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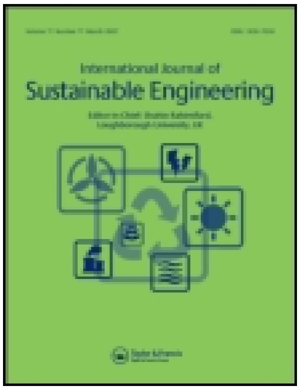

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Barriers, drivers and challenges for sustainable product recovery and recycling

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Barriers, drivers and challenges for sustainable product recovery and recycling

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There has been a significant growth in research and applications of product recovery and recycling over the last two decades, in particular with the view of recent product take-back legislation which has extended the responsibility of manufacturers to include the recovery and safe disposal of their products. However, at present, the global scale of product recovery applications is significantly disproportional to the total manufacturing output. Hence, to achieve the idealistic goal of 'zero landfill', there is a need to significantly improve and extend both the scale of product recovery activities and the range of manufacturing applications in which such activities have yet to be implemented. This paper examines a range of barriers, drivers and challenges in research and development for the next generation of product recovery initiatives. A range of existing applications and case studies undertaken for the UK market has been used to analyse issues related to: the need for improvement and expansion of current legislation on producer responsibility; product take-back and reverse logistic models for collection of used products; knowledge-based approaches for end-of-life considerations during the design phase; improved technologies and increased automation in pre- and post-fragmentation recycling processes and most importantly, the requirement for sustainable business models for establishing value recovery chains which can be based on the provision of services rather than products. The paper concludes by summarising the results of this analysis to bridge the gap between existing and future sustainable solutions for product recovery.

Keywords: product recycling; extended producer responsibility; reverse logistics; sustainable business models

1. Introduction

Sustainability will be one of the core themes of the twenty-first century and presents a truly global challenge for product developers to make additional considerations within their designs regarding material consumption and resource utilisation. Increasing world population, depleting natural resources and the emergence of newly industrialised nations, all highlight the necessity to develop new and innovative products to bridge the gap between current consumer trends and the goal of long-term sustainability. It is often argued that a paradox exists between the ideals of sustainability and those associated with the growth of free-markets and global consumerism. To do more with less, increase a product's durability or even taking it back for recycling or refurbishment at the end of its useful life, traditionally goes against the grain of a producer's business model which typically aims to encourage increased consumption. However, with the advent of prescriptive take-back legislation, combined with increasing consumer pressure and 'greener' corporate responsibility, the consideration for end-of-life product recovery and recycling is increasingly being included within the scope of a company's product development process. With this inclusion comes an increased need to improve the interaction between upstream manufacturing and downstream recovery activities, and this has generated a number of competing market drivers and convoluted stakeholder relationships.

Product recovery and recycling has historically been under-developed within the UK, with typical resource consumption far outstripping that of material recycling, see Figure 1 (DEFRA 2008).

This highlights that increasing the number of the product sectors considering end-of-life recovery and improving the efficiency of those that already adopted retirement models, will be critical in achieving the longer-term sustainability of recycling activities. This paper discusses a range of existing applications and case studies for the inclusion of end-of-life product recovery within various product sectors in the UK, and highlights some of the shortcomings associated with existing producer responsibility and product recovery models. The reported research utilises a systematic approach to discuss a range of issues that are most influential and problematic in achieving the next generation of sustainable product recovery models, as depicted in Figure 2. These issues include an appreciation for the legislative impacts on product recovery, complexities in establishing appropriate reverse logistic models and willingness by manufacturers to approve their design based on sustainable business models that safeguard their long-term prosperity. The remaining sections of the paper analyse the drivers, barriers and challenges identified in Figure 2,

