800 371849; 01895 251122 http://www.armstrong.co.uk/commclgeu/eu1/uk/gb/guarantee.html A list of ceiling tile manufacturers: http://www.ceilingtilesuk.co.uk/about.asp	Vitreous glaze	Ground	Incorporated	Effective	
42	Soft zircon glazes	Crystallization rate in waste-containing batch was higher (Grum-Grzhimajlo, Kvyatkovskaya & Kondrasheva 1992)		Glaze	Ground	Incorporated	Positive	
43	Polyester - Glass fibre composites.	the waste fraction richer in glass fibres, as filler for composites yielded higher water sorption and impact strength but similar hardness and tensile strength in comparison with calcium carbonate filled composites (Silva et al. 2012)	West Auckland, County Durham DL14 9PD http://www.aptecproducts.co.uk/home/ GRP moulding, prototyping, manufacturing and support. Burnley, Lancashire, BB11 5TY http://www.allscope.co.uk/contact.php Thermoset or thermoplastic composite recycling operations.	Filler	Chopped	Incorporated	Positive	

Table 6.16 Waste transformation ideas for fibre glass waste at JDH

	Reuse	**Description**	**Potential Customers**	**Purpose**	**Structure**	**State**	**Performance**	**Response**
44	Glass ceramic material	A powder glass sample (<63 µm) was then sintered and crystallized at 1013 °C, leading to the formation of a glass–ceramic material composed of wollastonite and plagioclase s.s. with possible building applications (López et al. 2012).	Wollastonite–plagioclase glass–ceramic material for architectural applications.	Glass-ceramic	Crystallised	Reprocessed	Positive	
45	GRP manhole covers and drainage covers	Use the glass fibre as a reinforcement	Kilns and fibre glass. Lancashire, WN8 9UP. http://www.hrfibreglass.co.uk/products.php-pid=GRP%20Manhole%20Covers%20and%20Drainage%20Covers	Reinforcement	Filament	Chopped	-	The material is not in a usable form for HR's processes.
46	Raw material substitute	Texturised roving, chopped strand	Closely located manufacturer, Rochdale, Lancashire: http://www.fibreglassproducers.co.uk/	Raw material substitute	Filament	Chopped	-	
47	Raw material substitute		Potential user of recycled material: http://www.nonwoventechnologies.com					
48	Screed reinforcement	Developed by a French company: http://www.avm-batiment.com/temp/index.php/Produits/RECY-FIB%20100	Potential customers: http://www.ecoscreed.co.uk/contact-us http://www.churchillflooring.co.uk/eco.html	Reinforcement	Fibre	Chopped	Proven	The potential customers deemed the use of the product unnecessary as their current products perform well without the glass fibre reinforcement. Using foreign material will cause non-compliance with the BS standards.

6.3.5.2 Transform

After analysing the waste transformation ideas presented in Table 6.16 it was observed that that the glass fibre waste would need to be chopped or ground for most applications. However, conserving the length and the current structure of the glass fibre would maximize the resource potential, so, an ideal application would make use of the reinforcing function provided by the scrim matrix and laminated tissue, this also reduces waste transformation costs.

6.3.5.3 Market

Market research was carried out by the researcher in order to gauge interest from the potential customers and to obtain knowledge about the specific product requirements. This knowledge helped discard ideas that were not feasible to implement. The co-product idea was marketed through “cold contact”; meaning that one reached the company with no previous introduction and relying purely on the formal channels of communication either by phone or email.

The form of contact used the following procedure:

1. Contact the main line, generic enquiry form or email.
2. Introduce yourself as a researcher from the University of Liverpool working in the area of Sustainable manufacturing.
3. Introduce the company in the case study and explain how the waste stream from the case study will benefit the potential customer, i.e. economic savings, raw material substitution, and better product/process performance (if applicable).
4. Request a direct contact with someone in the technical/engineering/production department to discuss the technical feasibility of the proposition.

5. Follow up on the conversation and provide the necessary information to help the decision making process of the potential customer.
6. Outline a proposal to engage the potential customer into a collaboration project with the company in the case study to develop a co-product that meets the requirements, needs and expectations of the market.
7. Initiate a co-product development project.

The findings of the market research are shown in the response column of Table 6.16. The market research produced similar results as in the gypsum waste case study: potential customers were too busy to participate in a co-product development project and they were not so keen on taking waste as a raw material substitute, so they would not provide further details on specific requirements for the waste to become a raw material substitute in their process. But even if the requirements were figured out and tested, there were other practical barriers to overcome before a manufacturer could incorporate a waste stream into their products. For instance, option 48 requires glass fibre waste to be chopped for reuse as reinforcement in screed flooring (this reuse form has been tested by a French company), but as pointed out by the potential customer, the incorporation of a foreign material will put the screed out of specification under the BS standard, so, the raw material substitution is deemed unfavourable.

6.3.6 Results

Churchill flooring is a company that saw the benefits of using glass fibre waste to prevent the propagation of micro-cracks during the first hours of screed formation; although still sceptical about the feasibility they saw the potential competitive advantage of a screed with glass fibre reinforcement and decided to explore this idea a little further by requesting waste stream samples for testing.

A Knowledge Exchange Expert (KEE) from the Material Transfers Network provided valuable advice on the possible reuse options for this type of “clean” waste glass fibre from JDH’s manufacturing processes. It was found that an Owens Corning division, OCV Non-Woven Technologies, was producing a similar type of “clean” glass fibre waste. The KEE introduced E4 Structures to the project. E4 structures is a company interested in developing innovative products using plastic waste streams; it develops low environmental impact materials using 100% recycled material and makes sure that the products themselves are 100% recyclable.

In coordination with the KEE all interested parties were brought together to explore the idea of developing value adding co-products from the combined glass fibre waste of James Dewhurst and Owens Corning. It was suggested that further research and development of innovative products could be carried out through the Centre for Global Eco-innovation at the University of Liverpool. Unfortunately due to Intellectual Property concerns, the partnership with E4 structures could not be consolidated, so, the product development was moved elsewhere, pursued independently by E4 structures.

Using the waste management and recycling professional networking group in LinkedIn, a potential industrial symbiosis opportunity was identified. Faurecia is a company that manufactures carpet systems for cars; the company was looking for glass fibre waste streams to reuse as soundproof material. Although Faurecia offers a long term solution for the “clean” glass fibre waste, due to transportation costs to the manufacturing sites located in France, Spain and Poland, Faurecia is unable to pay for the glass fibre waste. Waste samples were also sent to Faurecia for further testing.

6.3.6.1 Impact of the ATM methodology

The implementation of the ATM methodology served as a catalyst to bring together two big companies in the glass fibre textile industry and a small ecominded enterprise to initiate a research project that could lead to the development and commercialisation of high value products from their waste streams.

6.3.6.2 Steps taken as a result of the ATM methodology

JDH sent samples to run test trials with churchil flooring and Faurecia. The project coordinator at James Dewhurst also contacted the Marketing department to find out if there are current customers that could benefit from using the glass fibre waste output after further processing.

6.3.7 Discussion: review of the ATM methodology

This case study showed that waste transformations are some times better left to be carried out by companies specialising in developing eco-products made with high levels of recycled content. The ATM methodology and the wheel of waste are positioned to become useful to such types of companies.

Although the ATM methodology triggers business instincts to cash the embedded value of the waste, companies are not keen on investing in the development of a new product if that product does not fit well in their market sector; so, this situation limits the number of available waste transformations. It was advised to the project coordinator at James Dewhurst to find out if one of their existing customers could benefit from the waste stream material in its current state or with further processing and from there design a co-product.

6.3.7.1 Attributable benefits to the company

During the course of the project, James Dewhurst has made several contacts that could make use of their waste if the trials are successful. Although E4 structures did not sign up for a research project at the Centre for Global Eco-innovation at the University of Liverpool (due to intellectual property constraints), once E4 structures develops the products elsewhere they will be able to use James Dewhurst's waste streams.

6.3.7.2 Impact of the ATM methodology in the decision making process

No decision has been made with regards to the recycling route for the waste stream. It should be noted that when implementing the ATM methodology a company becomes more proactive in the search for recycling routes for the waste stream. In this case the company will explore more its own market and learn more about its customers instead of waiting for NISP to point to a potential industrial symbiosis.

6.3.8 Additional findings from implementing the ATM methodology

6.3.8.1 Theoretical high value co-products

It so happens that the glass fibre waste stream could be used as a reinforcement fibre in the Urchin board proposed in section 6.2.10.1 of case study two. Other theoretical uses arise from using Pothmann's hierarchy of waste reuse (see Table 6.17).

6.3.8.2 Findings in the industrial ecosystem

Although research has shown the technical feasibility of reusing glass fibre reinforced plastic (GFRP) recyclate in several applications, a recent report on research and development in composite recycling (Job 2010) points out that the economic case for recycling GFRP is not yet proven. Additionally there is a need for capital investment to initiate a GFRP recycling supply chain. This case study confirms that the glass fibre recycling market is still in its early stages, there are no major glass fibre recyclers. Big companies such Knauff recycle their manufacturing glass fibre waste within their own processes, but are not keen on taking waste from other manufacturers.

Table 6.17 Resource potential of a waste stream

Reuse waste hierarchy	**Scrim and laminated glass fibre waste**
1. Use of the total characteristics	Using the total characteristic of the waste stream would imply to make use of the glass fibre scrim trimmings they come in the roll form. One possible transformation would be to incorporate the rolls into a plastic injection moulding process to fabricate reinforced discs. Laminated glass fibre scrim cut offs could be reused directly in GRP applications, such as the dingy shell made entirely from manufacturing waste. [8]
2. Use of the physical components	The matrix of the scrim could be preserved and used as a reinforcement textile if chopped to a suitable size.
3. Use of the chemical components	The glass fibre material provides good sound and thermal insulation, this property has numerous applications as shown in the wheel of waste.
4. Use of the chemical bonding	The adhesives could be extracted for fuel recovery and the glass fibres could be recycled in glass furnaces.
5. Returning the original elementary constituents to nature	The safest way to return glass fibre to nature is to recycle it into glass and once the glass has reached its end of life it can be ground to a sand to be reused in the industrial metabolism or used as unbound aggregate in road construction.

Wait (2010) reports on the results of a research project at the University of Birmingham, a manufacturing process was developed to transform “waste slittings” and “direct loom waste” into filament wound composite tubes that are being reused in-house to replace existing cardboard box tubes at P-D Interglass, a weaver of technical glass fibre fabrics. According to personal communications with the project leader, Professor Gerard Fernando at Birmingham University, the project is awaiting final trial results, but the composite tubes are promising a ‘long and durable life’. Other companies, such as JDH, could start exploiting the

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[8] Details can be found at: http://www.compositemouldings.com/FibreglassRecycling.aspx

clean filament winding technology to transform a similar range of similar waste streams into value adding co-products using the "waste alchemist" business model introduced in section 6.2.10.2 of case study two. The clean filament winding technology is commercialised by Mouldlife © within their composites and tooling division (http://www.mouldlife.co.uk/Composites-Tooling.html). The feasibility of this waste transformation is still subject to approval for environmental regulations and the applicable industry standards.

6.3.9 Lessons learned

It was observed that there are several barriers to overcome in order to upgrade the glass fibre waste in this case study.

a) Research and development (R&D)

Limitations in R&D impair the development of new co-products, even when solutions are proven. For example, glass fibre waste from GRP has been incorporated into cement composites, bituminous mixes and rubber; in principle the glass fibre waste from James Dewhurst could be incorporated into such products but the optimal fibre length and quantities of glass fibre waste are yet to be determined given James Dewhurst's particular waste stream.

b) Lack of standards, waste protocols and product specification

Potential customers of waste co-products would be easier to persuade if a product made from upgrading waste is backed up by a waste protocol, an industry standard or if there is already a product specification to include recycled content material. This is shown in the case of the eco-screed manufacturers who are reluctant to include glass fibre waste into their product because the material is not included under the British Standard specifications.

c) Lack of waste exchange platforms

In this particular case study NISP was not able to find a waste symbiosis in the industrial region of the UK Northwest. But once a query was posted in the LinkedIn group, a request was made by Faurecia which has several plants across Europe. It is only recently that a new platform for waste exchange has been launched in the UK, namely http://www.wasteproducerexchange.com which could enable waste exchange across a broader audience (national and international).

6.3.10 Improvement of the ATM methodology

Companies looking to upgrade waste into a co-product should focus their efforts into developing a product that serves their market segment – as a way to diversify their product portfolio. Taking this approach will enable companies to learn more about their current customers and the way they use their products.

6.4 Case study 4 – Yorkshire Copper Tube

6.4.1 Company introduction

Yorkshire Copper Tube (YCT) is a trading division of KME Yorkshire Ltd which in turn is a member of the KME Group, Europe's largest producer of copper and copper alloy materials. Within the Group, YCT is the leading manufacturer of copper tube for the United Kingdom and many countries worldwide. Based in Liverpool, the company operates one the largest and modern copper tube factories in Europe.

6.4.1.1 Products

Yorkshire Copper Tube has a product family composed of ten product lines to offer customers a wide range of plain, plastic coated and special finish copper tube for diverse applications including gas, water and sanitation systems. YCT also supplies copper tubes to convey safely a diversity of fluids and gases ranging from liquid nitrogen at –196°C to high pressure steam at +205°C.

6.4.2 Implementation of the ATM methodology: context

Yorkshire Copper Tube (YCT) was first contacted at a NISP event dubbed "Waste not, want not – your trading place for manufacturing waste". The company was invited to give a presentation about its best practice in waste elimination. During the event the company's speaker was approached to propose a case study that could look into further improvements to their waste handling operations. The researcher proposed to investigate ways to reuse the dust copper waste instead of sending it back to the furnace for recycling. It is interesting to note that this company has already addressed the waste issue but it was also interested in improving their current solutions.

The case study proposal was sent to the facilities manager who sent it for approval with the Operations Director. Once the case study project was aproved, a site visit was scheduled for a tour of the manufacturing facilities and to collect samples of the "non-product output". During the site visit, the Facilities Manager expressed concern about the large quantities of metal forming lubricant (MFL) waste being generated and sent for energy recovery. Because disposing of MFL incurred large disposal costs, it was decided to start the project on this waste stream.

6.4.2.1 Initial conditions

Yorkshire Copper Tube (YCT) was already on the path of resource efficiency and had achieved significant cost savings. Hazardous waste was reduced by improving segregation. Waste was prevented by implementing a more effective purchasing strategy in order to avoid out of date products in stock, which incurred in disposal costs. The copper dust from the production process is sold at £900 per tonne to a company that turns it into copper sulphate.

6.4.2.2 Special circumstances

The implementation of the ATM methodology was carried out by the researcher in coordination with the Facilities Manager who provided all the necessary information and samples. This person had the role of overseeing the waste management and environmental aspects in the company and reported results directly to the Plant Manager. During the implementation of this case study symptoms of "short termism"—as defined by (Repenning & Henderson 2010b)—was observed, the waste transformation project was perceived to be in the low priority category.

6.4.2.3 Analysis of the company's operations using "the all seeing eye of business"

Implementing the all seeing eye of business was not necessary because the company already had identified specific sources of waste where the attention was focused.

6.4.3 Waste elimination strategies

6.4.3.1 Prevention

Waste could be prevented by eliminating the need to use metal forming lubricants (MFL), but even though gas phase lubrication (lubrication by a surrounding gas) has become a new and exciting field of research (Ohmae, Michel Martin & Mori 2005) this option is currently unavailable in the market place, but as long as research keeps progressing, it could become available in the near future.

There are several other approaches that could prevent the generation of waste oil. For instance, Bay et al. (2010) provides an overview of environmentally benign tribo-systems for metal forming, besides describing the development of new types of lubricants, Bay et al. (2010) propose four measures to solve the environmental challenges of tribo-systems: anti-seizure tool materials, anti-seizure tool treatments and structured work piece surfaces. Amongst these measures ceramic dies show good results for dry deep drawing of copper sheets; ceramic dies made of silicon carbide (SiC) and trisilicon tetranitride (Si_3N_4) worked well and showed limit drawing ratios close to those obtained with conventional lubrication. As in the case with gas phase lubrication, due to the experimental stage of the technique it is only available as a potential future solution if the technique could be adapted to the demands and requirements of copper tube drawing processes.

Electromagnetic forming provides an interesting approach to eliminate the need for metal forming lubricants; future research could investigate the technical and economic feasibility of developing an electromagnetic forming technology for copper tube size reduction. Researchers have shown that electromagnetic compression of copper and aluminium tubes can reach a 5% radius reduction without wrinkle formation (Murakoshi et al. 1985); it is probably for this reason that electromagnetic pulse technology is primarily used to expand and neck tubes (Schafer, Pasquale & Kallee). Unless there is a theoretical limit to the size reduction, the technology could be developed and tailored to provide a competitive advantage to copper tube manufacturers. In other words, electromagnetic production methods could transform copper tube manufacturing by doing away with the need to use large heavy machinery and lubricants to resize copper tubes in the same way in which electromagnetic pulse technology is promising to innovate the whole punching process in industry (The Economist 2010).

Three major approaches to prevent the use of MFLs have been identified. The scientific literature reports significant advance in technology development, but none of the technologies discussed above has been adapted to copper tube drawing. So, in the medium term, the use of MFL as an auxiliary input for the manufacturing process will be a necessity and will continue to generate at least some unavoidable waste output.

6.4.3.2 Minimisation

Minimum Quantity Lubrication (MQL) is a technique that uses *micro-dosing* to deliver extremely small quantities of lubricant (a typical flow rate of about 50 to 500ml/h) in an air flow directed towards the working piece, the technique is also known as “microlubrication” and “near-dry machining” (Boubekri, Shaikh & Foster 2010). The benefits of implementing MQL for yellow metal processing has been reported by Vaal et al. (2012) in a case study of South African firms; MQL was used as a way to address the negative consequences of conventional lubrication.

In MQL the lubricant is applied in an open environment, so environmentally friendly lubricants become essential; in their case study (Vaal et al. 2012) incorporated the use of plant oils and synthetic esters to obtain the benefits of almost zero toxicity. The benefits of implementing MQL include: a cleaner production environment, elimination of spent fluid, and improved health and safety conditions for personnel; further cost reductions are achieved because lubricant use is reduced significantly, whilst tool life is extended (Vaal et al. 2012). Using less lubricant also brings a reduction in the cost of cleaning parts and the elimination of spent oil disposal costs. So, by using less lubricant, less CO_2 is emitted whilst achieving bottom line cost savings (Vaal et al. 2012).

