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What should be recycled: An integrated model for product recycling desirability

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ABSTRACT

This research was focused on developing a new scientific approach for prioritising recycling of end-of-life products in a circular economy. To date, product complexity based on the mixture of materials has been used as a predictor of what gets recycled. While the separation of materials that make up a product has been modelled as a measure of product complexity, this does not taken into account the benefits and considerations in recycling products. In this paper, a new agenda and approach to prioritise the recycling of products was developed based on a recycling desirability index. The material mixing complexity measure was inverted into a simplicity index and then extended by modelling the security index for the mix of materials and the technological readiness level of recycling technologies. The extended model is proposed as an integrated measure of the desirability of recycling end-of-life products. From this analysis, an apparent recycling desirability boundary, enabling products to be prioritised for recycling, was developed. This model and analysis can be used as an information source in developing policies and product recycling priorities.

1. Introduction

A product made up of more than one material will usually be required to undergo material separation prior to recycling. Many manufactured products fall into this category. For instance, a mobile phone and television board can be made from a dozen of materials ranging from plastic to base metals and precious metals (Hagelüken, 2006). These products are more complex compared with beverage plastic bottles that are built typically using 96% plastic and 4% paper or plastic label (Yam, 2009). The higher the number of material types used in a product, the more complex material separation becomes (Dahmus and Gutowski, 2007).

End-of-life products retain substantial worth if they can be separated into isolated forms that used in the production of new products (Despeisse et al., 2015). Therefore, the act of separating material is key to recycling. A product may have been built from either one or a number of components. Similarly, one or many types of materials can make up a particular component. A product can also have similar types of materials distributed within different parts or components. Products built from a single type of material do not require material separation and directly proceed to the recycling process if the technology exists. Such a material is an easy candidate for recycling.

Research related to material separation can be traced back to Sherwood (1959) and Dahmus and Gutowski (2007). Both addressed the difficulty of material separation. Sherwood (1959) researched the relationship between the difficulty of extracting minerals from ore and the market price of the material. Dahmus and Gutowski (2007) later adapted a similar approach for products by establishing a mathematical equation for the difficulty of material separation.

1.1. The material separation adoption into product recycling

Sherwood (1959) analysed the connection between the market value of a metal and its concentration in the ore from which it was obtained. It was assumed that the metal is much easier to extract into its pure substance states from ore where it is in high concentrations. He concluded that the metal's market prices were proportional to their concentration.

The concept of the Sherwood plot was further developed by Gutowski and Dahmus (2005) who modelled material mixing in a product. The 'material mixing complexity measure' or 'complexity measure', H was defined as an index to assess the complexity of the

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task to separate and recover pure substances from mixtures. It is a function of the sum of binary logarithm of the constituent material fractions. They plotted the relationship between the recycled material's market value ($) and the complexity material mixing, H (bits). The authors identified a gradient line that separated products into those with a higher percentage of recycling (above the line), and those with a lower percentage of recycling (below the line). The line was named the apparent recycling boundary.

1.1.1. The complexity measure

The *'complexity measure of material mixing'* quantitatively evaluates the difficulty in separating materials that make up a product. This is quantified by a parameter H (bits) based on binary separation steps. This is the set of individual separations that are progressively required to separate the materials of a product. The concept is illustrated in Fig. 1 by the tree diagram. The trunk is the input stream (product) and the branch ends are the material group (Dahmus and Gutowski, 2007). In the example shown in Fig. 1, the product of mass M_{total} on the left hand side consists of five constituent materials that are then progressively separated into the form of a branching tree to masses M_1, M_2, M_3, M_4 and M_5.

In the material separation tree, each square represents a binary separation process ($Process_1$, $Process_2$, $Process_3$ and $Process_4$). For any given separation tree, the separation steps are taken as an assessment of material 'mixing'. Fewer separation steps would correspond to a product with relatively low material 'mixing' while more separation steps would correspond to a product with higher material 'mixing'. Based on this, the material mixing complexity measure formulation was developed. The mass fraction C_i, of a material to be separated was calculated by equation (1).

$$C_i = \frac{M_i}{M_{total}} \tag{1}$$

where C_i is the mass fraction of a material in a part that makes a product assembly, M_i is the actual mass in kilogram (kg) of the component/material and M_{total} is the total mass of the product assembly.

Summing up these separations represents the disassembly tasks. The complexity H_m of separating materials was modelled by equation (2).

$$H_m = K \sum_{i=1}^{M} C_i \log C_i \tag{2}$$

where M is the number of component materials in a mixture. C_i is the material mass fraction as defined before in equation (1), and K is a constant value of -1 used to change the values into a positive index. The base of two logarithms is used to represent the binary separation applied to retrieve a material or component.