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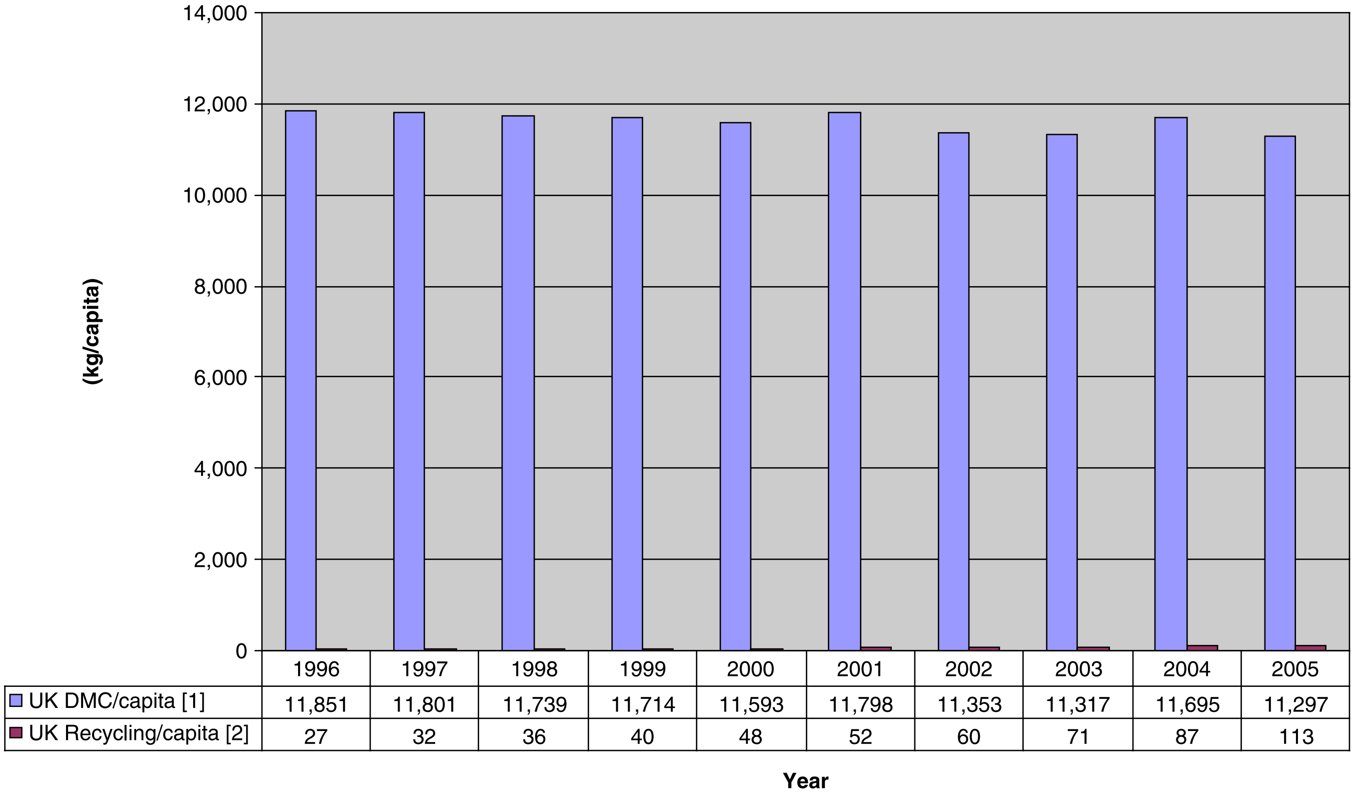

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
🟦 UK DMC/capita [1]	11,851	11,801	11,739	11,714	11,593	11,798	11,353	11,317	11,695	11,297
🟥 UK Recycling/capita [2]	27	32	36	40	48	52	60	71	87	113

Figure 1. UK domestic material consumption vs. UK material recycling (*per capita*).

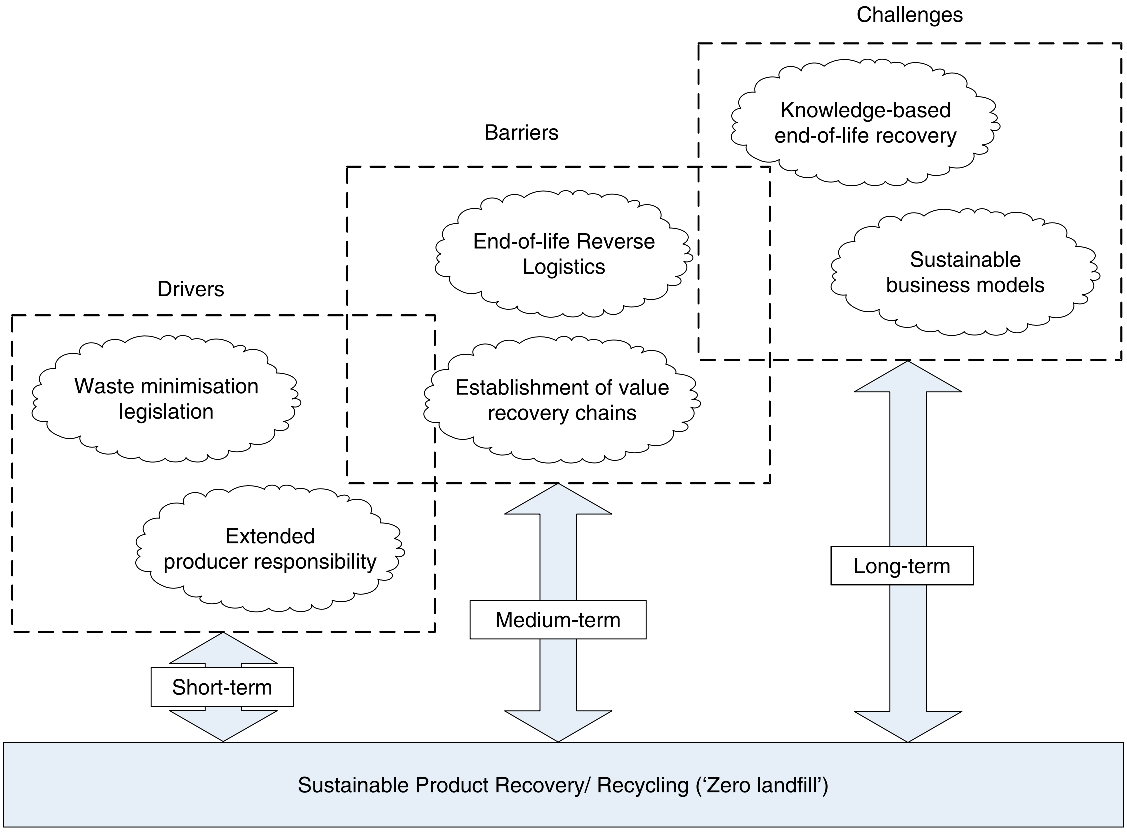

Figure 2. Overview of issues relating to the achievement of the next generation of sustainable product recovery models.

and although the outlined discussion is very much based on product recovery applications in the UK manufacturing industry, it is argued that similar issues are prevalent within other industrial countries.