In their case study, Vaal et al. (2012) describe the successful implementation of MQL in a number copper manufacturing processes. For example, when cutting hot cast billet material into logs, the use of MQL was cost effective and also eliminated the use of water in a molten metal environment, thus improving the health and safety of personnel.

Indeed, as Vaal et al. (2012) has previously shown, environmental impact could be minimised by substituting the current MFLs with environmentally benign alternatives. "*Vegetable oils are the semisolids or liquid products composed of glycerides of fatty acids*" (Sathwik Chatra, Jayadas & Kailas 2012). These oils have some advantages over mineral and/or synthetic based oils, for example: good solvents, good lubricity properties, less $C0_2$ production in their life cycle, high load carrying capacity, high thermal conductivity, low volatility, high viscosity index, low emission of CO and hydrocarbons, better fire resistance, ready and complete biodegradability, non toxicity, and, lastly, made from renewable resources (Sathwik Chatra, Jayadas & Kailas 2012). Chatra et al. also list the disadvantages of vegetable oils over mineral and/or synthetic oils: poor low temperature fluidity and higher pour point, high susceptibility to hydrolysis which leads to metal corrosion, poor resistance to foaming, limited oxidation in storage, tendency to clog filters, poor thermal stability, narrow range of viscosities (Sathwik Chatra, Jayadas & Kailas 2012). These disadvantages have to be overcome when using vegetable oils as metal drawing lubricants for copper tube manufacturing; for example, Sathwik Chatra, Jayadas and Kailas (2012) provide nine chemical modifications to overcome the disadvantages of natural oils.

Boubekri, Shaikh and Foster (2010) report that because synthetic polyol esters are able to remain liquid at room temperature, they perform better in terms of maintaining a clean working environment (compared to vegetable oils). Their molecular structure stability is also better in terms of product storage in outside environments. Synthetic lubricants also help to reduce the environmental impact of lubricants; for instance, a recent publication demonstrates an immediate and sustained decrease in friction coefficient on copper surfaces with the use of isopropoxy tetramethyl di-oxaborolane (Miller et al. 2012), these boron containing compounds are considered eco-friendly lubricant additives because the esters reacts with water to form a relatively harmless boric acid (Miller et al. 2012). In fact, Metalloid Corporation (**http://www.metalloidcorp.com/**) has already developed botanical and synthetic metal working fluids for conventional copper tube drawing processes, so, environmentally benign alternatives to mineral based lubricants are off the shelf alternatives to consider for future environmental improvement projects at YCT.

Even though the use of MQL has not been reported for a copper tube drawing process, the case study presented by (Vaal et al. 2012) shows that MQL performs well in several processes in the aluminium and yellow metals (e.g. copper and brass) industry as a way to eliminate mineral oil based lubricants and minimise lubricant waste in a cost effective way. Thus, implementing MQL in YCT's tube drawing process should be analysed and considered in future improvement projects.

Personal communications with the technical department at Metalloid Corporation have confirmed that MQL could be adapted for tube drawing processes. MQL is primarily used for cutting, sawing and roll forming applications, so the technique would have to be modified and fine tuned to the requirements of copper tube drawing.

Three main challenges have been identified for the use of MQL in copper tube manufacturing. First, in order for MQL to handle copper tube drawing, the microlubricant has to be formulated with a high viscosity—in the range of 2000 to 4000 SUS (Saybolt universal seconds) at 100°F. The second challenge is overcoming the high cost of bespoke high density microlubricants, the economic analysis of implementing MQL in a copper tube drawing process would have to prove that the higher cost of high viscosity microlubricants is offset by the elimination of waste oil disposal cost. The third challenge is of a technical nature, the nozzle opening of current MQL dispenser would have to be adapted to high viscosity microlubricant formulations.

6.4.3.3 Remediation

Wilson (1997) reports four main routes for reclaiming used oils:

- *"Recovery as fuel. The oil is heated, and then treated with demulsifiers to counteract the emulsifiers which keep solids in suspension during use, solids are removed by settling, and the oil is filtered. The resultant oil is blended to achieve the required specification." "Reclaimed fuel oil has low sulphur content; however other contaminants [such as copper] could lead to severe emission problems."* The main users of reclaimed fuels are the road stone industry, power generation companies and the metal refining industry.
- Reconditioning-on-site dewaters and cleans the oil without changing its chemical composition by means of vacuum treatment, centrifuging, filtering and earth treatment processes.
- Oil laundering. Water and solids are removed by heating and filtering, this method is suitable for the recovery of bulk loads of used industrial oils of known composition, the cleaned oil is returned to the same company for reuse.

- Re-refining. Is defined in the EU Directive 87/101/EEC as "*any process whereby base oils can be produced by refining waste oils, in particular by removing the contaminants, oxidation products and additives contained in such oils*". Wilson (1997) lists a number of re-refining processes and identifies two companies in the UK that provide this service: Orcol and Interline. Personal communications with OSS group (the company that acquired Orcol) revealed that Orcol company could not build a profitable business re-refining used oil due to a lack of demand and ever the ever increasing cost of environmental regulation, and so the service was out phased. Interline, almost followed the same faith, but it was acquired by Whelan Refining Ltd which refurbished the plant and commenced re-refining operations since 2007.

A key aspect for remediating MFL waste is the removal of copper content to safe limits for the end of life scenario. Copper is an essential element for human health, it plays an important role in enzyme mediated systems (Qi et al. 2008); the human body requires a daily intake of 2.5 to 5.0 mg of copper. "*However, high levels of copper are non-degradable and can bioaccumulate in living tissues. Therefore excessive Cu^{2+} in water should be removed to a permitted level of less than 1mg/L that makes the water safe and suitable for drinking purposes*" (Qi et al. 2008). For example, in an end of life scenario in which metal forming lubricants are burned as processed fuel oil, the applicable emission levels for copper and its compounds have to be less or equal to 0.5 mg/m^3 according to the directive 2000/76/ec of the European Parliament and of the council of 4 December 2000 on the incineration of waste.

It is in this light that remediation technologies become important. An interesting approach is the use of waste and by-products from industry and agriculture for the removal of heavy metals from aqueous solutions; certain plant residues possess adsorption capacities for heavy metal cations and can be used as a low cost technology to remove heavy metals from MFL waste (Šćiban, Klašnja & Škrbić 2008). In their study (Šćiban, Klašnja & Škrbić 2008) report on the copper adsorption capacity for several lignocellulosic materials, a selection of the highest performers is shown in Table 6.18. Some materials (wheat straw, soybean straw and corn stalk) had the disadvantage of leaching organic matter in the water during adsorption, thus causing chemical oxygen demands in the range of 113 mgO_2/l (from wheat straw) to 372 mgO_2/l (from soybean straw) (Šćiban, Klašnja & Škrbić 2008). This drawback was favourably solved in a cost effective way by water-washing the lignocellulosic materials and although the adsorption efficiency of some of the adsorbents decreased, in the range of 20-25% after washing, the process remains quite efficient and low cost.

Table 6.18 Copper adsorption by lignocellulosic materials

Adsorbent	**q (mol/g)**
Wheat shell	0.130
Soybean straw	0.085
Oat straw	0.081
Wheat straw	0.078
Wheat straw	0.070
Jute fibres	0.067
Corn Stalk	0.059

6.4.4 Waste transformation strategies

6.4.4.1 Intra-process

Reconditioning onsite and oil laundering will enable the reuse of the MFL within the copper tube drawing processes but no companies were found offering this service in the UK. Mineralöl-Raffinerie based in Dollbergen, Germany (http://www.mineraloel-raffinerie.de/) offers expert services for contract reprocessing of waste oils. Mineralöl-Raffinerie states that after laboratory analysis and a trial run through the solvent recovery unit (Technikum) the company is able to reprocess rolling oils according to predetermined specifications. The MFLs from YCT are within the limits of the distillation range of the Technikum process (none of the MFL has a higher boiling point than 270° C), so, under such requirements, waste oil reprocessing for YCT remains a possible alternative to be considered for further technical, economic and environmental feasibility studies.

If reconditioning is not possible, then the water could be treated to be reused within the tube drawing process. Karakulski and Morawski (2011) have figured out ways to treat the waste emulsion from a copper wire drawing process and reuse the treated water in the wire drawing process. The emulsion is described as a mixture of oil in water containing surfactant additives, antimicrobial agents, and antifoaming agents (Karakulski & Morawski 2011); this formulation is similar to the one used for copper tube drawing, so, in principle, the treatment technique should be also be applicable to waste oil from copper tube drawing processes. The treatment technique is an integrated two stage remediation process that uses tubular membranes both for ultrafiltration (UF) and nanofiltration (NF) (Karakulski & Morawski 2011). During the first stage of the process ultrafiltration is achieved using a polyvinylidene difluoride membrane with a molecular weight cut-off of 100 kDa (Dalton); at this stage of the process 99% of oil and lubricant particles are rejected whilst achieving a complete reduction of suspended solids (Karakulski & Morawski 2011). The pre-treated effluent from the first stage is passed through nanofiltration membranes; using NF90 reduces total organic contents to levels below 100mg/dm3 whilst concentration of copper ions is brought down to 27mg/dm^3 (Karakulski & Morawski 2011). This integrated UF and NF membrane technique allows the copper wire manufacturer to reuse the process water to top up fresh emulsion but does not make the water safe to enter the biological ecosystem.

6.4.4.2 Inter-process

Another alternative is to reuse the oil to generate heat for other processes or to heat the facilities. In order to reuse the waste oil in such a manner, the toxicity content in the waste oil must be brought down to safe burning levels using the remediation technologies described in section 6.4.3.3 and 6.4.4.1. Reusing the MFL waste oil onsite becomes an attractive proposition from an economic stand point. Energy Logic (http://www.energylogic.com**),** a US based company, offers on-site energy recovery technologies such as waste oil heaters, boilers and high volume – low speed (HVLS) fans. The company claims that a gallon of waste oil contains approximately 14,000 BTU of energy and whilst a hauler in the US would typically pay a third of the energy value in the waste oil, a waste oil generator could achieve significant savings by recovering the full value of the energy on site and reducing transportation emissions caused by hauling waste oil to third party recyclers. In the Resource Conservation and Recovery Act, in the Code of Federal Regulation Title 40, the US – Environmental Protection Agency (EPA) defines used oil and provides specific guidelines in order to safely burn the oil for energy recovery.

6.4.4.3 Regional metabolism

WRAP has identified two main uses for waste oils. The first use could be classified under the label of reuse as non-fuel product: it could be used to extract base oil, to manufacture re-generated lubricants and it could also be used as a chemical reducing agent in steel making blast furnaces. Another use falls into the category of recovered fuel oil in applications such as: fuel for cement and lime kilns, fuel for power stations and road stone coating plants, and various other uses as fuel oil.

The UK has only a limited capacity to re-refine waste oil into lubricants due to a historically strong market demand for waste oil for combustion which has deterred investment in modern oil refining plants (WRAP 2009). Whelan

Refining Ltd (http://www.whelanrefining.co.uk/) might be the only facility of its kind able to process waste oil to produce recycled base oil in the UK. "*Where due to technical, economic and organisational constraints it is not practicable to recycle to basic oil production then energy recovery options provide for a secure solution to this hazardous waste problem*" (Oil Recycling Association 2012). This is the case at Yorkshire Copper Tube where the current end of life treatment for MWF waste is to channel it to the OSS group (http://www.ossgroupltd.com/), a major producer of clean fuel oil. The OSS group produces processed fuel oil in accordance with the technical and legal requirements of the end of waste q*uality protoco*l for processed fuel oil; this oil is produced to the same BS2869 specification as virgin fuel oils.

A potentially cleaner energy recovery alternative is the use of plasma, pyrolysis or gasification technology. In their review, Joachim and Anthony (2008) describe numerous technologies and approaches for plasma treatment of wastes; the review explains the basic physical principles, description of process and the advantages and disadvantages of thermal plasmas. A plasma technology with potential for treating the waste oil was developed by Tetronics international, based in Swindon, UK, (http://www.tetronics.com).

Tetronics' offers single torch and twin-torch reactors; leach tests have shown that Tetronics' approach show heavy metal leach rates "*well below the regulatory limits"* (Joachim & Anthony 2008). In particular, "*the twin–torch arrangement shows reduced evaporation of metallic components and formation of fine particulates" (Joachim & Anthony 2008)*. For large waste streams, Tetronics uses a Gasplasma process that combines bed gasification with plasma cleaning of the resulting hydrogen rich syn-gas (Joachim & Anthony 2008). "*The plasma provides a high temperature environment for processing residual tars and chars, and allows vitrification of the ash into a non-leaching slag*" (Joachim & Anthony 2008).

Tetronics states that the company supplies direct current plasma arc systems with applications in the treatment of hazardous petrochemical waste (e.g. oil tank sludge) as well as metal recovery solutions (Tetronics 2012). Tetronics' recovery process allows the controlled combustion of the waste oil's organic component to form a fuel gas whilst the inorganic component is vitrified inert by-product dubbed Plasmarok® (Tetronics 2012). The resulting by-product could also be further processed in plasma arch systems designed to recover metals from electrical waste in order to extract the high copper content present in the MFL waste - if needed. Tetronics' processes claim to "*destroy PCBs (polychlorinated biphenyl) and other types of persistent, bio-accumulative and toxic pollutants at very high destruction and reduction efficiencies, above 99.9999%, across a wide range of concentrations*" (Tetronics 2012).

6.4.4.4 Market place

Mineralöl-Raffinerie is one of the big oil up-cycling companies in Europe; the company is able to up-cycle oil waste into base oils, glycol and lubricants, their reprocessing technology enables them to reuse all the oil content, thus producing no waste and operating in an environmentally friendly manner. Mineralöl-Raffinerie's services do offer a longer life cycle for the MFL waste compared to energy recovery options, however, in this reuse scenario transportation costs to Germany and associated risks become a factor of concern for YCT.

6.4.5 A general framework for waste elimination

6.4.5.1 Waste identification

As it was mentioned in section 6.4.2.1 on the Initial conditions of the project, the focus started with copper dust and then moved to waste oil. In addition to this, during the site visit and tour of the manufacturing facilities, it became evident that the company produced high amounts of copper offcuts at different stages of the tube drawing process, this offcuts are sent back to the ingot manufacturing to be recycled in the smelting furnace. It was during this tour site that another reuse opportunity was identified for the copper offcuts. These offcuts could be reused without re-melting in KME's ecological copper product range (made from recycled copper) for architectural applications. This product range consistsof copper sheets, strips, complete façade systems and pre-shaped components for building envelopes and roof drainage systems exclusively made from copper and copper alloys (http://www.kme.com/en/ecologicalcopper).

The development of a process to reuse YCT's copper offcuts without re-melting is a promising area for future improvement projects in terms of potential cost reductions. Substituting furnace recycling for reuse will not only reduce the environmental impact of KME's ecological copper but will also improve the integration of YCT's waste into KME's product portfolio. Reuse without re-melting is an approach being developed for the aluminium scrap (swarf) of the aerospace industry (Cooper 2010). This approach uses a "solid bonding" process to cold compact and extrude the aluminium scrap at 500° C, in this way, the process yields an average energy saving of 96% of the energy required for melting (Cooper 2010). If this kind of approach could be adapted for the copper offcuts generated during copper tube manufacturing, it could provide a good waste transformation opportunity for YCT. However, such a study falls outside the area of the scope of this case study and must remain as a separate unit of analysis for further research projects.

6.4.5.2 Select a specific waste stream for waste transformation

Oil waste consisting of a mixture of different metal forming lubricants (MFL) was chosen because it represents a high volume of waste and significant disposal costs in addition to environmental concerns due to the high copper content in the waste oil.

6.4.5.3 Identify the nature of waste and quantify the types of waste

Based on the best available techniques presented in section 6.4.3 waste oil could be classified according to nature of its origin within the production process: error, inefficiency, and unavoidable waste.

Waste caused by error: it was not possible to study the occurrence of this type of waste as part of this case study.

Inefficiency waste:

*C*onsidering minimum quantity lubrication (MQL) as the best available technique it becomes apparent that the current flood lubrication method used during the tube drawing process is highly inefficient in the use of metal forming lubricants. Unfortunately, due to the fact that MQL technique needs adjustment and tuning in order to be used in a copper tube drawing environment, no precise figures can be reported for the oil consumption in a MQL setting; however, it is possible to provide an estimate of the potential waste reduction. The current flooding lubrication technique produces approximately 109 tonnes of waste oil annually with an estimated ten per cent water content. So, if MQL for copper tube drawing achieves similar lubrication rates as in state of the art MQL for cutting operations where efficiency rates are in the range of 10-100 fold, and lubrication consumption rates are in the range of 2.0ml/h (Sapian, Omar & Abd Shukor 2011), then one would expect MFL waste to be reduced in the range of 10-100 times of the current waste output.

Unavoidable waste:

Under the current situation at YCT, the flooding technique generates large quantities of unavoidable waste. The MFL becomes waste because after a period of time the lubricants' performance is compromised; aging processes are induced by the thermal degradation of additives whilst by products and suspended solids gradually build up in the oil (Baderna et al. 2012; Karakulski & Morawski 2011), so, inevitably, the MFLs need to be replaced periodically.

When it is not possible to recondition or launder the waste oil, in order to conserve the original properties, re-refining becomes the next environmentally friendly end of life option. Re-refining processes are designed to recover the value of the base oil which could be prepared with fresh additives to produce new lubricants; base oils can be recycled n-times without any problem (Baderna et al. 2012). However, most re-refining processes are not 100% efficient; during re-refining another other type of waste is generated: lubricant sludge; this waste is from the solvent extraction process that recovers the base oils (Siti Kholijah et al. 2012).