In some cases, one hundred percent disassembly may not be possible due to the condition of parts or difficulty of reversing the joining method. This is not an uncommon problem in manufacturing and in such cases a utilisation factor can be used. For example 75% of the parts could be disassembled; the complexity could be increased by dividing them by 75%. Recent research has investigated the condition of parts and used this information to assess re-manufacturing feasibility (Colledani and Battaïa, 2016). More research is required to develop a disassembly difficulty rating for different joining methods and conditions of end-of-life products.

1.2. Further refinement of complexity modelling

The complexity measure was used to predict which materials get recycled for a number of products as shown in Fig. 1. However, there are a number of areas in which the research can be taken forward. The Dahmus and Gutowski's (2007) model was based on the total weight fraction of each material in a product. This does not capture the distribution of the same material category in different parts or components of the same product. If one material category is available in many parts of a product then this can imply more separation steps. It is recommended here that this would increase product complexity and can be solved by taking the fraction of each separate material part and extending Fig. 1. This is illustrated in Fig. 2 as M5-Part A and M5-Part B.

1.3. Research motivation

The authors also consider some of the drivers for a circular economy and the recycling business. It is argued here that some materials should be recycled if it is good for the environment and if it addresses materials scarcity, provided that the technology to do so is available and mature. In a world of constrained resources, it is important to consider what the recycling priorities should be for nation states and economic regions. The previous models, focussed on material separation steps only. The motivation for this study was to build on previous product complexity modelling, and to consider the additional factors important in prioritising product recycling. Material scarcity, and hence security and availability of technology, are modelled in a new approach capturing the desirability of product recycling.

2. Proposed new product recycling desirability model

The ease of material disassembly or separation is relevant to consider before recycling. Hence, the complexity index is used to measure the technical and physical challenges of material separation. However, it does not capture some important information regarding recycling. For instance, for recycling to be successful, a mature recycling technology needs to be in-place. The Technology Readiness Level (TRL) is suggested to be integrated as an

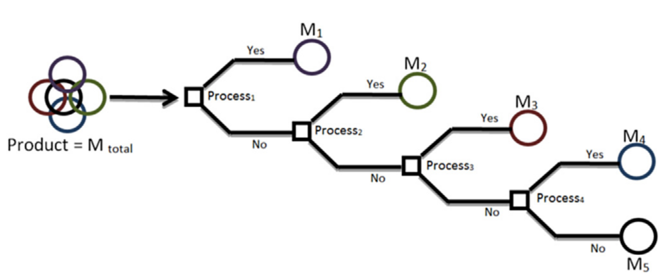

Fig. 1. Material mixing separation tree diagram, adapted from Dahmus and Gutowski (2007)

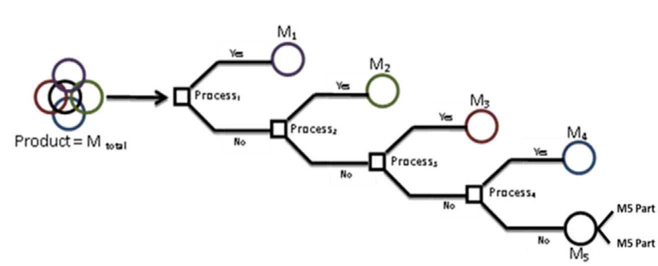

Fig. 2. Material mixing separation tree diagram considering multiple same material parts.

assessment method.

Another point that has not been addressed is the criticality of the particular product materials. There are some materials which can be classified as rare earth metals, precious metals and critical metals. These materials are highly desirable to recover from used products. These are materials which are either difficult to obtain, scarce, and/or the depletion of the reserves lower the security of the materials. In order to assess this, Material Security Index (MSI) was used. This index combines numerous complex factors interconnected to the importance of raw materials and changing supply conditions (Chapman et al., 2014).

Integrating product complexity, recycling TRL and the criticality of the materials, presents a more robust method for prioritising product recycling activities. This integration is presented here as a Recycling Desirability Index (RDI). The TRL and MSI are universally used and are independent principles and concepts. This integration into a desirability index builds upon accepted concepts enabling a generic approach to the global assessment of recycling potential. The rationale for integration is illustrated in Fig. 3.

2.1. Material security index

Material security can be simply expressed as the availability and access to the material resources on which economies depend on, as well as the ability to cope with volatility, increasing scarcity and rising prices (Eco-innovation, 2015). The baseline is that there is no harm to the country's economy due to the shortage or limited access to the specific material. Material security is a negative measure, i.e. a lack of scarcity in achieving the lowest acceptable limit, rather than a positive need for abundance (Morley and Eatherley, 2008).

Material criticality is also a determination of which materials that flow through an industry or economy are most important to the production process. It concerns the access to the raw materials to ensure economic sufficiency. Recently, its importance has increased due to limited short-term availability of some materials. Materials are most insecure when there is lack of substitutability in demanded applications and this is influenced by many factors. Research related to the critical materials can be found in literature and the concept has been established globally (Habib and Wenzel, 2015).