2. Drivers: EU directives and associated national legislation

The EU has formulated a number of prescriptive directives encompassing the design, production and treatment of a range of industrial and consumer products. All the directives have the philosophy of extended producer responsibility (EPR) at their core (Lindhqvist and Lidgren 1991), which aims to promote end-of-life considerations within the product design process, and the reduction of a product's overall ecological impact. Manufacturers have traditionally seen the remit of their responsibility ending at the termination of the product's warranty period, with ownership (and ultimately accountability) of the product being passed to the user/consumer. However, the introduction of EPR aims to change this, necessitating a rethink of the traditional product life cycle to encompass more end-of-life considerations, in the hope of promoting more sustainable closed-loop recovery and recycling. With this escalation in environmental regulation comes an increase in costs associated with the collection, treatment and processing of the end-of-life products; and a lack of distinction about which stakeholder should be responsible for covering these additional burdens. Despite the producer responsibility focus which many of the European directives advocate, numerous country-specific transpositions of EPR legislation have demonstrated variation within their interpretation. The following sub-sections provide an overview of these transpositions based on a range of consumer and business-centred levies, along with the use of end-of-life product value to economically support end-of-life recovery activities.

2.1 End-of-life levies for the consumer at point of sale

Automotive recycling Netherlands adopted this method when implementing the end-of-life vehicles (ELV) directive. A €45 waste disposal fee was placed on all first time vehicle registrations from 1 January 2004 (Perchard 2007), and indirectly made consumers pay the cost of recovery and disposal when initially purchasing the vehicle. The benefit of this approach is that it allowed end-of-life operators to pro-actively invest in end-of-life processing technology and gave them the resources necessary to investigate fringe-recycling methods that they would otherwise have discounted due to their poor economic feasibility. The disadvantage of the approach is that it also assisted in creating a number of artificial material markets, for which end-of-life operators were removing materials from ELVs based on their 'subsidised' not 'true' market value. Other more recent examples of this approach can be seen within other product sectors. The textile 'eco-tax' introduced in France in 2007, which proposes a charge 0.05€/kg on new leather and shoe products to cover the costs of reuse and recycling, is a prime example of post-consumer disposal costs covered by point-of-sale levies. Subsequent debate has raised questions about the legality of passing the cost burden of product recovery and recycling onto the consumer given the producer responsibility advocated within many of the European directives, and pro's and con's will continue to be discussed as other manufacturers in different sectors look at ways of financing their legislative commitments.

2.2 Take-back levies from manufacturers

This is an approach similar to that adopted within the packaging and electronics recycling sector, whereby quantities of 'product recovery notes' would have to be purchased by manufacturers from recyclers based on their market share, thereby enforcing the producers to pay for the recovery and recycling of their product. This then removes the reverse logistical costs associated with own brand (own marque) product collection. In this approach, each end-of-life recycler can agree to accept waste packaging or consumer products from any source irrespective of the original producer, which reduces the need for duplicated processing facilities and minimises the carbon-miles associated with brand-specific collection sites (as seen within the automotive recovery sector within the UK). Therefore, the major strength of this approach is that it attributes direct (economic) producer responsibility and assists in the process of recovery by creating an opportunity for large-scale recycling of generic product groups (e.g. TVs, mobile phones, fridges, etc.). This is important as it means that local council refuse sites are more than willing to accept these additional waste types which not only generate revenue but make it easier for consumers to associate product recycling with their normal disposal activities. The pitfall with this type of approach is the danger that these levies will ultimately be absorbed within the recommended retail price and so be borne by the consumer, giving little incentive to the producers to make pro-active environmental improvements to their product design. Also, given the relative infancy of recycling technology associated with the end-of-life processing of products such as consumer electronics, the current 'recovery note' system within the UK is geared towards percentage weights recovery, with no economic advantage for those manufacturers that do include 'design for recycling' consideration (such as easier disassembly for de-pollution) within their products.

2.3 Landfill taxation

One of the strongest catalysts for increased end-of-life product recovery and recycling in the UK has been the steep increase in the cost of landfill. The standard landfill tax rate at the beginning of 2008 was set at €35 per tonne, but from 1 April 2008, the annual rate of increase was raised from €4 per tonne per year to €11 per tonne per year (HM Treasury 2007). This tax has become an increasingly influential economic instrument, forcing end-of-life processors not only to make proactive investments based on their financial bottom-lines (Letsrecycle.com 2008), but also to requests that manufacturers fulfil their legislative commitments.