This sludge is the ultimate unavoidable waste at the end of this life cycle scenario, waste sludge from YCT is an environmental liability due to the high copper content and the inherent toxicity of the lubricants. For instance, in vivo studies have shown that "*acute exposure to used oils can result in important adverse effects on pulmonary efficiency, mainly due to the heavy metals content" (Baderna et al. 2012)*". The carcinogenic potential of used oils lies in the Polycyclic aromatic hydrocarbons (PAHs) content which could be activated either directly or indirectly and lead to ultimate carcinogens (Baderna et al. 2012). For these and other concerns explained in detail elsewhere, base oils are defined as "substances" for REACH legislation, this legislation requires specific obligations for everyone involved in the supply chain.

Waste sludge from oil re-refining is a potential candidate for a waste upgrade transformation using the ATM methodology. For instance, the production of grease using sludge as a thickener is reported as a new area of research (Siti Kholijah et al. 2012). Siti Kholijah et al. (2012) have reported favourable results for the production of high temperature grease from waste lubricant sludge and silicone oil; the best performing sample was silicone oil with a 10:90 ratio of fumed silica to sludge, the grease had a shiny black colour and a dropping point of 275° C. Although in their experiment (Siti Kholijah et al. 2012) report a low concentration of metal elements (Cu, Ni, Cd, Cr, Pb and Zn);

that is a desirable condition in their study; however, the presence of high copper content in YCT's oil sludge could actually be a desirable condition for the production of copper grease.

Copper grease is used in high temperature and high pressure applications. The copper content protects against rusting and corrosion and it also prevents the grease from hardening, melting, and makes the grease more resilient to vibration, contraction and expansion (http://www.chemodex.co.uk). United Products Oil limited (UPOL) (http://www.united-oil-products.com), an independent oil and grease manufacturer based in Monmouth, South Wales, could benefit from using oil waste with high copper content (such as that from YCT) for the production of eco-friendly (recycled) copper grease.

Research and development (R&D) should be carried out to develop a co-product that complies with REACH regulations. All the companies in the supply chain should cooperate for the appropriate end of life of the lubricant; these means that the original lubricant manufacturer, the user (YCT), the oil refinery (i.e. OSS group) and the end recycler (i.e. UPOL) should all cooperate with R&D efforts, with the ultimate responsibility of co-product development resting in the hands of the end recycler.

6.4.5.4 Calculate the true cost of waste in order to determine its impact on profits

YCT currently pays for the disposal of 109 tonnes of waste oil. In order to calculate the true cost of waste for an auxiliary material such as MFL one has to calculate the cost of true cost of the "lubrication service" and from there deduce the true cost the waste using the material flow cost accounting framework outlined in ISO 14551:2011. Due to time constraints in the project this cost analysis was not carried out.

6.4.5.5 Set up measures to eliminate waste caused by inefficiency and error

Minimum quantity lubrication (MQL) has reached a development stage where it is possible to adapt and the technology to a copper tube drawing process in order to test the technical, economic and environmental feasibility of the technology. This technology has the potential to eliminate the MFL waste to very small amounts (up to 100 times less than the current rates of disposal), if the implementation trials prove successful, it would reduce waste levels to a quantity so low that alternative waste transmutation projects would become an economically unfeasible option. MQL also improves health and safety working conditions and could also use environmentally friendly bio-based lubricants, so it should be a preferred waste elimination strategy for YCT.

6.4.6 Implement the ATM methodology for the selected unavoidable waste stream

In this case study, it was found that MQL is the most desirable option—from a strategic waste elimination perspective—because it could reduce MFL waste to only 1 tonne per annum. MQL could also incorporate environmentally friendly lubricants which would make the unavoidable waste stream less toxic. Based on this premise, it was decided that the ATM methodology should not be applied to the MFL waste from YCT.

6.4.7 Results

The implementation of the general framework of waste elimination in industry has shown that a waste minimisation strategy could deliver near zero-waste process performance and thus achieve the objective of the project.

Metalloid Corporation has been identified as a potential technology provider. The results of this case study will be presented to the plant manager and other decision makers in order to decide the best course of action.

Additionally, other waste transmutation opportunities were identified for the ATM methodology, these are: the transformation of copper tube offcuts into copper cladding and the use of oil sludge from third party re-refining operations to manufacture copper grease.

6.4.8 Discussion: review of the ATM methodology

This case study has shown the importance of considering a waste elimination strategy before taking remediation measures for a given waste stream. There are indeed several techniques to remediate and recycle the MFL waste; but, as it has been shown, more desirable waste minimisation measures could be developed in a short term. If a waste elimination strategy is absent, a waste remediation solution could become obsolete in the near future; sunken investments and contractual commitments would impair a company's ability to undertake future process improvements.

From a strategic perspective the most desirable solution is to develop MQL for YCT's drawing process; however, improvements could still be made on the current waste disposal methods (i.e. transforming oil sludge from re-refining operations into copper grease). Analysing the waste transformation strategies allows a company to explore a wide range of possible solutions for the end of life of a given waste stream. Having a wide range of alternatives for the end of life of a waste stream also makes a company's waste management more resilient to supply chain disruptions and changes in regulation.

For example, the waste oil directive (75/439/EEC as amended) required European Union Member States to give priority to the regeneration of waste oil above its use as a fuel (WRAP 2009). However, in 2001, a study commissioned by the Environment Directorate General concluded that, on the basis of all available life cycle assessments, "*the regeneration of waste oils has advantages and drawbacks in relation to other recovery options, such as incineration in* *cement kilns and gasification, but no clear overall advantage for regeneration was found*" (European Commission 2012) . On that basis, the Directive 2008 /98/EC (Waste Framework Directive) acknowledged that specific waste streams could depart from the waste hierarchy when justified by Life Cycle thinking on the overall impacts of the generation and management of such waste (WRAP 2009). This change in regulation has a negative effect on the supplies of waste oil directed towards regeneration plants because companies using the waste oil for energy recovery are able to give higher incentives to oil waste collectors due to their cost structures and the high fuel prices that the waste oil substitutes (Monier & Labouze 2001).

This previous example illustrates the importance of adding value to waste streams as a remediation strategy; ultimately the economic conditions play a key factor in the end of life scenario of a waste stream. Environmental regulations could reshape the market and push for more environmentally benign end of life treatments; but, as technology evolves and as the supply and demand shapes the supply chain, the waste streams will always be subject to economic laws and principles, just like any other product.

6.4.8.1 Attributable benefits to the company

Analysing waste elimination strategies for YCT's waste stream has linked the sustainability aspects of waste management with strategic planning in business management: analysing waste prevention strategies has brought attention to innovation and the long term planning of manufacturing processes; analysing waste minimisation strategies has shown process improvement opportunities; analysing waste remediation strategies has found ways to reduce the environmental harm of the waste stream and make a potential co-product from the oil sludge of oil re-refining operations.

The analysis of waste transformation strategies has identified a portfolio of solutions for the end of life treatment of MFL waste (summarised in Table 6.19).

6.4.8.2 Impact of the ATM methodology in the decision making process

The implementation of the ATM methodology within the framework of a waste elimination strategy has shown process improvement options for the long, medium and short term planning. In the short term it is worth implementing waste treatment for heavy metals removal from the MFL using biomass waste as a cost effective corrective action; this would reduce the toxicity of the waste stream whilst the solid residues are sent for energy and metal recovery in advanced plasma processing plants. A medium term project could look into adapting MQL for copper tube drawing processes. And in the long term, YCT should be considering ways to transform the production process into a leaner, greener and more flexible system by taking into account the MFL waste prevention technologies presented in section 6.4.3.1. Implementing the ATM methodology within the general framework for waste elimination shows a clear pathway towards zero waste and process improvement. This analysis should provide useful guidance during the decision making process at YCT.

Table 6.19 Summary of waste transformation strategies

Strategy	**Waste transformation**
Intra-process	Integrated ultra-filtration and nano-filtration of emulsion MFL reconditioning on-site
Inter-process	Onsite energy recovery
Regional metabolism	Offsite energy recovery options Re-refining by Whelan Ltd Processed fuel by OSS group Advanced Energy recovery by Tetronics
Market place	Re-refining and up-cycling by Mineralöl-Raffinerie Copper grease from oil waste sludge

6.4.9 Additional findings from implementing the ATM methodology

6.4.9.1 Waste prevention and process innovation

The implementation of the ATM methodology within the framework of three waste elimination strategies has shed some light on ways to prevent, minimise and remediate waste associated with MFL. Gas lubrication, ceramic dies and electromagnetic compression of copper tubes have been identified as future technologies that could prevent the use of MFL. The use of strategic thinking for waste elimination leads the company to process innovation that may provide other competitive advantages, e.g. reduced cycle times and reduced machinery downtime.

6.4.9.2 Theoretical co-products

The implementation of the ATM methodology within the general framework of waste elimination has shown several ways to transform the MFL waste into co-products. For instance, re-refining of MFL waste allows the recovery of base minerals and the production of glycol and secondary lubricants; the copper content of YCT's oil sludge could also be used advantageously to blend specialised greases with high copper content.

Typically, if a company needs to generate innovative solutions, it would have to rely on random idea generation tools such as brain storming. Academic methods also rely in brain storming sessions, e.g. step two of the novel assessment tool for the reusability of wastes proposed by Park and Martin (2007). Based on an understanding of the current waste transformation strategies it was possible to generate more ideas for potential waste transformations using the wheel of waste (described in section 5.3), using this tool a company is able to generate waste transformation ideas in a structured way. In order to use the tool, a table showing all the possible waste transformation was constructed. The PSSP language describes the level of change needed for the desired waste transformation (see section 5.3). The problem solver is encouraged to generate at least one idea for each possible waste transformation using the six fundamental uses of waste presented in section 5.3. Table 6.20shows the current waste transformations available for YCT's MFL waste stream as well as potential new transformations derived from the wheel of waste. Ideas are generated by linking a change in the waste attribute with a fundamental use of waste, this change could lead to a potential waste transformation. During idea generation, these theoretical transformations (marked with an asterisk in Table 6.20) need not be technically or economically feasible; their purpose is to reveal potential solutions that could have been overlooked.

Table 6.20 Idea generation for MFL waste transformations

Level of change	**Use of waste**	**Waste transformation**
Purpose	➢ Replace	• Repurpose the lubricant for energy recovery – replaces virgin fuels.
	➢ Function	• Use MFL as an heat carrying medium*
	➢ Incorporate	• Incorporate MFL waste as high energy fuel content in pyrolysis and gasification processes
	➢ Store	• Store the energy content of hydrocarbons*
	➢ Combine	• Combine with fumed silica for direct transformation into copper grease*
	➢ Extract	• Extract base oils for new oil formulations
Structure	➢ Replace	• Modify the chemical structure to produce Syngas for energy recovery • Modify chemical structure to produce specification diesel
	➢ Function	• Separate CO_2 for sequestration *
	➢ Incorporate	• Incorporate thickening agents*
	➢ Store	• Separate hydrogen molecules to store energy*
	➢ Combine	• Combine with silicone oil to produce copper grease from re-refining oil sludge
	➢ Extract	• Extract and Recover base oils • Extract and recover copper content • Separate H_2 for high end markets*
State	➢ Replace	• MFL reconditioning for reuse • Launder oil to replace new lubricants • Onsite re-refining
	➢ Function	• Energy recovery of cleaned MFL waste*
	➢ Incorporate	• Incorporate to other petrochemical waste for further treatment*
	➢ Store	• Treat and store the waste for immobilisation*

	➢ Combine	• Combine with other waste streams to create a higher fuel content input*
	➢ Extract	• Extract copper to create a less toxic waste stream
Performance	➢ Replace	• Replace virgin lubricants in low specification applications*
	➢ Function ➢	• Chemical reducing agent in steel making blast furnaces • Use in secondary lubrication* • Use for wood treatment applications*
	➢ Incorporate	• Incorporate untreated MFL waste as direct raw material input* (e.g. cement kiln)
	➢ Store	• Store MFL for future processing*
	➢ Combine	• Reformulate MFL with given its current high copper content* (add thickeners, additives)
	➢ Extract	• Extract contaminants in re-refining processes

6.4.9.3 Findings in the industrial ecosystem

It was found that market demand had played a key role in shaping the available technologies for waste oil treatment available in the UK; a historical strong market demand for waste oil for combustion had deterred investment in modern oil refining plants (WRAP 2009). Fitzsimons, Morley and Lee (2001) report several barriers for market penetration of re-refined oils, these barriers varied according to the market segment; but, in general, end users perceived the re-refined oils as an inferior product with low quality and unreliable standards.

For example, in the automotive lubricant market the variability in the composition of re-refined based oils makes quality assurance prohibitively expensive; additionally, management expressed brand concerns due to the perceived inferior quality and potential toxicity of a lubrication product manufactured from waste oil (Fitzsimons, Morley & Lee 2001). The customer's perception was not an unfounded one as some buyers have reported foul and dirty oil in their supplies (Fitzsimons, Morley & Lee 2001). These quality concerns would become an important factor in the successful commercialisation of co-products made from waste, just as it is for any other product in the market place. Fitzsimons, Morley and Lee (2001) had already identified 30-40 potential buyers of re-refined base oils, amongst these were marketers of metal working fluids, quench and process oils; but those potential customers only expressed some limited interest due quality concerns (odour and clarity of the oil). The OSS group is vertically integrating the supply chain, from waste collection and re-refining to the manufacturing of lubricants, as a way to improve the quality of the end products of re-refining (Fitzsimons, Morley & Lee 2001).

6.4.10 Lessons learned

This case study has shown the importance of analysing waste elimination strategies before embarking into waste remediation transformation activities (i.e. transforming waste into a co-product). Minimising the generation of waste using MQL would significantly reduce YCT's environmental impact; the waste minimisation strategy would require less research and development effort compared to implementing a remediation measures (i.e. removing copper ions from waste and transforming the MFL waste into a co-product) and would facilitate the remediation of residues with high copper content.

Two major barriers were identified to the transformation of waste into a co-product: quality concerns and legislation uncertainty. A co-product must adhere to the same quality standards as competing products made from virgin materials. A co-product requires a clear regulatory framework to prove that the waste stream from which is manufactured has ceased to be waste; up until the introduction of the Quality Protocols this situation was highly uncertain for re-refined waste oils, even within the agreed definition of waste stated in Article 3 of the EU waste framework directive 2008/98/EC. It is generally agreed that the quality protocol for processed fuel oil reshaped the waste oil market; it had a major role in the reduction of the oil re-refining services. Companies buying processed fuel oil (PFO) were able to pay higher prices; so, with the support of the quality protocol the market share of companies selling PFO grew rapidly (WRAP 2009).

Consumer perception of products made from waste remains as a key factor for the successful introduction of a waste based co-product in the market place. The market research stage of the ATM methodology should pay particular attention when addressing this issue. Lessons could be drawn from the re-manufacturing literature; for example, it is known that the perception of quality of remanufactured products affects consumer's willingness to pay (Hazen et al. 2012). Hazen et al. (2012) have found that when consumers do not fully understand the processes and procedures involved in remanufacturing, this creates an ambiguity that negatively affects their willingness to pay for remanufactured goods. It is therefore advised to shape customer's perceptions and educate them about the rigors of the remanufacturing processes (Hazen et al. 2012). This additional marketing cost to educate the customers might have an impact on the marketing budgets for co-product development, so it should be taken into consideration.

6.4.11 Improvement of the ATM methodology

The implementation of the ATM methodology would benefit from designing a waste elimination strategy for the short, medium and long term plan. This step would integrate the findings from section 6.4.3 into an action plan that would consider whether or not a remediation strategy is needed.

A corporate environmental strategy requires careful analysis and consideration using frameworks such as ecological foot print (EF), life cycle analysis (LCA) and environmental risk assessment (ERA) (Herva & Roca 2013). The findings from ATM methodology should contain enough information to allow the decision making process to begin, in other words, in-depth desk research needs to be undertaken to allow the use of appropriate decision making tools such as multi-criteria analysis (MCA). MCA is "*any structured approach to determining overall preferences among alternative options, where the* *options accomplish several objectives* (Herva & Roca 2013)", Herva and Roca (2013) conclude that MCA prove robust and reliable results when a large number of criteria are being considered; they also found that preference ranking organization method for enrichment of evaluations (PROMETHEE), analytic hierarchy process (AHP), analytic network process (ANP) where amongst the most frequently used methods in the cases reported in the scientific literature. Herva and Roca (2013) also found that the incorporation of fuzzy reasoning in decision making has increased significantly in recent applications; this is of no surprise in the light of this case study, given the high uncertainty of the re-refined oil market in the UK.

6.5 Case study research reflections

All four companies that took part in the case study research presented in this thesis were actively seeking to divert waste from landfill, but only James Dewhurst did not show signs of "short termism" behaviour during the interactions of the case study research. This case study research would have provided further findings if all companies implemented the proposed solutions, but that would have required considerably more time and direct involvement with company operations. This case study research was guided and limited by the observations of the research ethics committee in which it was made clear that contractual implications should be avoided when advising companies on the course of action for a given waste generation problem.

Implementation of the solutions proposed in this thesis would require a constructivist ontological paradigm in which the social actors take an active role in generating and implementing the solutions to the waste problem. This would be a way of avoiding the limitations posed by contractual implications for the researcher. Having employees directly tied to the research would also give the case study more priority within the internal objectives of the company. This approach is recommended for single case study research aiming to uncover the particular characteristics of an industry or a single waste stream.

Chapter 7. Analysis and Discussion

Following the epistemological considerations described in section 3.2, this thesis subscribes to the recommendations of the proponents of critical realism, thus, this section will present an analysis of generative mechanisms; the findings in each of the case studies presented in Chapter 6 will be analysed in order to identify the mechanisms that enable the transformation of unavoidable waste into co-products. The analysis of generative mechanisms will lead to a theory of waste transmutation (transformation of unavoidable waste into co-product). The generative mechanisms will be compared in a cross-case analysis and later discussed within the context of current waste transformations and developments in the global industrial ecosystem (external focus). The analysis and discussion from a cross-case point of view will make the findings more robust, whilst analysing the findings from an external focus will increase the external validity of the induced theory of waste transmutation (induced from case study findings).

7.1 Analysis of generative mechanisms

This section presents an analysis of the generative mechanism behind waste transformation processes; the method for analysing generative mechanisms has been described in section 3.8.3. The observations from each case study in Chapter 6 were classified and coded to generate a list of generative mechanisms that enable the transformation of waste into co-products.