Related to the material security for the UK economy, Morley and Eatherley (2008) ranked 60 insecure materials, the top 20 are extracted and shown in Table 1. These were ranked according to eight individual factor combinations that mainly fall under material risk and supply risk. Material risks included: global consumption

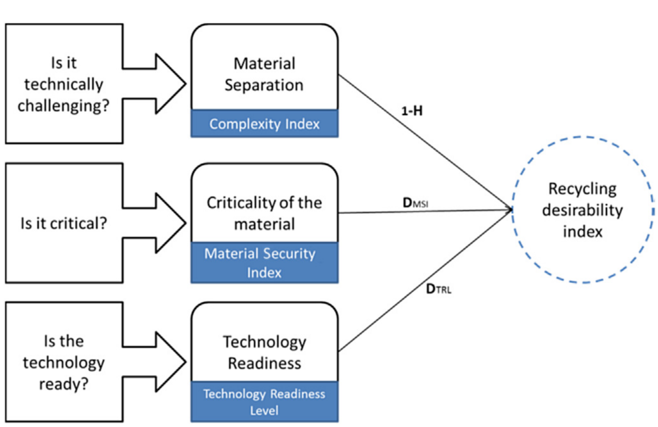

Fig. 3. Proposed product recycling desirability model.

Table 1
The Top 20 Highly Insecure Materials For UK Economy, extracted from Morley and Eatherley (2008).

Rank	Material	MSI	Material Risk				Supply Risk			
			GC	Sub	GWP	TMR	Scarcity	MS	PS	CCV
1	Gold	21	2	2	3	3	3	2	3	3
2	Rhodium	20	1	3	3	3	2	3	2	3
3	Mercury	20	2	2	3	2	2	3	3	3
4	Platinum	20	1	2	3	3	3	3	2	3
5	Strontium	19	2	2	3	2	3	1	3	3
6	Silver	19	2	2	3	2	3	1	3	3
7	Antimony	19	2	2	2	1	3	3	3	3
8	Tin	19	2	3	2	2	3	1	3	3
9	Magnesium	18	2	3	2	1	2	2	3	3
10	Tungsten	18	2	2	2	2	2	2	3	3
11	Baryte	18	2	2	2	2	2	2	3	3
12	Talc	18	2	2	2	2	2	2	3	3
13	Bismuth	18	2	2	2	2	2	2	3	3
14	Palladium	18	1	2	3	3	3	2	3	1
15	Nickel	18	3	2	2	2	3	2	3	1
16	Boron	18	3	2	2	1	2	3	3	2
17	Andalusite	18	2	2	2	2	2	3	2	3
18	Molybdenum	17	2	3	2	2	2	2	2	2
19	Zinc	17	3	2	1	1	3	1	3	3
20	Holmium	17	1	2	2	2	2	2	3	3

MSI- Material Security Index: GC- Global Consumption; Sub- Substitutability; GWP-Global Warming Potential; TMR-Total Material Requirement; Scarcity; MS-Monopoly Supply; PS-Political Stability; CCV— Climate Change Vulnerability.

level, lack of substitutability, global warming potential and total material requirement. Supply risks were categorised by: scarcity, monopoly supply, political instability in key supplying regions, and vulnerability to the effects of climate change in key supplying regions. The circular economy can be driven by an Extended Producer Responsibility Scheme. Under such a scheme, the manufacturer has the necessary information with regards the materials from which parts were made. In cases where third parties or end-users are doing the recycling, the product information could be assumed from the nearest known cases for initial analysis and then revised after disassembly. Three dimensional and x-ray scanning can also be used to identify components and materials in product assemblies.

2.2. Recycling technology readiness level

The Technology Readiness (TRL) is a technological maturity assessment approach. TRL examines program concepts, technology requirements and demonstrated technology capabilities. This concept originated from the United States National Aeronautics and Space Administration (NASA) TRL, which was developed by Stan Sadin in 1974 to serve NASA's space program (Straub, 2015). It contained seven levels of metrics which were later codified into nine after going through various stages of enhancement (Jimenez and Mavris, 2014; Sadin et al., 1989). The TRL is well-established and applied in various research approaches to assess technology readiness. In the UK aerospace industry, companies such as Rolls Royce Plc implement this as the Manufacturing Capability Readiness Level (MCRL).

At present, many industrial sectors are using TRL approaches for assessing their technology readiness. For instance, the composites recycling technology (Rybicka et al., 2016), automotive technology (Williamson and Beasley, 2011), aviation innovation (Nakamura et al., 2012), technologies to enable autonomous detection (Hookbarnard et al., 2014), waste processing facilities (Alexander and Sutter, 2008), system development planning (Magnaye et al., 2010), carbon dioxide capturing technologies (Bakhtiary-Davijany and Myhrvold, 2013), as well as nuclear fuels and materials

Table 2
TRL Description adapted from Williamson and Beasley (2011).