2.4 Free-market and end-of-life value

In recent years, a fourth economic model to fund the activities of end-of-life product recovery has emerged in the UK. It concerns the use of encapsulated material value to provide the financial resources needed to process the retired product. The transposition of the ELV directive is a good example of this approach. The directive requires each vehicle manufacturer to provide free take-back and treatment for all of its own vehicles post 2006, and meet stringent recycling and recovery targets of 85 and 95% by 2006 and 2015, respectively. It was widely believed that of the three options available, namely 'last owner pays', 'exchequer (i.e. government) pays' or 'producer pays' (Skinner and Fergusson 2005), the vehicle manufacturers would be the ones fiscally liable for implementing 'own brand' vehicle recovery, using the existing salvage industry in the UK. Yet, during the establishment of these vehicle collection systems, it became apparent that no direct financial support would be given to the vehicle salvage industry due to the substantial intrinsic value that ELVs possessed at the time of the legislative negotiations (Edwards *et al.* 2006). Hence, the high market values for ELVs (mainly due to their metallic content) is currently offsetting the costs of legislative conformance, but has ultimately left the vehicle salvage industry in an economically precarious position should the main drivers that underpin it significantly change, i.e. a collapse in the price of scrap steel and revenue from parts resale (Coates 2007).

3. Barriers: reverse logistics

The activity of end-of-life product collection and return to a recycling centre can be one of the most cost-intensive parts of the recovery process, both from a financial and environmental perspective (carbon-miles). The economics of implementing a product collection network very much depend on the model adopted and the consumer's willingness to support that model. In terms of available infrastructure, four possible reverse logistic scenarios can be identified for the return of end-of-life products:

(a) *Curb-side collection*. This utilises the existing municipal waste collection infrastructure currently in place and allows product to be recovered via traditional waste collection channels. Curb-side collection can also extend to the recovery of much larger consumer products (such as fridges, washing machines, sofas, etc.) should agreement be reached with the local district in charge of household waste management.
(b) *Recycling point centres*. Geographically distributed product collection sites, which on one hand could be for large specific products (such as vehicles through recovery agents collection sites), and on the other hand could be for small consumer products such as recycling banks placed in the supermarkets or at existing waste refuse sites. In both cases, these collection sites could act as hubs to which various product types can be returned by the final owner, and often tend to be owned and maintained by third party companies that have established business models to collect and reuse/recycle generic product types.
(c) *Return at shop outlets*. A number of large retailers have started to offer return facilities at the point of original sale, allowing consumers to return their end-of-life products while visiting a store to make a new purchase.
(d) *Postal returns*. A number of organisations currently offer free-post return envelopes for high-value consumer goods such as mobile phones to facilitate the recovery process.

The appropriateness and applicability of these four reverse logistic models for a specific product sector are very much dependent on the logistical costs associated with each model and the capabilities of the existing infrastructure in place to deal with the variation in retired products. Social aspects, such as consumer awareness and apathy, can be additional barriers to the extension of existing product collection activities, and present an argument that a cohesive and consistent message should be sent to consumers regarding the benefits of end-of-life product retirement before any additional investment is made on infrastructure and technology. Figure 3 provides an overview of the suitability of the four models in relation to two of the main technical and social aspects of the end-of-life product returns.

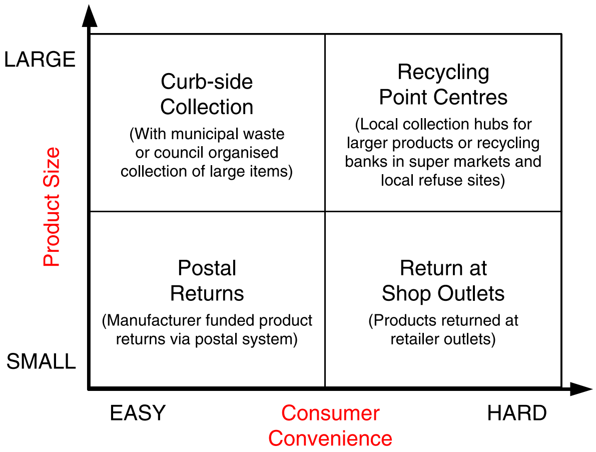

Figure 3. Selection of an appropriate product return model based on practical feasibility and social concerns.

4. Barriers: establishment of value recovery chains for recycled materials

One of the most critical issues regarding the viability of product recycling is the availability of markets for the recovered materials. Historically, products composed mainly of metallics have been mostly recovered, due to the availability of established reprocessing technologies and global second-use demand. These ferrous and non-ferrous materials also more closely approximate to the ideal goals of sustainable product recovery by having the potential to be used in 'closed-loop' applications (i.e. the steel from a retired automobile can be used within the manufacture of a new vehicle). Whereas, many of the plastics available at the end-of-life are not only lacking in commercial desirability, but are rarely suitable for closed loop recycling, with the majority being down-graded for use within less visible and structurally critical areas of new products. The following sub-sections discuss the technical and social reasoning behind these issues.