These generative mechanisms were classified in three categories (shown in Table 7.1). The micro level presents mechanisms that are dependent on the waste stream generated in the manufacturing process and thus vary according to waste type. Meso level mechanisms operate at the organisational level and are influenced by the characteristics of the organisation. Macro level mechanisms are beyond the direct control of the organisation and are determined by the environment in which the organisation operates. Generative mechanisms were also coded into several groups (shown in Table 7.1) as a way to provide another level of analysis to gain insight.

Table 7.1 Generative mechanisms for the transformation of waste into co-products

Micro (waste stream)	**Meso (Organisational)**	**Macro (Environment)**
CHARACTERISATION • Adequate waste volume. • Consistent quality of waste stream.	MANUFACTURING PROCESS • A proven unavoidable waste: organisational, technical and economic limitations • Available machinery for waste transmutation	MARKET CONDITIONS • Market potential for the co-product. • Positive customer perception of recycled products.
TRANSMUTATION BENEFITS • Savings on waste disposal costs. • Risk reduction for end of life scenario.	RESOURCES • Resource commitment: time, personnel and budget. • Know-how and expertise about the waste stream material. • Research and development capability.	STANDARDS & LEGISLATION • Adaptation to industry standards and specifications. • Progressive waste legislation for the specified material.
TRANSMUTATION POTENTIAL • Higher performance than conventional products • Cheaper than conventional products • Contribution to sustainability	BUSINESS PERSPECTIVE • Contribution to environmental management system objectives • Co-product integration in the product portfolio. • A business model that supports waste transmutation. • Improving environmental credentials.	INDUSTRIAL ECOSYSTEM • Lack of alternative manufacturing processes in the short term future • Available technology for waste transmutation. • Supply chain for waste input materials. • Resource efficiency culture

These generative mechanisms explain how manufacturing organisations are able to transmute unavoidable waste streams into profitable co-products. By means of abduction and theoretical reinterpretation, the micro, meso and macro level mechanisms are linked to the three stages of the ATM methodology: analyse, transform and market. The presence of these generative mechanisms leads to the transmutation of non-product output (i.e. unavoidable manufacturing waste) into profitable co-products. In fact, the identification of these generative mechanisms refined the ATM methodology which could now incorporate specific methodological steps in each stage, as described in Table 7.2.

Table 7.2 Reinterpretation of the ATM methodology according to generative mechanisms

Analyse	**Transform**	**Market**
CHARACTERISE WASTE • Describe the physical and chemical characteristics of the waste stream. • Ensure adequate waste volumes for the waste transmutation. • Ensure a consistent quality of the waste stream.	DEVELOP A TRANSMUTATION PROCESS • Design a waste transmutation process • Select machinery for the waste transmutation process. • Run waste transmutation tests. • Co-product verification and validation.	RESEARCH MARKET CONDITIONS • Identify the market potential for the co-product. • Identify market segments with positive customer perception for recycled products. • Calculate the market demand.
IDENTIFY WASTE TRANSMUTATIONS • Search for existing waste transformation techniques. • Use the wheel of waste tool to generate ideas for co-products. • Use Pothmann's waste hierarchy to classify and prioritise waste transmutation options.	SECURE RESOURCES • Ensure resource commitment: time, personnel and budget. • Gather know-how and expertise about the waste stream material. • Gather research and development capabilities.	EXPLORE THE INDUSTRIAL ECOSYSTEM • Identify innovative manufacturing processes that could eliminate waste in the short term. • Identify existing technologies for waste transformation. • Search for a recycling supply chain for the waste stream. • Seek for resource efficiency industry networks.

IDENTIFY WASTE TRANSMUTATIONS BENEFITS • Calculate the economic gains and savings. • Identify options with positive environmental performance. • Identify options with positive social impact.	ALIGN PROJECT TO BUSINESS OBJECTIVES • Align project to environmental management objectives. • Integrate co-product to the product portfolio. • Adopt a business model that supports waste transmutation. • Market the co-product's environmental credentials.	ANALYSE STANDARDS & LEGISLATION • Design co-products to in accordance to industry standards and specifications. • Identify progressive waste legislation for the specified material, i.e. waste exemption status. • Apply for environmental permits
SELECT A TRANSMUTATION • Co-products should perform equal to or higher than conventional products. • Co-products should cost equal or lower than conventional products. • Co-products should have sustainability credentials.		

In a retroduction analysis, these generative mechanisms were tested analytically in the context of the ATM methodology to determine the reasons why they should exist (the function they perform) and how their interaction brings about waste transmutations. In order to achieve this, each generative mechanism group was ordered in a logical sequence and according to the information and function they provide. The result of this analysis is the a refined ATM methodology for the transformation of waste into co-products (shown in Table 7.3).

Table 7.3 Retroductive analysis of the generative mechanisms and refinement of the ATM methodology

Analyse (A), Transform (T) and Market (M)	Retroductive analysis
A. EXPLORE THE INDUSTRIAL ECOSYSTEM • Identify innovative manufacturing processes that could eliminate waste in the short term. • Seek for solutions in resource efficiency industry networks • Search for a recycling supply chain for the waste stream. • Identify existing technologies for waste transformation.	Before implementing the ATM methodology it is important to make sure that the manufacturing waste stream is in fact an unavoidable waste and that it cannot be prevented in the short term. Hence, a number of steps are proposed to seek for available waste prevention, minimisation or remediation technologies in the industrial ecosystem.
B. SECURE RESOURCES • Management commitment: align project to environmental management objectives. • Ensure resource commitment: time, personnel and budget. • Gather technical know-how and expertise about the waste stream material. • Gather research and development capabilities.	If a waste stream is truly unavoidable and has the potential to become a co-product; then resources must be secured for the waste transformation design process. It is noted that management commitment is important to secure by aligning the project with environmental management objectives.
1. CHARACTERISE WASTE - (A) • Describe the physical and chemical characteristics of the waste stream. • Ensure adequate waste volumes for the waste transmutation. • Ensure a consistent quality of the waste stream.	The first step to take is to know the chemical and physical characteristics of the waste stream in order to discover the maximum resource potential of the waste's current state and structure. Waste volume and quality should be determined as it plays a key role in the technical and economic feasibility analysis.
2. IDENTIFY WASTE TRANSMUTATIONS – (A) • Search for existing waste transformation techniques and technologies. • Analyse waste in order to identify value adding capabilities • Use the wheel of waste tool to generate ideas for co-products. • Use Pothmann's waste hierarchy to classify and prioritise waste transmutation options.	In-depth desk research could provide with proven and readily available waste transformation processes that turn waste into useful products. The wheel of waste is used to generate large number of ideas for future feasibility analysis, it also helps to find new waste transmutations using the information from desk research. Pothmann's waste hierarchy helps to classify waste transmutations and provides a guide to select options that maximise resource potential.

Table 7.3 Retroductive analysis of the generative mechanisms and refinement of the ATM methodology

Analyse (A), Transform (T) and Market (M)	Retroductive analysis
3. ANALYSE STANDARDS & LEGISLATION – (T) • Design co-products in accordance to industry standards and specifications. • Identify progressive waste legislation for the specified material, i.e. waste exemption status. • Identify the required environmental permits	Once a large number of ideas have been generated then it is possible to apply a filter: the compliance with waste legislation and industry standards.
4. DEVELOP A TRANSMUTATION PROCESS – (T) • Design a waste transmutation process • Select machinery for the waste transmutation process. • Run waste transmutation tests. • Co-product verification and validation	This step is the technical feasibility part of the ATM methodology and will also serve as another filter. Only ideas that are technically feasible are taken to the next stage of development.
5. RESEARCH MARKET CONDITIONS – (M) • Identify the market potential for the co-product. • Identify market segments with positive customer perception for recycled products. • Estimate the market demand.	The waste transmutation process needs to be able to produce a co-product that meets the needs, requirements and expectations of the customers. Therefore these two steps remain closely interlinked without any gate filter.
6. IDENTIFY WASTE TRANSMUTATION BENEFITS – (A) • Economic feasibility analysis • Identify options with positive environmental performance. • Identify options with positive social impact.	This step ensures that the waste transmutation options are sustainable or at least have a unique selling point as environmentally friendly or socially responsible co-products.

Table 7.3 Retroductive analysis of the generative mechanisms and refinement of the ATM methodology

Analyse (A), Transform (T) and Market (M)	Retroductive analysis
7. SELECT A TRANSMUTATION – (A) • Co-products should perform equal to or higher than conventional products. • Co-products should cost equal to or lower than conventional products. • Co-products should have verifiable sustainability credentials.	This step ensures that co-products are competitive in the market place, these selection criteria should be considered in the decision making process.
8. ALIGN WASTE TRANSMUTATION PROCESS TO BUSINESS OBJECTIVES (T) • Integrate co-product to the product portfolio. • Adopt a business model that supports waste transmutation. • Market the co-product's environmental credentials.	A final factor to consider is that the transmutation of waste into a co-product becomes a strategic advantage for the company rather than burden and thus ensuring the long term viability of the transmutation.

The final step in generative analysis explains the transmutation of waste into a co-product in the context of the case study results (Chapter 6) as a way of empirical and analytical test. This contextualisation (shown in Table 7.4) provides evidence for each of the sequential steps of the refined ATM methodology. Steps that are not based on the generative have been market with an asterisk—these steps have been included during the refining process as logical requirements.

Table 7.4 Contextualisation of the ATM methodology derived from the analysis of generative mechanisms

Refined ATM methodology	Contextualisation
A. EXPLORE THE INDUSTRIAL ECOSYSTEM • Identify innovative manufacturing processes that could eliminate waste in the short term. • Seek for solutions in resource efficiency industry networks • Search for a recycling supply chain for the waste stream. • Identify existing technologies for waste transformation.*	• The YCT case study showed that innovative lubrication methods could eliminate waste in the short term therefore no waste transmutation was pursued for the MFL waste stream (see section 6.4.7). • Making use of resource efficiency networks on LinkedIn it was possible to identify an industrial symbiosis between JDH and Faurecia (see 6.3.6) • There are recycling supply chains for gypsum waste but they are focused on gypsum from plaster board and as a result high quality gypsum has to be mixed with low grade plasterboard gypsum waste. So, even if there are recycling routes, a company has the alternative to optimize the resource potential of the waste and cash in the added value (see section 6.2.11).
B. SECURE RESOURCES • Management commitment: align project to environmental management objectives.* • Ensure resource commitment: time, personnel and budget.* • Gather technical know-how and expertise about the waste stream material. • Gather research and development capabilities.	• A knowledge exchange expert (KEE) from the Knowledge transfer network provided advice and a valuable contact in the glass fibre recycling industry. This contact was E4 structures, a small company carrying out R&D for the reuse of clean glass fibre waste (see6.3.6).
1. CHARACTERISE WASTE - (A) • Describe the physical and chemical characteristics of the waste stream. • Ensure adequate waste volumes for the waste transmutation. • Ensure a consistent quality of the waste stream.	• Enough physical and chemical information for characterisation is provided in the material safety data sheets of the waste stream materials at BWT, JDH and YCT. This information was complemented by doing literature review about the waste stream. • Laboratory tests are sometimes required at this stage in order to assess the toxicity of the waste stream as was the case with First Choice (see 6.1.3.2) • The low net present value (shown in Table 6.13) for the waste transmutation options for

	BTW's gypsum waste stream demonstrates the importance of adequate waste volumes for a given waste transmutation. • Waste segregation at source is needed to maintain a consistent quality of the waste stream. Waste streams could be homogeneous in composition, as it was with BWT's gypsum waste (see section 6.2.1), thus making waste segregation easy to achieve. However there could be instances where waste streams vary widely—according to production outputs—in which case it is possible to group waste streams into categories with similar resource potential as was the case with JDH(see section 6.3.5.1).
2. IDENTIFY WASTE TRANSMUTATIONS – (A) • Search for existing waste transformation techniques and technologies. • Analyse waste in order to identify value adding capabilities • Use the wheel of waste tool to generate ideas for co-products. • Use Pothmann's waste hierarchy to classify and prioritise waste transmutation options.	• Recognised waste transformation approaches for gypsum waste were found in the industrial ecosystem as reflected in the quality protocol for plasterboard gypsum waste discussed in section 6.2.8.7. • The general guidelines provided by the ATM methodology described in 5.2 were useful in generating ideas for BTW and YCT's waste streams. • The wheel of waste was successful in generating large number or theoretical waste transmutations for BWT and YCT as shown in Table 6.4 and Table 6.16. • Pothmann's waste hierarchy helped to classify and prioritise waste transmutation options whilst providing strategies to maximise the added value of the waste transmutations for BWT and JDH's waste streams (see section 6.2.10.1 and 6.3.8.1 respectively). • The table that presents the ideas generated using the wheel of waste was improved in the YCT case study, the new table has a more systematic approach to idea generation (see section 6.4.9.2).
3. ANALYSE STANDARDS & LEGISLATION – (T) • Design co-products in accordance to industry standards and specifications. • Identify progressive waste legislation for the specified material, i.e. waste exemption status.	• Waste transmutations must achieve products that match current industry standards and specifications; this was the case with the transmutation of BTW's gypsum waste (described in section 6.2.8.7). This waste transmutation option shows the importance of identifying progressive waste legislation and environmental permits i.e. waste exemption status.

• Identify the required environmental permits	
4. DEVELOP A TRANSMUTATION PROCESS – (T) • Design a waste transmutation process • Select machinery for the waste transmutation process. • Run waste transmutation tests. • Co-product verification and validation*	• The transformation process for the gypsum waste at BWT required only one major processing step (see section 6.2.5.2). However, the development of a waste transmutation process for JDH would have required significant R&D and collaboration with a research university (see section 6.3.6) • The selection of machinery for BWT was carried out in two stages: first on the basis of technical feasibility and secondly on the basis of economic analysis. The economic analysis showed that a small and cheaper machine would be more expensive to operate (see section 6.2.5.2) • None of the projects reached the stage of co-product verification and validation but this step fits with the logical sequence of process development.
5. RESEARCH MARKET CONDITIONS – (M) • Identify the market potential for the co-product. • Identify market segments with positive customer perception for recycled products. • Estimate the market demand.	• Gypsum for animal bedding was identified as a price competitive and higher performance product in relation to other types of animal bedding. • Market research showed a number of farms in the Macclesfield area. • E4 structures is a growing company specialised in designing products from plastic waste streams and has deep knowledge of the eco-friendly product market segment.
6. IDENTIFY WASTE TRANSMUTATION BENEFITS – (A) • Economic feasibility analysis • Identify options with positive environmental performance. • Identify options with positive social impact.	• The gypsum waste stream at BWT could be transformed into three profitable co-products: gypsum for animal bedding, soil improver and raw material for Hanson Cements (shown in Table 6.13) • JDH's waste stream if incorporated in to the products of E4 structures could have a positive environmental impact (to be assessed). • Diverting waste from landfill is a way to address a social problem; so by definition transforming unavoidable waste into a co-product has a positive impact on society through improved resource efficiency.
7. SELECT A TRANSMUTATION – (A) • Co-products should perform equal to or higher than	• The case study at BWT found two potential customers for the gypsum for animal bedding co-products, these customers showed interest and were persuaded to test the co-product on

conventional products. • Co-products should cost equal to or lower than conventional products. • Co-products should have verifiable sustainability credentials.	the grounds of cost savings for their farms and better animal bedding performance. • Gypsum for animal bedding should comply with PAS 109:2008 BSI specifications to be able to enter the market place.
8. ALIGN WASTE TRANSMUTATION PROCESS TO BUSINESS OBJECTIVES (T) • Integrate co-product to the product portfolio. • Adopt a business model that supports waste transmutation.* • Market the co-product's environmental credentials.*	• A transmutation of unavoidable waste into a co-product is more likely to materialise if the co-product integrates into the company's product portfolio, this was hinted from the opportunity to transform copper tube drawing offcuts into copper cladding for a sister company of YCT. • A business model that supports waste transmutations could subsidise the economic losses caused by the transmutation process and gain reward points in social corporate responsibility performance. In this regards JDH was willing to give away waste output with high recycling value to a company that could also make use of the glass fibre waste stream because this would also consolidate the waste transport into a single operation.
• * Indicates that the step is not based on observed generative mechanisms. These steps were added during the refining process as logical steps that should be in place.	

7.2 Cross case analysis

Three of the companies (Senior Aerospace BWT, James Dewhurst and Yorkshire Copper Tube) in this research project can be analysed as very similar case studies. First of all, these companies were all contacted at a NISP event for waste trading by means of industrial symbiosis and they all had a form of unavoidable waste stream. BWT and JDH were trying to find alternatives to landfill disposal by means of industrial symbiosis whilst YCT was looking for a more environmentally friendly and more cost effective waste management solution for their oil waste. Based on these similarities it is possible to compare and contrast each step of the refined ATM methodology, this cross case comparison and analysis is shown in Table 7.5.

Table 7.5 Cross case comparison and analysis of the refined ATM methodology

Refined ATM methodology	BWT	JDH	YCT	Analysis
A. EXPLORE THE INDUSTRIAL ECOSYSTEM				
· Identify innovative manufacturing processes that could eliminate waste in the short term.	There were no readily available manufacturing processes that could prevent gypsum waste from BWT in the short term, although innovative 3D printing processes could be developed in the short term, these process would still produce a type of unavoidable waste.	JDH's waste stream could be minimised to lower levels using OTED techniques but due to organisational limitations it has not been able to do so. The benefits from OTED techniques need to outweigh the gains from simpler waste remediation options.	YCT's oil waste could be minimised to very low levels in the short term using readily available MQL techniques	Innovative manufacturing technologies cannot always eliminate waste as seen with 3D printing technology for BWT's processes. Unavoidable waste is not caused only by technological limitations, organisational and economic limitations are also determinant factors. Waste minimisation could reduce waste to very low levels, thus making redundant the need for waste remediation strategies.
· Seek for solutions in resource efficiency industry networks	An industrial symbiosis (IS) opportunity was identified with King Feeders. Due to low waste volumes IS proved to be the most economically attractive waste solution.	An IS opportunity was identified with Faurecia.	Oil re-refining companies were identified in the regional industrial metabolism as well as safer energy recovery technologies.	Using existing solutions is preferable than developing a waste transmutation, unless there are higher economic benefits, competitive advantage or strategic goals to be gained.