Descriptions	TRL
The technology has been successfully applied under real conditions	9
The technology has been proven to work in expected conditions	8
Multiple prototypes demonstrated in an operational environment	7
A prototype of the system demonstrated within a laboratory or similar operational environment	6
The component validated in a relevant environment	5
The technology component validated in a laboratory	4
Performance exploration by analytical experimentation/proof-of-concept	3
Experiments have been undertaken; Performance predictions have been refined	2
Basic principles observed or reported; The performance has been predicted	1

development (Carmack, 2014). The established TRL, as shown in Table 2, is proposed to be applied to the product recycling desirability model in Fig. 3.

A review on recycling technology based on the technology readiness was done by Rybicka et al. (2016) for composite materials. The TRL scale was mapped to various recycling technologies such as incineration, pyrolysis, mechanical grinding, fluidised bed and solvolysis. This assessment is shown in Table 3. Such a categorisation of recycling technologies for different materials can be done for a selected country and geographical location, taking into account the locally available technologies. If no recycling technologies exist then the assessment of technology readiness may be ignored. The materials found to be most desirable to recycle can then be targets for development or sourcing of recycling technologies.

2.3. The product recycling desirability index: a model development

In order to develop the new recycling desirability index, the scale of key attribute of factor is considered. The position of the target material on the scale is expressed as a percentage. For example, the material security ranking and TRL score for the UK data are divided by the maximum score or ranking of 24 (material security) and 9 (TRL) as in Tables 2 and 3. A similar approach is used for complexity where the complexity top scale was taken as 3.5. This enables normalising assessment measures to allow integration. Additionally, as in the complexity measure, the mass fraction is also considered. The new mathematical treatment is explained below.

The recycling desirability, considering the material security index, is modelled by parameterD_{MSI} according to equation (3).

$$D_{MSI} = \sum_{i=1}^{n} \left(\frac{M_i S_i}{M_T S_{top}} \right) \quad (3)$$

where n is the maximum number of a particular discrete material type in the product, M_i and M_T are the mass of material in a product or component and total product mass respectively, and S_i is the material security index of recycling a particular material that is part of a product assembly and S_{top} is the top scale for the material security index. This is taken as 24 for this study according to the United Kingdom scale published by Morley and Eatherley (2008). The country specific scales can be considered. An industry sector/company or stakeholder could also develop its material security index and use it for the purposes of this analysis.

The recycling desirability, considering recycling technology maturity, is represented by parameterD_{TRL}, as modelled in equation (4).

$$D_{TRL} = \sum_{i=1}^{n} \left(\frac{M_i R_i}{M_T R_{top}} \right) \quad (4)$$

where n is the maximum number of a particular recycling technology used in a product, M_i and M_T are the mass of the discrete material in a product or component and total product mass respectively, as defined before. R_i is the technology readiness level assessment of recycling technology for a particular material that is part of the product assembly, R_{top} is the top scale for the TRL scale and this is 9. In equations (3) and (4), the log scale has not been used because the material separation steps are modelled already in the complexity measure.

The recycling desirability index considering simplicity of separating materials (the inverse of complexity), is modelled according to equations (5) and (6).

$$D_{Simplicity} = 1 - \left(\frac{H}{H_{top}} \right) \quad (5)$$

where$D_{Simplicity}$ is material separation simplicity, taking into account mass fraction and distributed materials for parts. Where H is the complexity index which was obtained using equation (2) and H_{top}, is the top scale for the material complexity index taken as 3.5.

$D_{Desirability}$ is the aggregate desirability recycling index for a selected product considering multiple factors of products simplicity, material security index of constituent materials and the maturity of technologies for reclaiming the materials. This is modelled in equation (6).

$$D_{Desirability} = \left(D_{Simplicity} + D_{MSI} + D_{TRL} \right) \quad (6)$$

3. The product recycling desirability index: exemplary application

As an example for the refrigerator of Model 97 (Kim et al., 2006), the desirability index is calculated using equation (6). For the material security index materials that are not on the material security index list for a given country, are given a rank of zero. In this example of a refrigerator, brass was considered as zinc and copper at 40% and 60% as typical of navel brass (Granta Design, 2015). For the product, the material security ranking of iron, copper and zinc were used for obtaining material security index as these appeared on the UK list of insecure materials. Some of the calculation details are shown in Table 4.

The detailed calculations are shown below.

$$D_{MSI-copper} = \left(\frac{2.88kg \times 16}{99.8kg \times 24} + \frac{0.108kg \times 16}{99.8kg \times 24} \right) = 0.0197$$

Table 3
TRL score for composites materials (Rybicka et al., 2016).