4.1 Establishing end-of-life recycled material markets

In applications where the availability and value of virgin material is comparable to that of recycled material, establishing a sustainable end-of-life market can simply be infeasible. For example, despite the rapid growth in the recycling of post-consumer plastic packaging, there are still significant challenges related to the recovery of engineering plastics (used within higher specification applications). At present, minimal dismantling of plastic components from consumer products is undertaken at the majority of end-of-life processors. This can be attributed to a number of reasons: problematic high volume and low weight ratio of plastics (Foster and Simmons 2000); the lack of cheap and accurate material analysis equipment;

and the perceived high effort vs. low return for plastics removal. Therefore, the recovery of engineering grade plastics within some consumer products, with their increased mechanical properties when compared to those of packaging plastics, is yet to attract extensive investment and consideration by end-of-life operators. Bellmann and Khare (2000) refer to this as the 'chicken and the egg' situation, where investment and commitment to the recovery of recyclable materials will only be undertaken, if there is a market for the re-processed materials, a sentiment echoed in Ambrose *et al.* (2002) and Mark and Kamprath (2004). These authors identify all the need to establish a 'pull' recycling infrastructure, in which supplier demand for cheaper recyclable plastics can establish a market. Surprisingly, this supplier demand may ultimately be strengthened by the very thing that recycled materials are trying to conserve. For example, plastic and adhesives costs are playing an increasingly significant part within product manufacturing (€224–€269 in a typical four-door saloon vehicle; Kimberley 2004) and, with oil prices hitting record highs during 2008, the need for a cheaper alternative may ultimately facilitate the establishment of stronger markets for recyclable plastics.

4.2 Consumer perception of recycled materials

It is generally accepted that sustainability requires the cohesion of three main elements to make it work. The activity needs to prove its environmental performance, its technical and economical viability, and its ability to be widely accepted and adopted within today's society. Consumer perception of the materials recycled during product reclamation fits into the latter of those three elements, but is as vitally important when trying to move from a 'push' to a 'pull' recycling market. Examples of end-of-life product materials that have historically failed due to this consumer perception can be seen in the problems the tyre re-treading industry has faced within the automotive sector. Retread sales have fallen from 7.5 million units in 1995 to 1.3 million in 2001 (Used tyre working group 2007), due to public fears regarding retread safety. From a sustainable standpoint, a typical retread cycle for a commercial vehicle tyre saves ≈ 60 kg of materials plus an inherent energy saving of ≈ 37.4 kWh (AEA technology 2007), making it by far the most environmentally sound processing route. Yet, despite a counter marketing campaign to reassure retread customers and the introduction of compulsory quality standards, the UK's retread market is still in free-fall, in particular with the rapid increase of cheap brand new tyre imports.

This public perception regarding quality and safety issues is becoming increasingly prevalent within other end-of-life material streams, no more abundantly so than in the plastics recycling sector. The bad publicity regarding material quality that many reprocessed plastics have, despite the evidence to the contrary (Ambrose *et al.* 2002, Weatherhead 2007a, 2007b), is another example of the prejudicial perception that sustainable practices must overcome. Strangely, these quality perceptions do not extend to other more robust metallic materials, with 40% of current steel production coming from end-of-life products (Sullivan 2007).

These issues are further compounded by an expectation by consumers to pay less for products manufactured from recycled materials, thus providing another barrier to the establishment of higher-value market values for recycled materials.

5. Challenges: knowledge-based approach to design and end-of-life recovery

The intended aim of upstream manufacturer design considerations is to utilise the critical leverage point of the product design process to facilitate in-service and end-of-life disposal activities that occur further downstream. Making these allowances not only assists with the economics of product recovery (as it makes activities such as de-pollution and dismantling easier) but it can also tailor product attributes to favour a particular end-of-life recycling strategy. The following sub-sections discuss the barriers relating to the encapsulation of end-of-life value through design and the difficulties producers face when choosing an appropriate 'Design for X' paradigm for implementation.

5.1 Manufactures' resistance to improving design for end-of-life recovery

Decisions made within the product development phase have the greatest bearing on the available environmental treatment options at end-of-life. Figure 4 provides an overview of the environmental choices that each stakeholder can make within a product's life-cycle relating to material use, conservation and collection.

Many manufacturers face the difficult choice as to how much of a role they play within the recovery of their own products. A lot of research has highlighted the possibility of manufacturers 'vertically integrating' into the product recovery chain and the benefits this would have in terms of potential product reuse, available information exchange and 'design for' disciplines. Although, there are some successful examples of such an approach, e.g. Caterpillar's engine remanufacturing services (Caterpillar Remanufacturing Services 2007), where the manufacturer has taken over the control of collection, recovery and reuse of its products; in most cases, the producers have tended to move away from this model, and utilise the existing technologies and salvage industry already in place. In such cases, the lack of cohesion, combined with an absence of