Table 7.5 Cross case comparison and analysis of the refined ATM methodology

Refined ATM methodology	**BWT**	**JDH**	**YCT**	**Analysis**
· Search for a recycling supply chain for the waste stream.	There were several waste recyclers for plasterboard gypsum waste streams but few of them could take gypsum mould waste. The high purity of the gypsum is lost in the process of waste collection and transport when mixing BTW's gypsum with lower grade plasterboard gypsum.	There are available recycling supply chains in China; however the company wanted to reduce risks from exporting waste and find a local solution.	Waste oil reconditioning and laundering is available in Germany but it might not be cost effective.	Recycling supply chains should be studies to determine their adequacy, reliability, and cost effectiveness. Waste recycling supply chains need to be adequate to ensure the conservation of the waste stream's resource potential.
· Identify existing technologies for waste transformation.*	Readily available machinery could crush gypsum waste for three uses specified in the quality protocol for recycled gypsum waste from plasterboard.	There were no available technologies to transform glass fibre waste into a co-product but E4 structures was ready to invest in R&D to develop new eco-products that could incorporate the waste stream from JDH.	Oil Re-refining technologies is available in the UK but is offered by only one company. A process to transform re-refining oil sludge into grease was identified	Existing technologies to transmute waste could be readily adopted or even outsource the transmutation processing.
B. SECURE RESOURCES				
· Management commitment: align project to environmental management objectives.*	NA	NA	NA	The case studies did not investigate the degree of management commitment nor the integration waste management activities into environmental business objectives.
· Ensure resource commitment: time, personnel and budget.*	NA	NA	NA	

Table 7.5 Cross case comparison and analysis of the refined ATM methodology

Refined ATM methodology	**BWT**	**JDH**	**YCT**	**Analysis**
· Gather technical know-how and expertise about the waste stream material.	NA	A KTN knowledge exchange expert provided valuable information and contacts for companies interested in glass fibre waste recycling.	NA	Knowledge and expertise about the reuse and recycling of waste streams is a key ingredient to generate sensible waste transmutation ideas. This expertise should also include the legal aspects of waste reuse, e.g. waste quality protocols. Bringing experts to the field saves time and effort searching for readily available solutions.
· Gather research and development capabilities.	BWT was linked to a researcher at the University of Liverpool in order to test the feasibility of using gypsum waste for the manufacturing of geopolymers.	In partnership with a research University E4 structures would carry out the R&D for co-products that incorporate clean glass fibre waste.	NA	Government grants and collaboration with other companies and universities are ways to overcome R&D limitations.
1. CHARACTERISE WASTE - (A)				
· Describe the physical and chemical characteristics of the waste stream.	Implemented.	Implemented.	Implemented.	The characteristics of the waste stream could be determined by studying the raw materials and the way in which they are used in the manufacturing process.

Table 7.5 Cross case comparison and analysis of the refined ATM methodology

Refined ATM methodology	BWT	JDH	YCT	Analysis
Ensure adequate waste volumes for a waste transmutation scenario.	Waste volumes would determine the feasibility of waste transmutations as was the case with BWT.	Waste streams could be consolidated with other companies, as is the case with the clean glass fibre waste from JDH and Owens Corning.	YCT would not be able to implement in house oil re-refining or oil laundering due to the large scale of operations required for such solutions. But it could use small machinery for on-site energy recovery.	Using the knowledge and expertise on the field of waste recycling it is possible to determine the prospects of a successful waste transmutation project.
· Ensure a consistent quality of the waste stream.	Consistent gypsum waste stream.	Glass fibre waste stream varies in coating types, and glass fibre diameter, but it could be consolidated into groups depending on the requirements of the waste transmutation.	The waste oil is a collection of several types of MFL used in the production process with approximately 10% water content.	Large volumes and a consistent quality of waste stream are ideal waste streams for transmutation.
2. IDENTIFY WASTE TRANSMUTATIONS – (A)				
· Search for existing waste transmutation techniques and technologies.	Available options are specified in the quality protocol for recycled gypsum from waste plasterboard	Several promising techniques are reported in academic journals but the solutions need to be further tailored to the specific characteristics of JDH's waste stream.	A waste transmutation technique is reported (in the academic literature) for the unavoidable oil sludge from re-refining operations.	There is a growing number of academic papers reporting techniques that reuse waste in innovative applications. But it was found that few of the techniques have been proved in industrial scenarios. Companies need support to carry out tests to fine tune the solutions to their particular waste stream.

Table 7.5 Cross case comparison and analysis of the refined ATM methodology

Refined ATM methodology	**BWT**	**JDH**	**YCT**	**Analysis**
· Analyse waste in order to identify value adding capabilities	Implemented	Implemented	Implemented	This step is actually implemented along with the wheel of waste but it is stated as a separate step to add emphasis to the search for value adding solutions.
· Use the wheel of waste tool to generate ideas for co-products.	Implemented (see Table 6.4)	Implemented (see Table 6.16)	Implemented (see Table 6.20)	The wheel of waste is best implemented in a systematic way as it was shown in the YCT case study Table 6.20.
· Use Pothmann's waste hierarchy to classify and prioritise waste transmutation options.	Implemented after the wheel of waste.	Implemented after the wheel of waste.	Implemented before the wheel of waste and incorporated to the idea generation table.	When Pothmann's waste hierarchy is implemented after the wheel of waste, it serves to classify and prioritise ideas; when implemented before the wheel of waste it helped generate ideas in a prioritised manner and trigger more theoretical waste transmutation ideas. The second approach is preferred.
3. ANALYSE STANDARDS & LEGISLATION – (T)				
· Design co-products in accordance to industry standards and specifications.	Gypsum waste products have to comply with PAS 109:2008 BSI specifications and with the quality protocol for recycled gypsum from waste plasterboard.	Eco-screed manufacturers were concerned about including clean glass fibre waste into their products because that will cause non-compliance with BSI standards.	There is a Quality protocol for processed fuel oil.	Quality protocols Publicly available specifications (PAS) for products made from waste are very useful to ensure quality and instil confidence in the market.

Table 7.5 Cross case comparison and analysis of the refined ATM methodology

Refined ATM methodology	**BWT**	**JDH**	**YCT**	**Analysis**
· Identify progressive waste legislation for the specified material, i.e. waste exemption status.	Progressive legislation also prevents unsafe uses of waste as it was the case with the position statement for the restriction of the use gypsum and plasterboard in animal bedding.	NA	NA	Identify progressive legislation in the making that could enable waste streams to achieve waste exemption status, these are often communicated by position statements issued by the environment agency.
· Identify the required environmental permits	This extra step was added to the ATM methodology during this study.	NA	The Quality protocol for processed fuel oil reshaped the waste oil market by instilling confidence and expanding the market share of processed fuel oil (see section 6.4.10)	Waste legislation
4. DEVELOP A TRANSMUTATION PROCESS – (T)				
· Design a waste transmutation process	A crushing step is the major process required for the identified co-products	E4 Structures would carry out the R&D and determine the required process	NA	The ideal waste transformation would require a minimum number of processing steps whilst maximising the resource potential of the waste stream and thus increasing the added value.
· Select machinery for the waste transmutation process.	Off the shelve crushing machines were selected	Likely to use machines for chopping glass fibre to suitable lengths.	NA	The use of complex machinery is avoided by maximising the resource potential of the waste stream.
· Run waste transmutation tests.	Arranged.	NA	NA	NA
· Co-product verification and validation*	NA	NA	NA	NA

Table 7.5 Cross case comparison and analysis of the refined ATM methodology

Refined ATM methodology	**BWT**	**JDH**	**YCT**	**Analysis**
5. RESEARCH MARKET CONDITIONS – (M)				
· Identify the market potential for the co-product.	Co-products generated from the processing of 8 tonnes of waste could be easily supplied to one or two local farmers.	The market potential would benefit from the growing demand for E4 structures' products.	NA	The co-product's market potential should be big enough for the waste volume generated by the company.
· Identify market segments with positive customer perception for recycled products.	Two farms expressed interest in testing animal bedding made with BWT's gypsum.	E4 Structures operates in the market segments for eco-friendly products.	Re-refined waste oil was not perceived as a good quality product in the market (discussed in section 6.4.10)	Identifying waste transformation options in eco-friendly product markets would ease product entry and provide a more stable market demand for the co-product.
· Estimate the market demand.	It was not necessary to estimate the total market demand for the co-products because local demand was bigger than the waste output.	NA	NA	The co-product's market demand should be big enough for the waste volume generated not only by the company but also considering similar waste types.
6. IDENTIFY WASTE TRANSMUTATION BENEFITS – (A)				
· Economic feasibility analysis	Five landfill diversion options were analysed with positive NPV and payback periods ranging from 3.4 to 4.7 years (see Table 6.13)	NA	NA	Even for the low waste volumes at BWT there were profitable waste transmutations that could be implemented in the short term. This waste transmutation could be implemented whilst improved manufacturing process develop (i.e. 3D mould printing).

Table 7.5 Cross case comparison and analysis of the refined ATM methodology

Refined ATM methodology	**BWT**	**JDH**	**YCT**	**Analysis**
· Identify options with positive environmental performance.	Further environmental analysis is needed to verify the environmental benefits.	NA	Re-refining of waste oil is only beneficial from a global warming perspective when compared to burning waste oil (in cement factories of power stations) in situations where it replaces fuels such as oil and gas (WRAP 2009).	By definition, waste transmutations should have a positive environmental impact.
· Identify options with positive social impact.	Using gypsum waste as soil improver safely diverts gypsum waste from landfill. If the gypsum is given away free of charge as analysed in one of the scenarios, BWT will benefit the local farmers.			Social aspects should also be included in the analysis of waste transmutations.
7. SELECT A TRANSMUTATION – (A)				
· Co-products should perform equal to or higher than conventional products.	Gypsum for animal bedding outperforms performs other animal bedding materials.	E4 structures designs composite materials that outperform conventional plastics.		If co-products were to achieve a waste alchemy profit levels they should outperform conventional products in terms of function, features and wow factors.

Table 7.5 Cross case comparison and analysis of the refined ATM methodology

Refined ATM methodology	**BWT**	**JDH**	**YCT**	**Analysis**
Co-products should cost equal to or lower than conventional products.	Gypsum for animal bedding is cheaper than sawdust, sand, straw or paper where costs have a price range of 7p to 27p per cow per day. Usage or gypsum is around 2kg per cow per day costing in the range of 4p to 6p per cow per day—depending on application conditions. (Extracted from www.rwn.org.uk)	NA	NA	If co-products are competing with conventional products, they should be cheaper in order to gain market share.
· Co-products should have verifiable eco-friendly or sustainability credentials.	Having verifiable labels or certifications could help marketing the animal bedding gypsum—if it were to be sold directly to consumers.	NA	NA	Adopting eco-friendly or sustainability credentials could help improve customer perception about co-products made from waste.
8. ALIGN WASTE TRANSMUTATION PROCESS TO BUSINESS OBJECTIVES (T)				
· Integrate co-product to the product portfolio.	Gypsum waste transmutations could not be developed into co-products that could fit into the product portfolio because gypsum waste is an auxiliary material and is not used directly in the aerospace industry.	Given the variety of markets in which JDH operates, it would be strategic to develop a co-product that could be sold to their current customer base. In this scenario, co-products could even be used as strategic loss output and loss leaders.	Copper offcuts from the tube drawing process could be used to manufacture products for KME ecological products range. A waste transmutation for copper grease could be integrated into the product portfolio of KME and could also be used as a strategic loss output or loss leader.	

Table 7.5 Cross case comparison and analysis of the refined ATM methodology

Refined ATM methodology	**BWT**	**JDH**	**YCT**	**Analysis**
· Adopt a business model that supports waste transmutation.*	NA	NA	NA	If there are significant sustainability improvements from waste transmutations, a company could consider being more generous during the investment appraisal of these projects and accept long payback periods or low NPV.
· Market the co-product's environmental credentials.*	NA	NA	NA	Companies could use waste transmutation to divert unavoidable from landfill and achieve Zero waste status.

7.3 Validation of case study findings

(Eisenhardt & Graebner 2007) suggests that “the use of extensive tables and other visual devices that summarise the related case evidence are central to signal depth and detail in empirical grounding”. Following Eisenhardt’s (2007) advice, a separate was constructed in order to summarises the evidence for each theoretical construct (steps of the ATM methodology), as an effecting way to present case evidence. The so called “construct tables” create a strong bridge from the qualitative evidence to theory-testing research; Table 7.6 presents each of the steps of the refined ATM methodology in the context of the evidence provided in the previous table (Table 7.5), this construct table tests the refined ATM methodology for the replication logic of case study. Replication logic suggests that a construct is not just idiosyncratic to a single case (Eisenhardt & Graebner 2007). The validation test claims replication if the step of the ATM methodology (construct) was applied or provided some information for the transmutation of waste into a co-product. Further research should consider testing the replication of those steps that did not provide evidence.

Table 7.6 Validation of case study findings

Refined ATM methodology	**BWT**	**JDH**	**YCT**	**Validation**
A. EXPLORE THE INDUSTRIAL ECOSYSTEM				
· Identify innovative manufacturing processes that could eliminate waste in the short term.	Applied	Applied	Applied	Replication
· Seek for solutions in resource efficiency industry networks	Applied	Applied	Applied	Replication
· Search for a recycling supply chain for the waste stream.	Applied	Applied	Applied.	Replication
· Identify existing technologies for waste transformation.*	Applied	Applied	Applied	Replication
B. SECURE RESOURCES				
· Management commitment: align project to environmental management objectives.*	NA	NA	NA	
· Ensure resource commitment: time, personnel and budget.*	NA	NA	NA	
· Gather technical know-how and expertise about the waste stream material.	NA	Applied	NA	
· Gather research and development capabilities.	Applied	Applied	NA	Replication
1. CHARACTERISE WASTE - (A)				
· Describe the physical and chemical characteristics of the waste stream.	Applied	Applied	Applied	Replication
Ensure adequate waste volumes for a waste transmutation scenario.	Applied	Applied	Applied	Replication
· Ensure a consistent quality of the waste stream.	Applied	Applied	Applied	Replication
2. IDENTIFY WASTE TRANSMUTATIONS – (A)				
· Search for existing waste transmutation techniques and technologies.	Applied	Applied	Applied	Replication
· Analyse waste in order to identify value adding capabilities	Applied	Applied	Applied	Replication
· Use the wheel of waste tool to generate ideas for co-products.	Applied	Applied	Applied	Replication
· Use Pothmann's waste hierarchy to classify and prioritise waste transmutation options.	Applied	Applied	Applied	Replication
3. ANALYSE STANDARDS & LEGISLATION – (T)				
· Design co-products in accordance to industry standards and specifications.	Applied	Applied	Applied	Replication
· Identify progressive waste legislation for the specified material, i.e. waste exemption status.	Applied	NA	NA	

Table 7.6 Validation of case study findings

Refined ATM methodology	**BWT**	**JDH**	**YCT**	**Validation**
· Identify the required environmental permits	Applied	NA	Applied	Replication
4. DEVELOP A TRANSMUTATION PROCESS – (T)				
· Design a waste transmutation process	Applied	Applied	NA	Replication
· Select machinery for the waste transmutation process.	Applied	Applied	NA	Replication
· Run waste transmutation tests.	Applied	NA	NA	NA
· Co-product verification and validation*	NA	NA	NA	NA
5. RESEARCH MARKET CONDITIONS – (M)				
· Identify the market potential for the co-product.	Applied	Applied	NA	Replication
· Identify market segments with positive customer perception for recycled products.	Applied	Applied	Applied	Replication
· Estimate the market demand.	Applied	NA	NA	
6. IDENTIFY WASTE TRANSMUTATION BENEFITS – (A)				
· Economic feasibility analysis	Applied	NA	NA	
· Identify options with positive environmental performance.	Applied	NA	Applied	Replication
· Identify options with positive social impact.	Applied	NA	NA	
7. SELECT A TRANSMUTATION – (A)				
· Co-products should perform equal to or higher than conventional products.	Applied	Applied		Replication
Co-products should cost equal to or lower than conventional products.	Applied	NA	NA	
· Co-products should have verifiable eco-friendly or sustainability credentials.	Applied	NA	NA	
8. ALIGN WASTE TRANSMUTATION PROCESS TO BUSINESS OBJECTIVES (T)				
· Integrate co-product to the product portfolio.	Applied	Applied	Applied	Replication
· Adopt a business model that supports waste transmutation.*	NA	NA	NA	
· Market the co-product's environmental credentials.*	NA	NA	NA	

7.4 Discussion

At the beginning of the research, several large multinational manufacturing companies members of the University of Liverpool industrial liaison board were contacted using a case study protocol (see appendix 1), during the interviews with one of the large global companies, it was found that it was not willing to implement the ATM methodology due to its premature stage of development. But now, with a refined ATM methodology based on the analysis of generative mechanisms, it will be easier to persuade companies to adopt this approach and cash the value lost due to unavoidable waste. This refined ATM methodology improves the chances of finding a solution that transmutes waste into a profitable product.

Even if companies are too busy with their day to day activities to be able to pay closer attention to optimising waste management strategies, companies could still benefit from the increased price paid for their waste stream if the waste transmutation is done by a third party: i.e. a waste alchemist (as proposed in section 6.2.10.2). If a co-product does not integrate into the company's product portfolio, managers could be reluctant to undertake waste transmutations, companies are arguably not in the business of waste recycling. But companies are neither in the business of manufacturing waste and loosing profits, so they should invest resources in improving their waste management strategies.

If carried out holistically and systematically, improving waste management strategies could have a positive impact in the key aspects of a business: profitability, process improvement, environmental performance and social corporate responsibility. This thesis proposes the use of the all seeing eye of business (All-SEB) to manage the outputs if a manufacturing process in a holistic manner. Unfortunately, due to time and resource limitations for the PhD research project and given the context of the case studies, it was not possible to fully implement the All-SEB and to carry out an exhaustive investigation of its use as a business tool to manage a holistic product portfolio (one that includes loss output, waste output and co-product output).