Composites Recycling Technology	Carbon Fibre	Glass Fibre
Incineration and landfill	9	9
Pyrolysis	9	7
Mechanical grinding	7	8
Fluidised bed	4	4
Solvolysis	4	4
Microwave heating	3	3

Table 4
Refrigerator's material composition for recycling desirability index calculation.

Material	Mass (Kg)	$\frac{M_i}{M_{total}}$	D_{MSI}	D_{TRl}	$D_{Simplicity}$	$D_{Desirability}$
Steel	56.60	0.566				
Iron	5.40	0.054				
Aluminium	2.50	0.025				
Copper	3.20	0.032				
Brass	0.20	0.002	0.055	0.998	0.509	1.562
Rubber	28.10	0.281				
Fiberglass	0.10	0.001				
Glass	3.40	0.034				
Refrigerant	0.10	0.001				
Oil	0.20	0.002				

$$D_{MSI-zinc} = \left(\frac{0.072kg \times 17}{99.8kg \times 24}\right) = 0.0005$$

$$D_{MSI\ refrigerator} = (0.0304 + 0.0197 + 0.0005) = 0.0551$$

The recycling technology for most electrical and electronic equipment including a refrigerator is considered mature and hence a TRL scale of 9 was used. The recycling process is possible using available recycling technology. This had developed due to EU legislation adopted by the UK on Waste Electrical and Electronic Equipment (WEEE); Restriction of the use of certain Hazardous Substances in electrical and electronic equipment (RoHs); and Registration, Evaluation, Authorisation and restriction of Chemicals (REACH) (Sezen and Çankaya, 2013; Umeda et al., 2012).

$$D_{TRL\ refrigerator} = \left(\frac{56.60kg \times 9}{99.80kg \times 9}\right) + \left(\frac{5.40kg \times 9}{99.80kg \times 9}\right) + \left(\frac{2.50kg \times 9}{99.80kg \times 9}\right) + \left(\frac{3.20kg \times 9}{99.80kg \times 9}\right) + \left(\frac{0.2kg \times 9}{99.80kg \times 9}\right) + \left(\frac{28.10kg \times 9}{99.80kg \times 9}\right) + \left(\frac{0.10kg \times 8}{99.80kg \times 9}\right) + \left(\frac{3.4kg \times 9}{99.80kg \times 9}\right) + \left(\frac{0.1kg \times 9}{99.80kg \times 9}\right) + \left(\frac{0.2kg \times 9}{99.80kg \times 9}\right) = 0.998$$

The complexity of material mixing value of 1.72 is calculated using equation (2). Due to inverse nature of the complexity index in this model, the value was subtracted to obtain a positive mathematical index as in equation (5).

$$D_{Simplicity\, refrigerator} = 1 - \left(\frac{1.720}{3.500}\right) = 0.509$$

$$D_{Desirability\ refrigerator} = (0.055 + 0.998 + 0.509) = 1.562$$

So, the product desirability index for the refrigerator is 1.562.

For this study, a number of products were considered from the work done by Dahmus and Gutowski (2007). These were supplemented by the wind turbine blades to reflect the work being done by the authors in composite recycling (Shuaib et al., 2015). The products data summary is shown in Table 5 for all the selected products. The aggregate value of the product materials and the recycling rates for the products was also captured.

3.1. The "what should be recycled": a new model

The discrete indices for material recycling desirability were plotted against the product's total virgin material value. Fig. 4 shows the aggregate desirability index for the product data shown in Table 5. The price data was obtained from CES Edupack Educational Edition (Granta Design, 2015). Fig. 4 illustrates the distribution of products based on recycling desirability index. Circles in the figure demonstrate the product's recycling rates in the United Kingdom based on Table 6. Table 6 shows recycling rates and production amount of selected products in the United Kingdom (UK) and the United states (US). A refrigerator, tyre and car battery, had high recycling rates in both countries. The wind turbine blade, mobile phone and coffee maker had low recycling rates. This data was gathered from publicly available sources such as from the UK Waste and Resources Action Programme (WRAP) and the US Environmental Protection Agency (EPA). The details of data sources and additional information are available in Appendix A1–A4. The

Table 5
Product indices value towards products recycling desirability index.