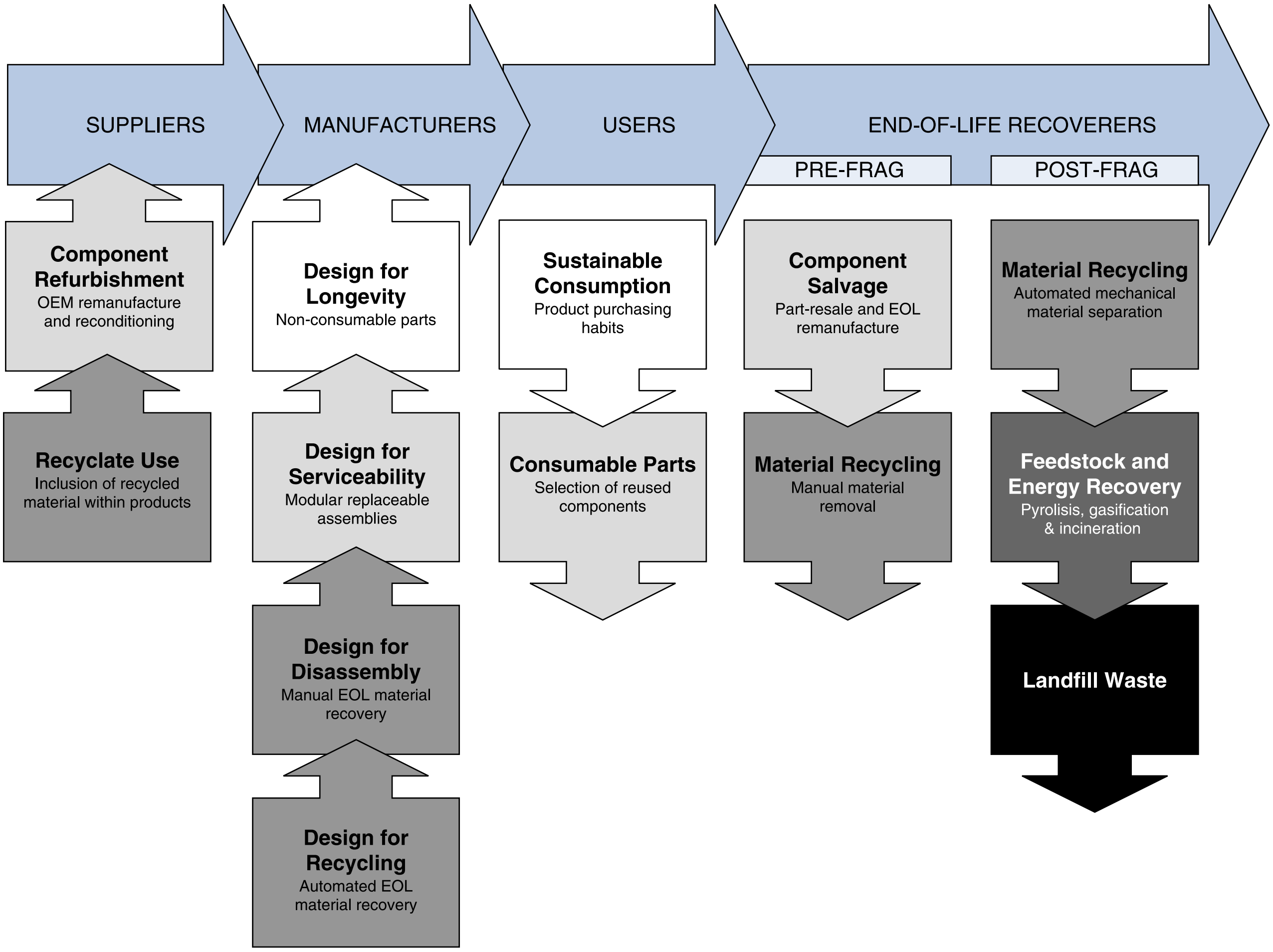

Figure 4. Manufacturer design influence on the environmental pyramid for end-of-life products.

any historic collaboration between these two stakeholders, has created a complex situation. The manufacturer can determine how much value is placed within a product, and how easy it is to liberate that value at end-of-life (through its various material choices and design initiatives), but often it does not benefit economically from making any of these additional design improvements. This therefore poses the question: why should manufacturers adopt a 'design for end-of-life value recovery' approach and promote sustainable product recycling, if other stakeholders are ultimately reaping the economic benefits of their design practices?

5.2 Selection of an appropriate 'design for X' approach

Sustainable end-of-life product recovery can only be achieved, if designers have an appreciation for the current technologies and market trends driving the reclamation sector, both in terms of recycling practices and the market values of recycled materials and sub-assemblies. Designing for end-of-life value recovery based on widely available disposal scenarios has the potential to substantially improve the sustainability of products by releasing more of their encapsulated value. Some may argue that this practice has been in effect for many years with the use of numerous 'design for disassembly' and 'design for recycling' methodologies in many higher-value consumer products. Yet, the reality for many developed nations is that the labour costs that underpin the manual disassembly of products cannot be justified when compared to the large-scale automated techniques based on fragmentation and separation technologies, currently preferred by many product recyclers. Hence, the focus should be on manufacturers to gain an appreciation for the main separation requirements of these preferred post-fragmentation technologies and gain a firm understanding of the problematic material combinations and contaminations. These issues can then be subsequently incorporated within the product development phase, with the aim of encapsulating enough economic end-of-life value within the product to justify more comprehensive and sustainable recovery once it is retired.

This use of end-of-life recovery knowledge within the design phase is obviously a two-way process. From an end-of-life perspective a better understanding of encapsulated value would facilitate greater economic transparency of current end-of-life activities and allow operators to make more effective processing decisions based on more reliable information. This could be as basic as the release of manufacturer teardown databases and technical information systems, to the more widespread availability of product compositional data to assist in value realisation. Conversely, a more comprehensive understanding of downstream product recycling technologies and industry direction, would assist manufacturers in selecting more appropriate 'design for X' initiatives, namely 'design for shredding' (Edwards *et al.* 2006), 'design for gasification', etc.