The All-SEB was used to illustrate the way in which a waste transmutation could divert waste from landfill whilst contributing to add profits to the bottom line. Managers of the waste stream had grasped the concept intuitively and agreed to pursue a co-product that could reach “waste-alchemy” status. The All-SEB was also used to generate waste elimination strategies for a given waste stream: prevention, minimisation and remediation. The analysis of waste elimination strategies proved to be useful steps in the general framework for the elimination of waste. Two case studies (BWT and YCT) had found ways to prevent waste in the short term future whilst JDH could minimise waste immediately. Analysing waste streams from this perspective directs attention to ways in which manufacturing processes could be improved and how they are affected by current technological developments. This analysis is important for manufacturers from a strategic point of view because it could spur innovation and add a competitive advantage to the business.

Based on the findings in the BWT and YCT case study, it is proposed that focusing on waste analysis using the All-SEB’s strategies (waste prevention, minimisation and remediation) integrates waste reduction and cleaner production into the broader context of process innovation and business strategy. This approach could make sustainability issues to become part of business core decisions instead of leaving them as afterthought decisions. Unilever, for instance, leads a strong commitment to waste elimination from its factories, this year it declared that by 2012 more than 50% of all its 252 factories have achieved zero waste to landfill status, and that by 2015 none of them will send waste to landfill (Dötsch 2012).

The holistic approach to waste management presented in this thesis aims to bring management awareness of waste prevention from the physical waste stream at the end of the production line, to the manufacturing process itself all the way to the product design stage by means of “fit thinking” design (introduced in section 4.1). In fact, a recent report from McKinsey on manufacturing resource productivity recommends to downstream manufacturers to focus on optimising their products in order to use materials more efficiently (Mohr et al. 2012).

The ATM methodology was implemented using the guidelines and principles described in theoretical propositions (see section 5.2). The iteration between each stage (analyse, transform and market) was carried out with a pragmatic approach and striving to find a viable solution that could be implemented by the company if they were to decide to do so. This approach did limit the development of higher value co-products, but given the short time and lack or resources it would have not been possible to carry out intense research and development for the theoretical high value co-products. A pragmatic approach also seemed more beneficial for the companies involved in the case study. Exploring pragmatic and ‘real life’ options provided an understanding of the current waste management practices (recycling routes, legislation, technological developments, etc.) The adoption of a pragmatic approach gives generative a ‘real life’ context and increases the applicability of the ATM methodology to real industrial waste disposal problems.

These case studies have shown that companies would have difficulty carrying out with the research and development required to transmute unavoidable waste into profitable co-products. It also appears that waste recyclers are not currently undertaking such research; so, in effect, this leaves a gap where innovation needs to take place in order to maximise the resource potential of the waste stream. This finding in in line with McKinsey’s recommendation for waste-management companies; the consulting firm advices them to start by optimising processes and developing new markets for material reuse (Mohr et al. 2012). Indeed as McKinsey points out, waste management companies have an opportunity to develop services that allow manufacturers to capture value from unavoidable waste streams (Mohr et al. 2012). For example, waste management companies could provide the crushing of gypsum and transportation to nearby farms and assume the role of "waste alchemists" in the industrial ecosystem. If waste management companies decide to transform themselves into raw-materials and energy suppliers as Mohr et al. (2012) point out, they would also benefit from methods and tools to find innovative uses for waste (i.e the wheel of waste) and methods to transform waste into products for new markets (i.e. ATM methodology).

Crowdsourcing is another way in which companies could find innovative solutions to reuse their unavoidable waste streams. a waste transmutation challenge was posted twice on Innocentive: dealing with drill cutting waste during bitumen extraction and alternative market/uses for asphaltenes, offering an award of 10,000 USD. Details of the problem cannot be described due to confidentiality agreements, but the fact that a company is willing to pay a generous reward shows that the waste stream has potential to become a source of profits. As it is the case with waste management companies, the problem solvers from Innocentive would benefit from using the wheel of waste to generate ideas and the ATM methodology to design a waste transmutation process that turns waste into a profitable co-product. Marblar is a new crowdsourcing website that has a different approach to innovation: it crowdsources market applications for dormant and emerging technology. In this approach, the growing waste transformation technologies developed by the research community could be marketed to companies wishing to find innovative applications for their waste stream. This second type of crowdsourcing would reduce R&D efforts from the companies and would also link them to researchers that could fine tune their techniques to the specific waste stream in question.

Adopting the holistic waste management strategy proposed in this thesis has the potential to reduce waste to landfill independent of whether it is implemented by the manufactures themselves, waste management companies, crowdsourcing problem solvers or external consultants.

The refined ATM methodology has the potential to reduce waste levels in industry. For instance, mining and mineral-processing waste is one of the world's largest chronic waste concerns (Bian et al. 2012). The generation of mining and mineral wastes could be considered an unavoidable necessity because they are closely related to the formation of the target resource minerals and need to be separated (Bian et al. 2012), the fact that these wastes are unavoidable makes them a perfect candidate for waste transmutation. These wastes are generated in large quantities; for example, slurry from coal production may reach levels of 10 to 30% of total production (Bian et al. 2012), these high levels of unavoidable waste would justify investment in R&D for waste transmutation and it would also make the economic feasibility more favourable. In their analysis, Bian et al. (2012) do recognise the potential environmental impact of reusing mining wastes, and recommend to always implement appropriate environmental monitoring and assessment studies during the reuse design process. Bian et al. (2012) also observe that economic cost-benefit analysis "*is the ultimate driver for the feasibility of a specific reuse technology*"… "*even the most eco-friendly process methods will be difficult to implement without regulatory or government subsidies*". In that light, profitable waste transmutations are the appropriate waste remediation strategy; unless the mining company is willing to subsidise the waste transmutation as part of their environmental management objectives.

Another area of opportunity is in the valorisation of waste biomass; Tuck et al. (2012) also focus their research on ways to get higher value from unavoidable biomass waste. Tuck et al. (2012) point out that, due to the enormous waste volumes around the world (megatonnes per year), merely targeting the production of high value chemicals won't have any significant impact in reducing waste levels around the world, so they argue to start with the production of high volume chemicals. This relates to the observation in the ATM methodology to match the waste stream volumes to the market demand: a profitable waste transformation might not be able to use all of the waste stream volume. Waste generators and waste management companies have ample areas of opportunity. For instance, currently, "*most lignin is used as an energy source in the pulping industry, and that there is no route to valorisation beyond the energy route, although new catalysts are being discovered*" (Tuck et al. 2012)… for the production of aromatic compounds. Tuck et al. (2012) provide a review on ways to valorise bulk chemicals from carbohydrate residues and ways to transform protein waste into platform chemicals. Indeed, technologies for reusing waste are being developed at an accelerated phase, as evidenced by the growing number of publications in the academic literature, but they need to find their way to manufacturers and succeed in the market place and that's where the ATM methodology could provide its contribution to waste reduction in the industrial ecosystem.

An illustrative case about the importance of managing unavoidable industrial waste is related to the red mud spill in Ajka, Hungary (described in end of section 2.1.1). Prior to the Ajka accident, several reutilisation schemes had been developed for the red mud; however common industrial practise is to store the red mud in giant open-air ponds. It is in such situations that the ATM methodology could ensure that economically viable solutions are found for the specific conditions of the manufacturer's waste stream. The red mud case reflects several of the generative mechanisms for the transmutation of waste into a profitable co-product. The waste transmutation uses an unavoidable waste stream, and transforms it into a high value co-product with competitive advantage over conventional products. The transmutation step is achieved in a single step utilising available machinery (dust treating electric arc furnace).

A theoretical scenario is formulated to further explore this case. If a company wants to remediate their red mud waste (following the general waste elimination framework proposed in this thesis) it will be guided to consider waste elimination strategies (i.e. the adoption of Orbite's process) before implementing the novel red mud treatment. The general framework for waste elimination would require the company to analyse whether the waste is truly unavoidable in the short, medium and long term. If there is enough room for manoeuvrings, the company could implement the waste transmutation process (novel red mud treatment) if it proves economically feasible in that time frame. If there is not an economic case, the company would be better off by exploring the industrial metabolism to find optimal recycling routes, for example by industrial symbiosis, external waste alchemists, or waste improved management services. Of course, if the company realises the environmental risk reduction and corporate social responsibility benefits from a waste transmutation approach, then the company could sell the co-product even as a strategic loss output.

Following the guidelines of the refined ATM methodology, this theoretical company would ensure that the mineral wool complies with industry standards & legislation, it would also identify an adequate market segment in the mineral wool market—given the specific characteristics of the co-product—and it would also ensure that the waste transmutation is aligned with the business objectives of the theoretical company. This theoretical exercise proves that the generative mechanisms are relevant to other similar industrial contexts.

Chapter 8. Conclusions and future work

In the introduction to a special issue on working with waste, Wigginton, Yeston and Malakoff (2012) point out that people have been imaginatively working with waste from millennia, but that it is becoming an increasingly complex challenge.

Starting from a company perspective, this thesis can confirm that working with waste is indeed becoming an increasingly complex challenge. Helping companies eliminate waste to landfill requires a systematic and holistic approach to waste management. Waste permeates all aspects of a business, from the conception of the product design, the resource efficiency of the manufacturing process, to the end of life of the product itself and all the associated non-product outputs. As such, waste management permeates to all levels of business strategy. The All-SEB is a holistic model that integrates waste management to the chore of day to day business decisions. Having a model that manages product output and non-product output side to side is a powerful visual tool that highlights where profit is being created and where it is being lost. The All-SEB proved to be a use useful model for understanding the nature of waste, this understanding was the based upon which three waste elimination strategies were drawn: prevention, minimisation and remediation.

Companies are operating in a rapidly changing world amidst fierce competition from a globalised market. This situation requires that companies be prepared for change and disruptive technologies not only for their product output but also with regards to their non-product output. The case studies presented in this thesis have shown that analysing waste elimination strategies using the All-SEB could have wide range implications for strategic business objectives ranging from product design, process improvement, profitability levels, environmental performance and corporate social responsibility. It is therefore important that companies have these types of business tools to allow them make holistic decisions with regards to the performance of the business.

The general framework for the elimination of waste provides guidelines based on the insights gained from the All-SEB and should be implemented before waste remediation strategies are undertaken; this ensures that only unavoidable waste output is remediated.

The All-SEB also provides understanding about the potential uses of waste and the way in which waste streams could be turned into profit. The theoretical propositions suggested that waste output could be transmuted into co-products with low, medium and high profit margin. The findings from the case studies suggest that waste can in fact be transformed into profitable co-products. But this profit levels depend on factors such as: waste volume, ability to develop transmutation technologies that maximise resource potential, and a positive market and regulatory environment.

From a design process perspective we can observe that transmuting waste into a co-product is a particular engineering design challenge that requires tailored tools for idea generation and selection. The wheel of waste was tested in the three case studies; it is most useful when implemented in a systematic way, doing so allowed the PSSP language to yield more theoretical uses of waste. Ideas are classified and prioritised according to Pothmann's waste reuse hierarchy. This hierarchy should not be taken for granted as the most desirable options, but it serves as a guiding principle in the selection process. Further steps would require the use environmental analysis tools to verify the environmental credentials of the proposed waste transmutation.

The general ATM methodology serves as a guiding principle for designing the process of waste transmutation and ensuring that the co-product achieves a maximum value. The general methodology is complemented by the refined ATM methodology. The refinement of the ATM methodology was carried out during generative mechanism analysis. The refined ATM methodology ensures that waste transmutation proposals can become a successful co-product in the market place under current waste legislation. Based on an analysis of generative mechanisms, the refined ATM methodology takes into account the necessary conditions that should be satisfied in order for the waste transformation to be successfully implemented.

Wigginton, Yeston and Malakoff (2012) also point out that to minimize the amount of waste generated and wring the most value out of the rubbish we create requires a mix of smart science, practical policy and appropriate technology. This observation requires a view from the macro perspective of the industrial ecosystem. Companies should become more aware of their industrial ecosystem, not only in a geographical meaning but from a supply chain perspective. It was found that co-products that integrate well within the product portfolio have more chances of succeeding in the market place because they not only benefit the company generating the waste but could also add non-monetary value to current customers. Co-products that integrate well into the product portfolio are also more likely to get subsidised as strategic loss output.

Waste management solutions do not have to be constrained to the capabilities of the company generating the waste, besides industrial symbiosis there are a number of strategies to transform unavoidable waste into profitable co-products. Waste management companies could be approached to get resource optimisation services, i.e. transmutation processing services, logistic services, waste and legislation advice, etc. Waste management companies are also well positioned to become waste alchemist and carry out the waste transmutation process in exchange of a share of the profits generated.

The application of the All-SEB, the general framework for waste elimination, the ATM methodology and the idea generation tools are not constrained to manufacturers producing waste, this methods and tools could be used by waste management companies to improve their understanding of manufacturing waste, it could be used by consultants looking for innovative recycling solutions, it could also be used by regulators to be one step ahead and discover progressive waste legislation ideas.

As logn as manufacturing processes depend on material substractive methods and as long as the laws of thermodynamics increase apply to manufacturing, there will always be some unavoidable waste to focus on.

The analysis of generative mechanism that was used to derive a refined ATM methodology identified the necessary conditions for a waste transmutation project to be successful. Future research should test the necessity versus the sufficiency of the elements in this 'causal recipe' in order to keep refining the ATM methodology.

The fit thinking framework for product design could not be tested in the set-up of the case studies presented in this thesis, so it is left to the eco-product design research community to test and validate the soundness of the approach and its effectiveness in optimising resource consumption.

The All-SEB could not be implemented in its full format due to the time constraints and resource limitations of the research project, testing the soundness of the All-SEB is deemed more appropriate for the field of 'green' business research and product portfolio management. The question is how well does the All-SEB integrates waste prevention and cleaner production into a corporate sustainability strategy and into the business chore?

Another area for future research is the study of ways in which waste mangement companies could evolve into 'resource and energy providers' and what business models could they adopt?. It would also be interested to find out how would a waste alchemist fit into the industrial ecosystem? And what business models could they adopt? Linking the two propositions, researchers might as if waste management companies could become waste alchemists?

A final area to explore for further insight is to apply the ATM methodology to unique and special waste streams, such as radioactive waste from nuclear power plants and to world food waste. The institue of mechanical engineers has just published a report which has estimated world food waste to be between 30-50% of the total world food production (estimated to be four billion metric cubes per annum) (IMechE 2013).

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Appendix 1. Case study protocol

Case study proposal

The ATM methodology: How to Analyse, Transform and Market unavoidable industrial waste.

Background

The objective of this case study research is to test the concepts, methods and tools developed as part of the PhD project titled "sustainable manufacturing: turning waste into profits". The concepts are presented in two separate academic papers (available on request). The paper titled "**introducing the all seeing eye of business: a model for understanding the nature, impact and potential uses of waste**" provides the theoretical background for the project and it also introduces the fundamental concepts and vocabulary used throughout the project; this paper is currently being peer reviewed at the Journal of Cleaner Production. The other paper is titled "**introducing the ATM methodology: how to analyse, transform and market unavoidable industrial waste**", the ATM methodology provides guidelines for analyzing waste in manufacturing processes, there are also guidelines for transforming unavoidable waste (due to thermodynamic or technological limitations) into high margin co-products. To achieve this, the methodology uses structured questions and a tool for idea generation dubbed "the roulette of the fundamental uses of waste". This paper was presented at the International Conference on Remanufacturing 2011.

Introduction

Production processes have two kinds of outputs: product output and non-product output. Non product output (NPO) is what constitutes waste, emissions and pollution. A paint manufacturer that implemented Material Flow Cost Accounting techniques (MFCA) realized that "only *12% of purchased materials by weight went into the product, the rest had to be disposed of at high costs or had to be treated with cleaning technologies"* (Jasch 2009a). Current accounting systems do not measure the "true cost of waste", this paint shop found out that, by monetary value, only 39% of the raw and auxiliary materials purchased were actually transformed into products (Jasch 2009a).

There are abundant methods and techniques for preventing, reducing and eliminating the NPO caused by inefficiency and error e.g. lean manufacturing, six sigma, Total Preventive Maintenance, Health and Safety best practices etc. But in spite of all efforts, some NPO will always exist and will be "unavoidable" due to the nature of the manufacturing process. Current manufacturing processes depend on subtractive methods i.e. milling machines and trimming operations; certain chemical processes require the use of solvents to break the bonds in the starting materials of a reaction; thus leading to unavoidable by-products. So what is the best strategy for dealing with unavoidable NPO?

Our research provides some answers. First, let's explore the current approaches. Unavoidable NPO could be reused within the same manufacturing process; however, this is not always possible. Industrial symbiosis promotes the concept of waste exchange within industry, this is a more viable option for some wastes; however, unless the waste has adequate levels of quality and reliability, companies would not pay a premium over the scrap value associated with the waste.

The Analyze stage of the ATM methodology aims to find new uses for the unavoidable NPO stream; the objective is to add value to the waste and, ideally, transform it into a highly profitable co-product. The ATM methodology also analyzes the technical feasibility of the NPO transformation; this includes developing the manufacturing steps necessary to add value to the NPO. The methodology is a specific type of product development: the marketability of the proposed NPO transformations will be studied in order to determine the investment potential of the transformation project. The end result will be a technical report describing the waste transformation process and a business case detailing the potential profits and socio-environmental benefits gained from re-using and transforming unavoidable NPO.

The aim of implementing the ATM methodology is to figure out the best strategy for dealing with unavoidable NPO. Considering growing environmental concerns and regulations disposing NPO into landfills is not a sustainable option. Recycling is energy intensive and adds little or no value to the company generating NPO. Waste exchange through industrial symbiosis is a viable alternative; however, waste is typically exchanged at scrap value. The ATM methodology, in a way, tries to do "waste alchemy" transforming waste into a highly profitable co-product. Our research project aims to test, improve and validate the ATM methodology in a diverse range of industrial settings. We look forward to building win-win scenarios of collaboration with your company. Remember, cash your waste; do not waste your cash.

The proposal

The case study will provide benefits for both the industrial collaborator and the researcher. The industrial collaborator will benefit from cutting edge thinking about sustainable manufacturing whilst being linked to an extensive academic network brought by the researcher, but the most tangible benefit for the company is the opportunity to transform current unavoidable waste into a highly profitable co-product, that adds to the triple bottom line of profit, planet and people.

These case studies will help the researchers build a deeper understanding of the modus operandi of sustainable manufacturing whilst observing and documenting the implementation of the ATM methodology in a real manufacturing setting; this will be a way of testing the theoretical propositions of the research. The academic findings will be published in the researcher's doctoral dissertation. When necessary, confidentiality agreements will be put in place, the publication of the research will be governed by the University of Liverpool's research ethics standards.