No	Product	Simplicity	Material Security Desirability	Technology Readiness Desirability	Total Recycling Desirability	Total Virgin Material Value (£) (Granta Design, 2015)
1	Car battery	0.64	0.446	1.00	2.08	56.15
2	Mobile Phone	0.38	0.569	1.00	1.95	10.26
3	PET bottle	0.92	0.000	1.00	1.92	0.09
4	DVD-R	0.51	0.401	1.00	1.91	10.91
5	Desktop computer	0.25	0.587	1.00	1.83	281.22
6	Wind turbine 100 kW	0.78	0.003	0.90	1.68	43322.13
7	Wind Turbine blades 20 kW	0.73	0.000	0.89	1.62	946.50
8	Wind Turbine blades 5 kW	0.73	0.000	0.89	1.62	353.85
9	Refrigerator	0.51	0.055	1.00	1.56	346.67
10	Tyre	0.55	0.000	1.00	1.55	28.90
11	Coffee maker	0.52	0.019	1.00	1.54	2.21
12	Ergo chair	0.50	0.000	1.00	1.50	25.00

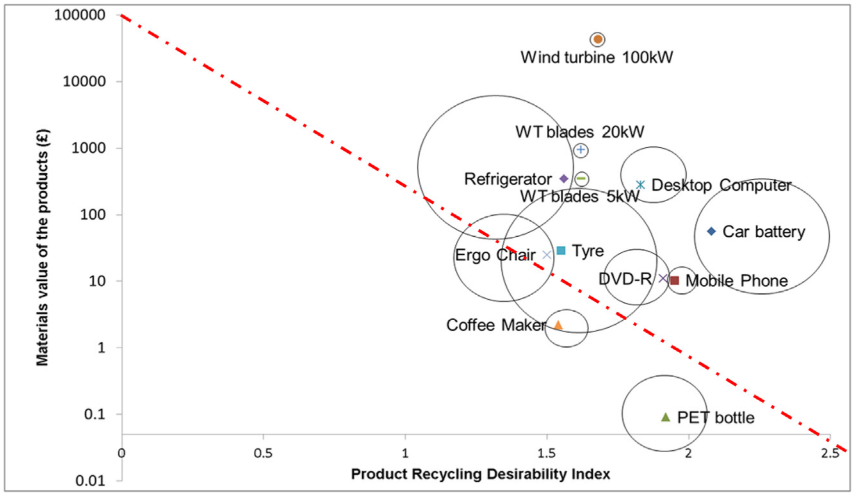

Fig. 4. Distribution of Selected Products in the 'what should be recycled' Model.

Table 6
Recycling rates and the number of selected products.

No	Product	Recycling Rates (%)		Amount		
		UK	US	UK	US	
1	Car battery	90	99	1 270 000	2 730 000	unit
2	PET bottle	52	31	3 518 800	2 600 000	tonnes
3	Mobile Phone	11	11	89 900 000	235 600 000	unit
4	DVDR Player	38	29	23 600 000	25 230 000	unit
5	Desktop Computer	38	40	2 355 000	23 500 784	unit
6	Refrigerator	98	82	2 400 000	11 639 000	unit
7	Tyre	98	80	1 500 000	252 700 000	unit
8	Coffee Maker	22	29	6 900 000	24 000 000	unit
9	Ergo Chair	75	54	30 000	35 000	unit
10	Wind turbine blade	2	0	7410	4300	unit

Pearson product-moment correlation coefficient analysis is a measure of the strength and direction of the linear relationship between two variables. Based on this, both the US and UK have positive correlation 0.82 in term of recycling rates. It means that there is some coherence in recycling uptake for the two countries.

From Fig. 4, products appearing in the top right hand corner i.e. high recycling desirability index and high material value, should be prioritised for recycling. A recycling desirability boundary is introduced in Fig. 4 and shown by the dotted line. To aid further discussion the details of the recycling rates are shown in Fig. 5 (which magnifies an area of interest from Fig. 4). It is noted that;

- The desirability model indicates that the car battery (with 90% UK recycling rate), is a highly desirable product for recycling. This is due to less material separation process and also, high amount of precious metal (e.g. lead), captured in the model. This is a good example where the uptake of recycling is in synergy with recycling desirability.
- The refrigerator is desirable to recycle and the market uptake of recycling appears to reflect this value.
- The mobile phone (with 11% UK recycling rates), is ranked very high in terms of recycling desirability. This is because it has a substantial number of critical materials (e.g. gold, silver, chromium, copper, iron, nickel, lead, palladium, tin and zinc). The recycling of mobile phones needs to be prioritised. The desktop computer and the DVD-R are also desirable products to prioritise for recycling. Current uptake is modest.
- The wind turbine blades show the lowest recycling rates. However the larger wind turbine (with 2% UK recycling rate), appears to be one of the most desirable to recycle. This is because it is relatively simple compared to consumer products. It is notable that the number of wind turbines installed was also smaller than the other products. However, this is the right time to start and plan the end-of-life management of wind turbine blades because most of the installed wind turbines will be deployed after 15–25 years of usage. Legislation on disposal of composites to landfill could also encourage greater recycling. In addition, if the value of composites is captured (they are not currently on material security index), their recycling could be desirable.