The selection of a suitable design paradigm to support end-of-life value recovery is ultimately dependent on the processing technology available to liberate encapsulated value at the time of eventual retirement, and the market value of the materials within the product considered. Designers of products with relatively long-life spans (i.e. 13 years for an average end-of-life vehicle) would find it difficult to justify selection of a particular 'design for X' paradigm at the early stages of development, given the changes in end-of-life processing technologies during an extended period of time. Hence, 'design for end-of-life value recovery' should be targeted at products that have short use phases and that encapsulate enough value to justify recovery of core materials and sub-assemblies. The time horizon for designing for value based on material market prices is even shorter, as the prices of many material groups can vary substantially over a short period of a few months and give contradicting messages to designers regarding material selection. Therefore, improvements in product design to support end-of-life value recovery should primarily be based on those recycling technologies that are well established, and design decisions based on material values should only be used for products with extremely short life-spans.

5.3 Knowledge based end-of-life value recovery

Effective end-of-life value realisation is essential when trying to shift the opinion of used product from a waste management problem to an environmentally beneficial resource, but this will only be achieved if certain requirements are fulfilled and changes made at various stages of the product's life cycle. To date, producer responsibility legislation has been the main driver to effect change, attempting to force the manufacturers to focus on more downstream recovery issues. However, end-of-life legislation has been a catalyst for self-regulated improvement based on the introduction of industry environmental standards and disposal taxation. Figure 5 provides an overview of the challenges affecting end-of-life value recovery, and highlights the

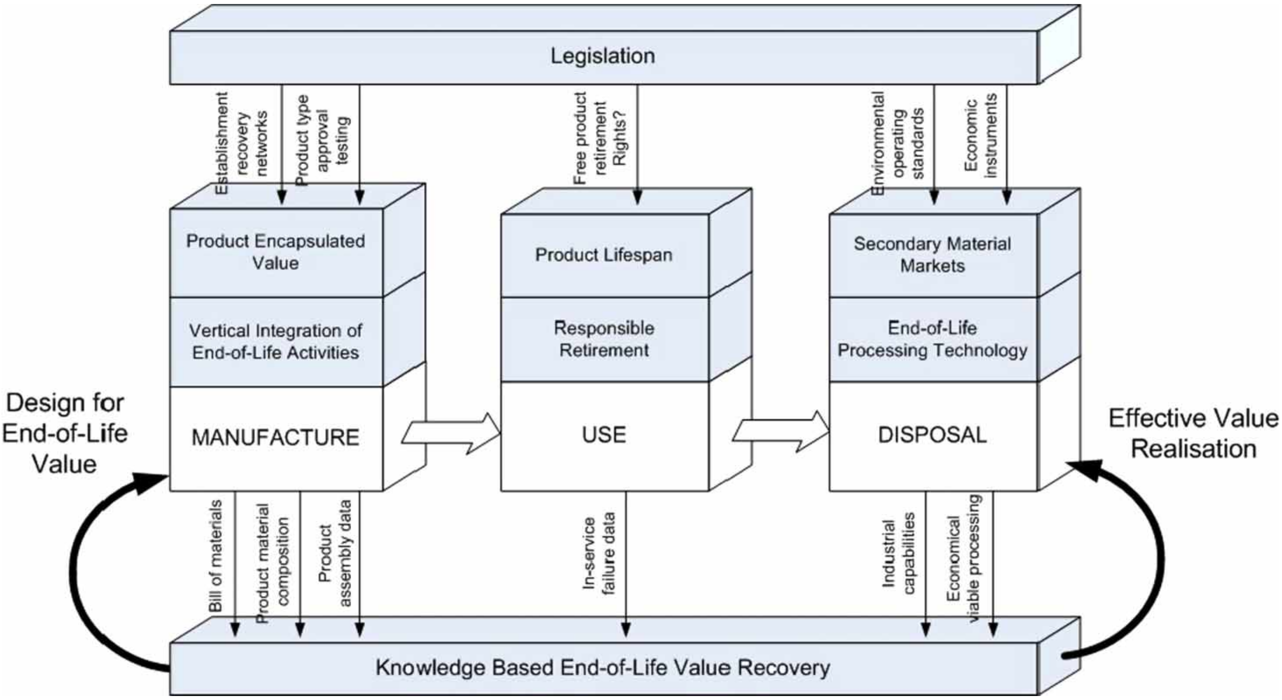

Figure 5. Sustainable product reclamation through effective knowledge-based value realisation.

influence of legislation that has tried to effect change at each of the life-cycle stages. In addition, the current requirements needed to provide homogeneity between stakeholders across the product value chain are then outlined, before highlighting the beneficial contribution this would have in terms of life-cycle knowledge and future product sustainability, if better synergy could be achieved.