Implementing the ATM methodology and deploying waste transformations will require several steps, in broad terms, these will include the following:

a) Understand the context in which the company operates; gather background information, visit the site and understand the production process.
b) Analyse the production process and find areas for maximum potential.
c) Gather necessary information and data for the waste transformation.
d) Implement the ATM methodology.
e) Deploy the waste transformation project.
f) Measure and monitor performance.
g) Review and improve the waste transformation process.
h) Write a case study report.

As researchers we understand that each business environment is different and each one has different policies and priorities, so, in that light, we are open to different approaches for the implementation of this industrial research project; our ultimate aim is to investigate, in a real industrial setting, the soundness of the theoretical propositions described in the introduction.

We envisage a number of possible scenarios of collaboration that will satisfy our objective; these are presented in *Table 1* in increasing degrees of research objective fulfilment. The list also reflects the degree of involvement in the company and, in a way, the degree of commitment from, both, the researcher and the company. We are happy to discuss and adjust any of the possible scenarios of collaboration, bearing in mind your company's needs, requirements and expectations.

Table 1 - Scenarios of collaboration

Scenario of collaboration	Description of scenario
1. Industrial feedback.	A session to review the academic propositions, discuss and provide feedback.
2. Focus group review.	Review the theoretical propositions with the manufacturing team
3. Site visit and idea generation.	Make a tour of the manufacturing site and gain enough information to generate ideas for waste alchemy opportunities.
4. Technical and business case report.	Gain an understanding of the production process in order to generate a technical and business report for a potential waste transformation.
5. Implementation project – guidance and advice.	The researcher assists the manufacturing team to implement waste transformation projects
6. Implementation project – collaboration.	The researcher works along with the manufacturing team to implement the waste transformation projects
7. Implementation project – immersion.	The researcher becomes part of the manufacturing team and helps implementing waste transformation projects.

Initializing the ATM project

The first phase of the case study projects consists in the agreement for collaboration. The due diligence relevant to the project is carried on, conditions are set and agreed upon; the purpose is to establish a formal framework for the project.

A brief description of the ATM Methodology

The first level of implementation of the ATM methodology suggests using MFCA and the all seeing eye of business (ALLSEB) to illustrate the impact of waste on the profitability of the product mix in the production line.

The second level of implementation of the ATM methodology is an iterative cycle of design improvement that aims to transform "unavoidable" waste into profitable co-products. Based on a deep understanding of the nature of waste and its physical and chemical characteristics, it becomes possible to develop sound ideas for potential co-products by answering key questions in a systematic way. The three steps (analyse, transform and market) are closely intertwined, as shown in figure 3. The following paragraphs describe the steps in the proposed ATM methodology.

ANALYSE

1. **Use the All Seeing Eye of Business (figure 1) to understand the nature and impact of waste.**
    a. Use material flow cost accounting techniques to account for the true cost of waste.
    b. What is the nature of waste in the production line (unavoidable, inefficiency, caused by error)?
    c. What is the impact of generating waste (economic, ecologic and social)?
2. **Use the roulette of the fundamental uses of waste (figure 2) to identify a value adding capability for unavoidable waste streams.**
    a. What purpose or function can the waste provide given its state and structure?
    b. What would be the performance of this function, given the waste’s state and structure?
    c. Can the waste’s state/structure be improved?
    d. Can the waste’s purpose/performance be changed?

TRANSFORM

1. **Deploy waste elimination strategies to transform the production process in order to:**
    a. Prevent waste.
    b. Minimize waste.
    c. Remediate waste.
2. **Transform unavoidable waste into value adding co-products.**
    a. Design a production process to transform the waste into a co-product.
    b. Is the transformation process (waste to co-product) technically, economically and environmentally feasible?
    c. Is the estimated production price competitive in the market place?
    d. Is there a business case for investment?

MARKET

1. **Market waste elimination strategies to stakeholders**

   a. Obtain management commitment
   b. Obtain employees’ commitment
   c. Communicate environmental achievements to stakeholders.

2. **Identify and analyse the market potential for the desired co-product.**
   a. Is there a market need for a co-product with such function?
   b. Who are the customers and possible competitors?
   c. What are the customer needs, requirement and expectations?
   d. Is there a market opportunity for such a co-product?

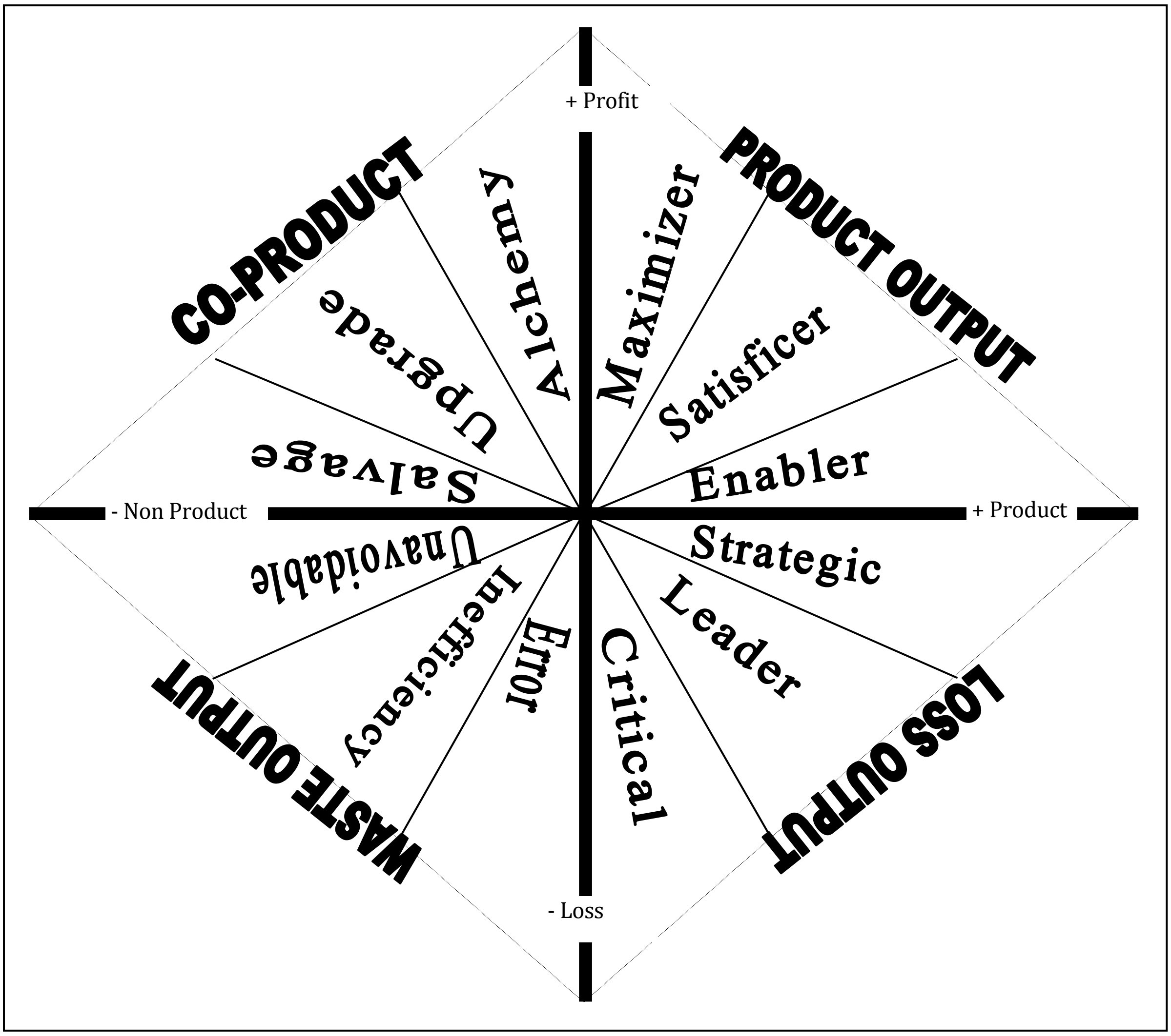

Figure 1- A tool for output analysis: the all seeing eye of businesses.

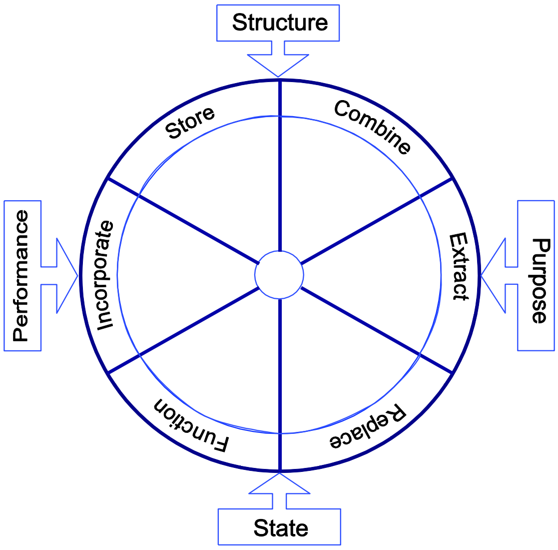

Figure 2- The roulette of the fundamental uses of waste.

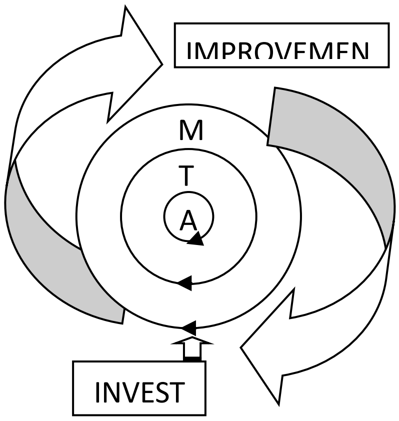

Figure 3- The ATM methodology: an intertwined and iterative design cycle.

Prepared by	**Reviewed by**	**Date**
		11TH October
Samuel Bautista Lazo PhD Candidate.	Dr. Tim Short Primary Supervisor	2011

Appendix 2. Case study structure

1. Company introduction
2. Products and production process
3. Implementation of the Methodology
3.1 Initial conditions
3.2 Special circumstances
3.3 Analysis of the company's operations using "the all seeing eye of business"
4. Results
4.1 Implementing the ATM methodology
4.2 Impact of ATM analysis
4.3 Steps taken as a result of ATM analysis
4.4 Description of the co-product
4.4.1 Process
4.4.2 Cost
4.4.3 Profit
5. Discussion: review of the methodology
5.1 Attributable benefits to the company
5.2 Impact of the methodology in the decision making process

Prepared by	Reviewed by	Date
Samuel Bautista Lazo PhD Candidate. Scholarship ID: 211271	Dr. Tim Short Primary Supervisor University of Liverpool	

Appendix 3 Economic feasibility analysis for Senior Aerospace BWT waste transformation projects

3.1 Transform waste into Gypsum for animal bedding using a small hammer mill crusher, option 1

This section presents the economic feasibility analysis for transforming gypsum waste into animal bedding using a small hammer mill crusher imported from China. The following quote was obtained from Firstmining Machinery (Shangai) Co. Ltd.

- Small hammer crusher mill: $1,500 + $2,500 shipping cost. The total of $4,000 USD is equivalent to £2,555 GBP (calculated on 4 July 2012 with **http://www.xe.com**). Machine capacity: 20-80 kg/hr. Output size: less than 3mm.

Several quotes were obtained and some assumptions had to be made in order to calculate the total costs and revenues quotes. The following list explains the origin of the data used for the economic feasibility analysis.

1. Assuming a service life of ten years for the machinery, the monthly depreciation is calculated by spreading the total cost of machinery over the entire 10 years.
2. Assume an average machine processing capacity of around 80%, or more precisely, assume a capacity of 65 kg/hr to process 8 tonnes of gypsum waste per month, this requires 4hrs of processing per day.
    2.1 Based on this assumption, electricity consumption is calculated using the formula: KWh/month x electricity price. Under load and overload conditions can’t be taken into account until actual operation, so, the energy consumption is assumed to be the maximum energy consumption expressed

by the manufacturer: 11 kW. Industrial electricity was quoted at 10.50 pence per kW hour.

3. The labour required consists in loading the gypsum waste, overseeing correct functioning of the machine and unloading the processed gypsum into the shipping vessel. The required level of skill for this operation calls for a worker on minimal wage compensation.
4. Transportation cost for the processed gypsum would require a single one day skip hire and delivery to nearby farms quoted at £70.00 from Blockerhurst skip hire.
5. Taking a conservative stand, the economic feasibility analysis will take into account the worst case scenario. Richard Webster Nutrition (RWN) is a is an independent specialist supplier of dairy feeds and associated farm inputs. RWN quotes gypsum for animal bedding at £18 to £28 per ton delivered on site on 20 – 29 tonne loads. Given the small volumes of processed gypsum, it could be safely assumed that local customers (e.g. surrounding dairy farms) would be willing to pay £18 per tonne for the processed gypsum. Market prices for gypsum for animal bedding had a wide range of prices, from £18 up to £35 per tonne.
6. Waste disposal costs reflect the cost in the current scenario (no waste transformation).

Using the quotes and assumptions described above, Table 8.1 shows the data source for the economic feasibility analysis of this waste transformation project as the first option. A profit and loss projection shows that this option is not a profitable waste transformation strategy (Table 8.2), it incurs in a £5,444.30 loss. Further simulations on the spreadsheet showed that even assuming a price of £35 per tonne, this option still incurs in losses (-£3,812.30).

Running a simulation using the excel spreadsheet revealed that even if the gypsum is sold

Table 8.1 Data source for waste transformation, option 1

Costs			**Revenue/Savings**		
Machinery:	Hammer mill crusher	£ 2,555.00	Animal bedding	Animal bedding £/ton	£ 18.00
	Service life (yrs)	10		8 ton skip of gypsum (month)	£ 120.00
	Monthly depreciation	£ 21.29	Waste disposal	Monthly waste disposal	£ 375.00
Labour:	Hours per day	4			
	Wage/hr	£ 6.19	**Animal bedding quotes:**	**Min**	**Max**
	Monthly wages	£ 742.80	RWN	£ 18.00	£ 28.00
Transport:	Single delivery	£ 70.00	Wood Yew Waste	£ 35.00	
Energy	11 kW Motor. Hr/day	4			
	Electricity price/KWh	£ 0.11			
	Montly electricity consumption	£ 138.60			

Table 8.2 Table of profit and loss, option 1

Costs	**Monthly cost**	**Annual cost**	**Revenue/Savings**	**Monthly**	**Annual**
Machinery depreciation	£ 21.29	£ 255.50	Crushed gypsum (revenue)	£ 144.00	£ 1,728.00
Labour	£ 742.80	£ 8,913.60	Disposal costs (savings)	£ 375.00	£ 4,500.00
Electricity	£ 138.60	£ 1,663.20			
Transport	£ 70.00	£ 840.00			
Totals	£ 972.69	£ 11,672.30	**Totals**	£ 519.00	£ 6,228.00
		Annual loss:	-£5,444.30		

3.2 Transform gypsum into recycled raw material for Hanson Cements

This section presents the economic feasibility analysis for transforming gypsum waste into a raw material suitable for cement kilns. The following list explains the origin of the data used for the economic feasibility analysis.

1. The machine chosen for crushing gypsum for animal bedding is the single jaw roll crusher from Glen Creston Ltd (described in section 6.2.5.2), quoted at £11,252, adding 20% VAT and around £500 for shipping and installation costs results in an estimated total machinery cost of £14,000.
2. Assuming a service life of 15 years for the machinery, the monthly depreciation is calculated by spreading the total cost of machinery over the entire 15 years.
3. Machine processing capacity is approximately 2 ton/h; so, processing 8 tonnes of gypsum would require 4.4 h per month, assuming a 90% machine processing capacity.
4. Electricity consumption is calculated based using the formula kWh/month x electricity price. Under load and overload conditions can't be taken into account until actual operation measurements; hence, the electricity consumption is based on the motor's maximum power rate: 4kW.
5. The labour required consists in loading the gypsum waste, overseeing correct functioning of the machine and unloading the processed gypsum into the shipping vessel. For practical purposes, assume that these activities account for 5 hours per month. The required level of skill for this operation calls for a worker on minimal wage compensation.
6. Transportation cost for the processed gypsum would require a single one day skip hire and delivery to Hanson Cements' kilns at

Padeswood Works, Chester Road, Padeswood, Mold, Flintshire CH7 4HB. Blockerhurst skip hire quoted this delivery at £200.

7. Hanson cements generally charges a gate fee for alternative raw material inputs delivered to their kilns. However if the gypsum could be supplied to a particle size distribution of less than 63 mm, the company could pay a price premium of £10 per tonne of gypsum.
8. Waste disposal costs reflect the cost in the current scenario (no waste transformation).

Using the data in Table 8.3 it was possible to project a profit and loss statement for annual operations (Table 6.6), this calculations project £2,032.13 in annual profit. This profit is the combined cost saving from waste disposal and the profit generated from the sale of the co-product (raw material for Hanson cements).

In order to calculate the payback period it is necessary to consider the annual profit contribution from the given investment: Table 8.5 shows the profit contribution, year by year. The project is expected to last at least 7 years; a point where the production process might be able to change to additive manufacturing methods. Given the machine life time, it could be sold at the end of the project; the resale value is around £ 5,000 to £8,000 (according to current market prices for used machinery and considering the depreciation rate). Considering the machine low usage rate, it is expected that it will remain in good condition and could reach a high market value, estimated to be £7,000.