3.2. Applications of product recycling desirability index internationally

The European Union (EU), USA and India material criticality data was assessed in addition to the UK data in order to investigate the international perspective. Material Security Index for the EU was calculated by utilising information on supply risk and economic importance of 49 types of materials (European Commission, 2014). The EU supply risk evaluates the recyclability, substitutability and Herfindahl–Hirsch-mann-Index, while economic importance is based on the total value added of the production sectors that depend on the specific raw material (Asamrai and Raheb, 2015).

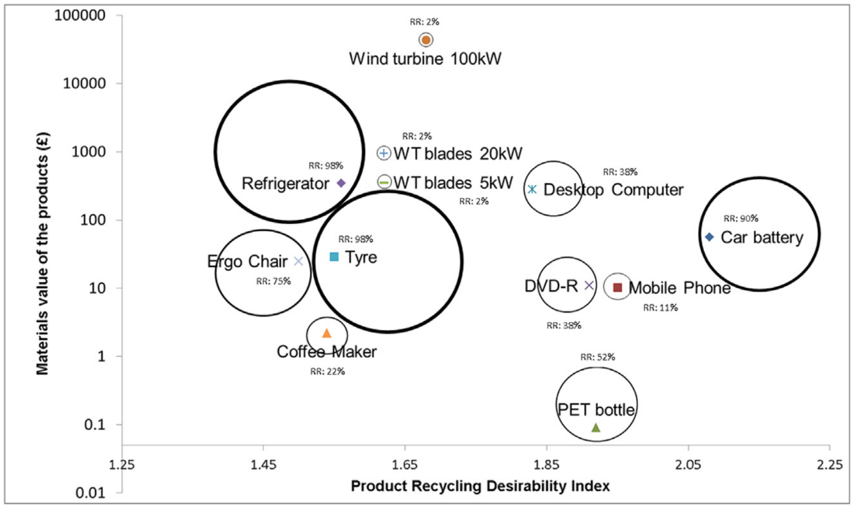

Fig. 5. UK recycling percentages and recycling desirability detail.

Table 7
Product recycling desirability index on international applications.

	Product	Desirability UK	Desirability EU	Desirability USA	Desirability India
1	Car battery	2.08	1.65	1.79	1.73
2	Mobile Phone	1.95	1.76	1.56	1.93
3	PET bottle	1.92	1.92	1.92	1.92
4	DVD-R	1.91	1.54	1.52	1.81
5	Desktop Computer	1.83	1.72	1.85	2.25
6	Wind turbine 100 kW	1.68	1.68	1.71	1.74
7	WT blades 20 kW	1.62	1.62	1.62	1.62
8	WT blades 5 kW	1.62	1.62	1.62	1.62
9	Refrigerator	1.56	1.69	1.58	1.68
10	Tyre	1.55	1.86	1.55	1.55
11	Coffee Maker	1.54	1.53	1.53	1.62
12	Ergo Chair	1.50	1.68	1.65	1.64

Whereas for the USA, 78 types of material were assessed as highly insecure by considering supply risk, production growth, market dynamics and potential criticality (National Science and Technology Council, 2016). Whilst, India only recognised 33 types of materials as critical based on their economic importance and import dependency (Gupta and Ganesan, 2014).

Table 7 shows product recycling desirability index for the EU, the USA and India in comparison to the UK. The results indicate that the inferred ranking of recycling varies between countries as predicted by differences in material security lists and indexes. This is an important factor to consider when developing priorities. Local material security factors should be modelled in order to make better prioritisation or recycling decisions.

4. Generic importance of recycling desirability approach

The existing body of knowledge and work found in literature is based on the hypothesis that product complexity can be used as a predictor of what gets recycled. In this new contribution, authors have improved the implementation of the complexity measure by considering number of components and not just number of materials. This is important because in a complex assembled product, many components may be made from one material. Thus, considering the number of material combinations misses the total possible number of dis-assembly steps needed to enable recycling.

In this paper, authors have further set a new agenda for research by proposing the need to evaluate what should be recycled. Authors have brought the important factor of material security into the decision tool as well as availability of recycling technology. This is a generic and important approach that can be used by other researchers in considering other factors that should influence priority in a circular economy. The new mathematical models for recycling desirability provide a blueprint for other researchers to develop decision tools for recycling. This information system can be important for a company that has many end-of-life products and wants to decide where to focus recycling. The approach can also be valuable for a country when developing priorities for recycling. Stakeholders can be engaged to define the critical parameters and then these can be modelled using the new information theory on recycling desirability.

The new information theory and desirability model in this paper has been applied to recycling, but it can equally be used for other options in a circular economy, for example, when prioritising remanufacturing.