6. Challenges: sustainable business models

The scarcity of natural resources, legislative pressures and consumer demand have resulted in a number of fundamental questions about the long-term viability of traditional manufacturing business models based on the 'mass production and consumption of cheaply produced goods'. The current consumer attitudes (e.g. ever-changing fashion, must-have technology) which are the main drivers in many contemporary product development initiatives are diametrically opposed to the ideas of manufacturing sustainability and product longevity. Consequently, considerable quantities of products are disposed of each year with little or no control over their end-of-life processing routes. In addition, there is a fundamental pressure to shift the responsibility for the management of post-consumer waste from users and local governments towards manufacturers, distributors and retailers. Furthermore, it is commonly reported that in order for product recovery to be economically viable and recycling schemes to be successful, there must be sustainable end-markets for recyclable materials. These factors highlight the need to investigate new business models for design, production, consumption and disposal of product that meets the consumer needs as well as legislative, environmental and ethical standards whilst safeguarding the future prosperity of manufacturing companies. One such business model has been proposed based on the concept of 'product service system' (Mont 2002b) in which the ownership of the product is retained by the manufacturer and the revenue is generated through provision and selling of services to potential customers. Product service systems (PSS) represents a step change in the way the customer interacts with the producer with the focus on developing services to meet the needs of the consumer without actually selling them the physical object (Baines *et al.* 2007). For example, a PSS approach to personal mobility would be to lease a car to the consumer, providing the ability to travel over a certain time period with protection against the need to pay maintenance costs. Whereas within the traditional approach, the consumer would be sold a vehicle and accept all the responsibility associated with ownership. In short, PSS try to align the goals of the producer with the needs of the consumer, for mutual economic and environmental benefit.

Furthermore, the issues discussed earlier within this paper, created via the traditional model of consumer ownership and manufacturer responsibility, clouds the issue of who owns the right to dispose of the product and who is ultimately accountable for its end-of-life processing. PSS address these problems by a clear attribution of responsibility to the producer by allowing them to retain the ownership of the products they create. This approach has a number of consequential benefits:

- Greater control over product returns, in terms of timing and volume.
- The value of end-of-life 'design for X' paradigms can be exploited by the manufacturers (refurbishment, remanufacturing, recycling, etc.).
- The use of design knowledge to support end-of-life processing has less confidentiality issues, as it is up to the manufacturer to donate the products and contract a third party company, if they are unwilling to deal with the product themselves.
- In-service (RFID tagging data) and end-of-life data can be more effectively incorporated within the design of subsequent products.
- Product durability and life-extension have more of a central focus in the product development process to reduce the longer-term costs associated with manufacturer maintenance.
- Products containing less material are created, reducing the overall environmental load of the approach.

Currently, PSS have only been considered within complex high-value products (jet engines, automobiles, etc.) and its applicability and extension to general consumer goods is yet to become well established. Large hurdles still exist regarding the willingness of both manufacturers and consumers to accept these new ideas of product ownership and use, highlighting the need for more detailed research in this area to assess the global impact of such new business models within both developing and developed countries.

7. Concluding remarks

This paper has considered some of the main issues relating to the establishment of sustainable product recovery and recycling, and highlighted the main market drivers and barriers in a number of key areas. The review of the various options available to finance the EPR legislation currently affecting manufacturers have highlighted the challenges in attribution of direct responsibility. End-of-life levies at point-of-sale passes the cost burden to the consumer, and although it is suggested that this method has been the most effective, in so far as raising the funds to deal with the retired products, it does not attribute direct producer responsibility to the manufacturer in question. Equally, the use of business-centred levies and the creation of 'product recovery notes' has the potential for indirectly passing the cost burden onto the consumer and does not incentivise environmental improvements for those manufacturers that pro-actively develop their products to be more easily processed at end-of-life. End-of-life taxation is a good method of ensuring waste management companies improve their effectiveness, but ultimately this economic instrument has little influence on product manufacturers. Furthermore, the use of end-of-life product value to fund the retirement processes disassociates the recoverer from the manufacturer. This review of legislative drivers has highlighted an essential need to develop more cohesive and intelligent ways of instigating producer responsibility to encourage manufacturers to invest in the environmental improvements of their products.

The establishment of end-of-life value chains, particularly in the area of post-consumer plastics, has been identified as one of the drivers in increasing the applications of recovery and recycling among wider product sectors. Such value chains will be strongly dependent on reverse logistical models, with a number of environmental, technical and social aspects influencing the selection of the most appropriate model for a product recovery scenario.

The active involvement of manufacturers through implementation of environmental improvements at the design phase is of paramount importance to the long-term sustainability of product recovery and recycling applications. This requires cross-stakeholder collaboration throughout the product life cycle to create more effective information and knowledge sharing activities to support a 'design for end-of-life value recovery' approach in product recovery and recycling applications. Such new design approaches to increase value recovery, in addition to a more tradition emphasis on 'design for disassembly', should also focus on the specific requirement of fragmentation and separation processes through the concepts for 'design for shredding', as within specific applications this would provide the most environmentally and economically viable option for product recovery and recycling.

Finally, one of the most significant challenges in this area relates to the development of sustainable business models that underpin the long-term viability of product recovery and recycling applications. In this respect, the potential benefits offered through the implementation of PSS could support the establishment of such sustainable business models. However, this requires further investigation of their applicability in general consumer goods sectors and the willingness of both manufacturers and consumers to accept these new ideas of product ownership.

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