Table 8.3 Financial data for the production of Gypsum for Hanson cement's kilns

Costs			**Revenue/Savings**		
Machinery:	Roll mill	£ 14,000.00	Hanson cement	Crushed gypsum (£/t)	£ 10.00
	Service life (y)	15		8 ton skip of gypsum	£ 80.00
	Monthly depreciation	£ 77.78	Waste disposal	Monthly waste disposal	£ 400.00
Labour:	h/month	5			
	Wage/h	£ 6.19			
	Monthly wages (10 h)	£ 30.95			
Transport:	Skip hire	£ 200.00			
Energy	h/month	4.4			
	Electricity price/KWh	£ 0.11			
	Montly electricity consumption	£ 1.87			

Table 8.4 Profit and loss projection for Hanson Cements alternative

Costs	**Monthly cost**	**Annual cost**	**Revenue/Savings**	**Monthly**	**Annual**
Machinery depreciation	£ 77.78	£ 933.33	Crushed gypsum	£ 80.00	£ 960.00
Labour	£ 30.95	£ 371.40	Disposal costs	£ 400.00	£ 4,800.00
Electricity	£ 1.87	£ 22.40			
Transport	£ 200.00	£ 2,400.00			
Total cost	£ 310.59	£ 3,727.13	**Total revenue/Savings**	£ 480.00	£ 5,760.00
	Annual Profit:		£ 2,032.87		

The annual net cash inflow is calculated by adding annual depreciation costs to the annual profit contribution (shown in Table 8.6). Using data from the net cash flow projection the payback period can be calculated from table by locating the year which has the cumulative net cash inflow closest to the machinery investment, in this case 4 years. The remaining investment is

£2,135.20; this is expressed as a percentage of the annual net cash flow for the following year, equal to 70%. So the payback period is equal to 4.7 years.

Table 8.5 Hanson cement project—annual profit contribution

Initial cost of machinery	£ 14,000.00
Project life (yrs)	7
Annual profit increase	
Year 1	£ 2,032.87
Year 2	£ 2,032.87
Year 3	£ 2,032.87
Year 4	£ 2,032.87
Year 5	£ 2,032.87
Year 6	£ 2,032.87
Year 7	£ 2,032.87
Resale value at year 7	£ 7,000.00

Table 8.6 Hanson cement project—net cash flows

Year	**Net cash inflow**	**Cumulative**
1	£ 2,966.20	£ 2,966.20
2	£ 2,966.20	£ 5,932.40
3	£ 2,966.20	£ 8,898.60
4	£ 2,966.20	£ 11,864.80
5	£ 2,966.20	£ 14,831.00
6	£ 2,966.20	£ 17,797.20
7	£ 9,966.20	£ 27,763.40

In order to take into account the time value of money throughout the entire project, the net present value of the project is calculated using discount factor values drawn from discount factor tables as shown in Table 6.9. This project assumes a discount factor of 8% (as an average estimate for manufacturing projects in the UK). The resulting net present value is positive, which means that the discounted cash inflows exceed the discounted cash outflows even when taking into account the time value of money, thus making the proposal an economically viable project.

Table 8.7 Net present value for Hanson Cement project

Year	Net cash flows	Discount factor 8%	Present value
0	-£ 15,000.00	1	-£ 15,000.00
1	£ 2,032.87	0.926	£ 1,882.43
2	£ 2,032.87	0.857	£ 1,742.17
3	£ 2,032.87	0.794	£ 1,614.10
4	£ 2,032.87	0.735	£ 1,494.16
5	£ 2,032.87	0.681	£ 1,384.38
6	£ 2,032.87	0.63	£ 1,280.71
7	£ 9,032.87	0.623	£ 5,627.48
Machinery Resale value	£ 7,000.00		
	Project value		£ 13,230.07
	Net present value:		£ 25.42

The downside, however, is that the net present value is very low and depends on the resale of the machine at the end of the seventh year in order to make the net present value positive. In order to have the Hanson Cement project provide similar economic benefits as the gypsum for animal bedding project (option 2), the price per tonne of gypsum has to reach £25. Assuming a loss on machinery value at the end of year seven, the price per tonne of gypsum needs to reach £19 to have the net present value remain positive: £196.96 (shown in Table 8.8) and a payback period of 3.6 years.

Running a simulation on the excel spreadsheet using the financial data source and assumptions from Table 8.3 it was observed that price of gypsum would have to reach £25 per tonne in order to achieve similar economic results as the gypsum for animal bedding project; this simulation results in a payback period of 3.1 years and a net present value of £7,579.66. Table 8.9 presents a wide price scenario analysis for the purpose of comparison and insight.

Table 8.8 Net present value for Hanson Cement project—no machine resale value

Net present value			
Year	**Net cash flows**	**Discount factor 8%**	**Present value**
0	-£ 15,000.00	1	-£ 15,000.00
1	£ 2,896.87	0.926	£ 2,682.50
2	£ 2,896.87	0.857	£ 2,482.61
3	£ 2,896.87	0.794	£ 2,300.11
4	£ 2,896.87	0.735	£ 2,129.20
5	£ 2,896.87	0.681	£ 1,972.77
6	£ 2,896.87	0.63	£ 1,825.03
7	£ 2,896.87	0.623	£ 1,804.75
Machinery Resale value	£ -		
	Project value		£ 5,278.07
	Net present value:		£ 196.96

Table 8.9 Price scenario analysis for the Hanson Cement project

Price	Profit	Payback	NPV	NPV-2
£ 10.00	£ 2,032.87	4.7	£ 25.42	-£ 4,335.58
£ 15.00	£ 2,512.87	4.06	£ 2,543.50	-£ 1,817.50
£ 19.00	£ 2,896.87	3.66	£ 4,557.96	£ 196.96
£ 25.00	£ 4,538.96	3.18	£ 7,579.66	£ 3,218.66

3.3 Transform gypsum into soil improver for agricultural applications

This section presents the economic feasibility analysis for transforming gypsum waste into a soil improver for agricultural applications. This scenario uses exactly the same data and assumptions as the Hanson Cement project, except for the elimination of transport costs (skip hire) and the price per tonne of crushed gypsum (Table 8.10). The annual profit and loss statement was projected using the previously described data; the results are annual savings worth £2,358.89 (shown in Table 8.11).

Table 8.10 Financial data source for the soil improver gypsum project

Costs				**Revenue/Savings**			
Machinery:	Roll mill	£	14,000.00	Hanson cement	Crushed gypsum (£/t)	£	-
	Service life (yrs)		15		8 ton skip of gypsum	£	-
	Monthly depreciation	£	77.78	Waste disposal	Monthly waste disposal	£	400.00
Labour:	Hrs per month		5				
	Wage/hour	£	6.19				
	Monthly wages (10 hr)	£	123.80				
Transport:	Skip hire	£	-				
Energy	4 kW motor. Hr/month		4.4				
	Electricity price/KWh	£	0.11				
	Montly electricity consumption	£	1.85				

In order to calculate the payback period it is necessary to consider the annual profit contribution from the given investment. Table 8.12shows the profit contribution, year by year. The project is expected to last at least 7 years; a point where the production process might be able to change to additive manufacturing methods. Given a machine life expectancy of 15 years and considering the same reasons as in the Hanson Cement scenario, assume that the machine could be sold at the end of the project for £7,000 as shown in Table 8.12.

Table 8.11 Annual profit and loss projection for the soil improver gypsum project

Costs	**Monthly cost**	**Annual cost**	**Revenue/Savings**	**Monthly**	**Annual**
Machinery depreciation	£ 77.78	£ 933.33	Crushed gypsum	£ -	£ -
Labour	£ 123.80	£ 1,485.60	Disposal costs	£ 400.00	£ 4,800.00
Electricity	£ 1.85	£ 22.18			
Transport	£ -	£ -			
Total cost	£ 203.43	£ 2,441.11	**Total revenue/Savings**	£ 400.00	£ 4,800.00
		Annual profit:	£ 2,358.89		

Table 8.12 Annual profit contribution for soil improver gypsum project

Year 1	£ 2,358.89
Year 2	£ 2,358.89
Year 3	£ 2,358.89
Year 4	£ 2,358.89
Year 5	£ 2,358.89
Year 6	£ 2,358.89
Year 7	£ 2,358.89
Resale value:	£ 7,466.67

The annual net cash inflow is calculated by adding annual depreciation costs to the annual profit contribution as shown in Table 8.13. Using data from the net cash flow projection the payback period can be calculated from table by locating the year which has the cumulative net cash inflow closest to the machinery investment, in this case 4 years. The remaining investment is £831.10; this is expressed as a percentage of the annual net cash flow for the following year, equal to 25%. So the payback period is equal to 4.25 years.

Table 8.13 Annual net cash flow for the soil improver gypsum project

Year	Net cash inflow	Cumulative
1	£ 3,292.22	£ 3,292.22
2	£ 3,292.22	£ 6,584.45
3	£ 3,292.22	£ 9,876.67
4	£ 3,292.22	£ 13,168.90
5	£ 3,292.22	£ 16,461.12
6	£ 3,292.22	£ 19,753.34
7	£ 10,758.89	£ 30,512.23

In order to take into account the time value of money throughout the entire project, the net present value of the project is calculated using discount factor values drawn from discount factor tables as shown in Table 8.14. This project assumes a discount factor of 8% (as an average estimate for manufacturing projects in the UK). The resulting net present value is £2,026.47; a positive value means that the discounted cash inflows exceed the discounted cash outflows even when taking into account the time value of money, thus making the proposal an economically viable project.

Table 8.14 Net present value for the soil improver gypsum project

Year	Net cash flows	Discount factor 8%	Present value
0	-£ 15,000.00	1	-£ 15,000.00
1	£ 2,358.89	0.926	£ 2,184.33
2	£ 2,358.89	0.857	£ 2,021.57
3	£ 2,358.89	0.794	£ 1,872.96
4	£ 2,358.89	0.735	£ 1,733.78
5	£ 2,358.89	0.681	£ 1,606.40
6	£ 2,358.89	0.63	£ 1,486.10
7	£ 9,825.56	0.623	£ 6,121.32
Machinery Resale value:	£ 7,466.67		
Project earnings			£ 8,978.90
Net present value:			£ 2,026.47

A price scenario analysis for the use of gypsum as a soil improver was carried out using the data source for this project (shown in table Table 8.10). The analysis explores four different price scenarios and an alternative net present value (NPV-2) scenario where the value of the machinery is zero at the end of the project. The results are shown in Table 8.15.

Table 8.15 Price scenario analysis for soil improver gypsum project

Price	Profit	Payback (y)	NPV	NPV-2
£ -	£ 2,358.89	4.25	£ 2,026.47	£ 489.74
£ 5.00	£ 2,838.89	3.71	£ 4,544.55	£ 3,007.82
£ 10.00	£ 3,318.89	3.29	£ 7,062.63	£ 5,525.90
£ 15.00	£ 3,798.89	2.96	£ 9,580.71	£ 8,043.98

3.4 Material flow cost accounting data

Using the general framework for environmental management—material flow cost accounting (MFCA)—detailed in the BS EN ISO 14051:2011, quantity centres were defined and the cost items listed in an excel spreadsheet for future calculations, once the data is provided by the accounting department.

Table 8.16 Material flow cost accounting data

1. Master mould making					
Material	**Totals**	**Energy**	**Totals**	**System costs**	**Totals**
Soft model board	£ -	CNC machine	£ -	Labour cost (% of time dedicated to making master moulds)	£ -
Poplar wood	£ -			Floor space m^2	£ -

Resins	£ -			Equipment depreciation (CNC machine and other tooling)	£ -
Gel coats	£ -				
Biaxial fibre glass	£ -				
Chopped strand (Loose fibre glass)	£ -				
Woven roven	£ -				
Sum Totals:	£ -		£ -		£ -

2. Storage room for master moulds

Material	Totals	Energy	Totals	System costs	Total
NA	NA	NA	NA	Floor space m^2	£ -
Sum Totals:	£ -		£ -		£ -

3. Plaster mixing

Material	Totals	Energy	Totals	System costs	Totals
Plaster	£ -	Extraction machine	£ -	Labour cost (7 people during the day, 6 at night shifts)	£ -
Glue	£ -	Lift	£ -	Floor space	£ -
Water	£ -	Oven	£ -	Equipment depreciation	£ -
Personal protection equipment: Shoes, gloves, glasses, overall suits.	£ -	Bench down draft machine	£ -		
		Air power tools	£ -		

		Mixer	£ -		
Sum Totals:	£ -		£ -		£ -

4. Finished moulds Storage

Material	Totals	Energy	Totals	System	Totals
NA	NA	NA	NA	Floor space m^2	£ -
Totals:	£ -		£ -		£ -

5. Mould waxing

Material	Totals	Energy	Totals	System	Totals
Barrels of wax:	£ -	Spraying gun (runs all day)	£ -	Labour cost (hours per day/year)	£ -
Crease paper	£ -	Air extraction machine	£ -	Equipment depreciation	£ -
Sum Totals:	£ -		£ -		£ -

6. Product retrieval (from moulds)

Material	Totals	Energy	Totals	System	Totals
NA	NA	Neumatic tools	£ -	Labour (% of time per person/year)	£ -
		Drillers	£ -	Floor space	£ -
				Tooling depreciation (Hammers, wooden hammer)	£ -
Sum Totals:	£ -		£ -		£ -

7. Disposal cost

Material	Totals	Energy	Totals	System	Totals
NA	NA	NA	NA	Skip hire collection cost:	£4,800.00
				Gate fee:	£ -
				Landfill tax:	£ -
Sum Totals:	£ -		£ -		£4,800.00

3.5 Value stream mapping of the gypsum moulds at BWT

The production steps involving gypsum were studied using value stream mapping and material flow cost accounting (MFCA). Value stream mapping highlights the composite layup and the curing stage as the only value adding activities in the process, i.e. these production steps shape and cure the composite into the desired products; the other steps are in support or a consequence of these two processes. Value stream mapping provides a framework for process improvement; for example, if 3D printing methods were to be used for manufacturing the moulds, it will become important to know exactly what is the cost of producing the mould using the current casting process and compare that cost with 3D printing methods. MFCA calculations will help to determine the true cost of waste in each production step as well as the total cost of producing gypsum waste at the end of the production process.

Table 8.17 Value stream mapping of the gypsum moulds at BWT

PRODUCTION PROCESS FLOW	VALUE STREAM COSTING		MATERIAL FLOW COST ACCOUNTING			
WOOD WORK	Quantity centre: Wood work	Totals	Quantity centre:	Wood work	Quantity centre:	Wood work

	Material costs:	Product output (kg):	8,000.00	Material loss (kg):	0.00
	Energy costs:	Material costs:	£ -	Material costs:	£ -
	System costs:	Energy costs:	£ -	Energy costs:	£ -
	Waste management costs:	System costs:	£ -	System costs:	£ -
				Waste management costs:	
	Quantity centre costs:	Cost of product:	£ -	Costs of material loss:	£ -

MOULD MAKING	Quantity centre: Mould making Totals	Quantity centre:	Mould making	Quantity centre:	Mould making
	Material costs:	Product output (kg):	0.00	Material loss (kg):	0.00
	Energy costs:	Material costs:	£ -	Material costs:	£ -
	System costs:	Energy costs:	£ -	Energy costs:	£ -
	Waste management costs:	System costs:	£ -	System costs:	£ -
				Waste management costs:	
	Quantity centre costs:	Cost of product:	£ -	Costs of material loss:	£ -

STORAGE	Quantity centre: Storage Totals	Quantity centre:	Storage	Quantity centre:	Storage
	Material costs:	Product output (kg):	0.00	Material loss (kg):	0.00
	Energy costs:	Material costs:	£ -	Material costs:	£ -
	System costs:	Energy costs:	£ -	Energy costs:	£ -
	Waste management costs:	System costs:	£ -	System costs:	£ -

					Waste management costs:	
	Quantity centre costs:		Cost of product:	£ -	Costs of material loss:	£ -

MOULD WAXING	Quantity centre: Mould waxing	Totals	Quantity centre:	Mould waxing	Quantity centre:	Mould waxing
	Material costs:		Product output (kg):	0.00	Material loss (kg):	0.00
	Energy costs:		Material costs:	£ -	Material costs:	£ -
	System costs:		Energy costs:	£ -	Energy costs:	£ -
	Waste management costs:		System costs:	£ -	System costs:	£ -
					Waste management costs:	
	Quantity centre costs:		Cost of product:	£ -	Costs of material loss:	£ -

COMPOSITE LAY UP	Quantity centre: Composite lay up	Totals	Quantity centre:	Composite lay up	Quantity centre:	Composite lay up
	Material costs:		Product output (kg):	0.00	Material loss (kg):	0.00
	Energy costs:		Material costs:	£ -	Material costs:	£ -
	System costs:		Energy costs:	£ -	Energy costs:	£ -
	Waste management costs:		System costs:	£ -	System costs:	£ -
					Waste management costs:	
	Quantity centre costs:		Cost of product:	£ -	Costs of material loss:	£ -

CURING	Quantity centre: Curing	Totals	Quantity centre:	Curing	Quantity centre:	Curing
	Material costs:		Product output (kg):	0.00	Material loss (kg):	0.00

🟩	Energy costs:	Material costs:	£ -	Material costs:	£ -
	System costs:	Energy costs:	£ -	Energy costs:	£ -
	Waste management costs:	System costs:	£ -	System costs:	£ -
				Waste management costs:	
	Quantity centre costs:	Cost of product:	£ -	Costs of material loss:	£ -

PRODUCT RETRIEVAL	Quantity centre: Product retrieval Totals	Quantity centre: Product retrieval	Quantity centre: Product retrieval
	Material costs:	Product output (kg): 0.00	Material loss (kg): 0.00
	Energy costs:	Material costs: £ -	Material costs: £ -
	System costs:	Energy costs: £ -	Energy costs: £ -
	Waste management costs:	System costs: £ -	System costs: £ -
			Waste management costs:
	Quantity centre costs:	Cost of product: £ -	Costs of material loss: £ -

DISPOSAL	Quantity centre: Disposal Totals	Quantity centre: Disposal	Quantity centre: Disposal
	Material costs:	Product output (kg): 0.00	Material loss (kg): 0.00
	Energy costs:	Material costs: £ -	Material costs: £ -
	System costs:	Energy costs: £ -	Energy costs: £ -
	Waste management costs:	System costs: £ -	System costs: £ -
			Waste management costs:
	Quantity centre costs:	Cost of product: £ -	Costs of material loss: £ -

TOTAL COSTS:	TOTAL PROCESS COST	PRODUCT OUTPUT:	0.00	NON PRODUCT OUTPUT:	0.00
	Material costs:	% Product output:		% Non product output:	
	Energy costs:	Material costs:		Material costs:	
	System costs:	Energy costs		Energy costs	
	Waste management costs:	System costs:		System costs:	
		Total costs:		Total costs:	

VALUE STREAM COST	Value adding activities - Product Output	
	Non value adding activities - Non product output	