5. Conclusions

This paper has presented a new approach to evaluate material recycling desirability of different products. The work presented here captures and quantifies four factors that are significant in the recycling of products at their end of life. This was based on the simplicity in taking products apart, material security index, maturity of recycling technology and monetary value of materials.

Material security has to be considered because it captures material scarcity, depletion, substitutability, total material requirement, monopoly of supply, political stability, global warming potential and climate change vulnerability.

The new information model allows for a mathematical approach and the application of a quantitative analysis model, to better understand and evaluate priority products for recycling. This generic approach can be valuable for setting regional, national and international recycling policy, or for companies deciding on priority products for a circular economy.

Existing approaches based on material complexity were able to predict what gets recycled. However, they did not address the question of what should be recycled.

For the products considered in the UK, the findings suggest that the mobile phones, car batteries and large wind turbines should be prioritised for recycling. The recycling rates for mobile phones are currently low. Wind turbines will become more critical in recycling as more products reach their end of life so it is timely to develop the technology now.

The product complexity model was refined to capture the distribution of the same material category in different parts or components of the same product. If one material category is available in many parts of a product then this can imply more separation steps. It is recommended here that this would increase product complexity and can be solved by taking the fraction of each separate material.

5.1. Discussion of assumptions and future work

- It has been assumed that the material security assessment is available and date stamped. While this was true for the countries considered in this paper, this information may not be available for other geographical locations or industry and companies. In this case, a rank can be developed with the engagement of stakeholders.
- It has been assumed that to recycle products, all materials have to be recovered. In practice, dismantling occurs and some of the materials are sacrificed. In this case, the bill of materials can be revised to ignore the sacrificed materials and still enable assessment by the methodology developed.
- The value of virgin materials was used in this study but materials value can reduce after recycling. However, the residual value is usually proportional to the value of virgin materials. Where recyclate material values exist, these can be used to refine the analysis.
- It was assumed that recycling takes place through available mature technologies. The maturity of technologies is an evolving target. For nations or regions considering recycling priorities of the future, they may ignore modelling the TRL scale and define priorities that enable the development of new relying technologies for priority products.
- The separation of materials is not just a binary challenge and can be affected by the joining technologies used. It has been assumed in this paper, and in previous papers, that separation is a possibility. In future research, it may be necessary to consider different weights according to the ease of reversing the joining/welding technology used. Alternatively, partial dismantling has to be considered.
- Legislation has banned and can ban disposal of some products and materials to landfill. In this case, prioritisation is less critical because legislation has to be met.
- In the future, there may be need to develop a support software or database to help in end of life decisions. Product bill-of-materials information could be better shared by manufacturers or carried in a product passport.
- There is need to publish updated material security indices for different countries as well as available recycling and remanufacturing technologies.
- The production volume of products, and the amount of end-of-life products, will influence recycling uptake if the products and waste are collected. As an example, there are currently almost 90 million mobile phone users in the UK and 236 million in the US (Appendix Tables A1 and A2). These large numbers of mobile phone will influence the need for recycling and a circular economy. Future research is needed to consider these core supply chain factors.
- The study considered three factors: complexity, technology readiness level and materials security index. Whilst these have been considered to be comprehensive, they are not exhaustive. Stakeholders could consider other factors to aggregate into the analysis.

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Appendix

Table A1
Product volume for the United States.

Sources	Product	Amount	Note/Assumptions
(NationMaster, 2010)	Car battery	2 730 000	Assumed to be equal to car production
(US EPA, 2011)	Mobile phone	235600000	–
(Jozefek, 2014)	PET bottle	2 600 000	Tonnes, yearly production
(Statista, 2013)	DVD-R	13 840 000	–
(US EPA, 2011)	Desktop computer	23 500 784	–
(AWEA, 2015)	Wind turbine	4300	Yearly production
(Statinfo, 2005)	Refrigerator	11 639 000	–
(MTD, 2015)	Tire	252 700 000	–
(Statista, 2010)	Coffee maker	24 000 000	–
(Rookley, 2016)	Ergo chair	35 000	Personal contact with Aeron Chair.

Table A2
Product volume for the United Kingdom.

Source	Product	Amount	Note/Assumptions
(NationMaster, 2010)	Car battery	1 270 000	Assumed to be equal to car production
(PlasticsEurope, 2013)	PET bottle	3 518 800	Yearly Demand in tonnes
(Ofcom, 2015)	Mobile phone	89900000	Total user
(Statista, 2013)	DVD-R	23 600 000	Yearly production
(McDonald, 2013)	Desktop computer	2 355 000	sales in unit
(RenewableUK, 2013)	Wind turbine	7410	Total 23597 installed in the UK. 7410 yearly installation
(BBC, 2004)	Refrigerator	2 400 000	Unit/Wasted yearly
(TIF, 2011)	Tire	1 500 000	Yearly production unit
(Silverman, 2013)	Coffee maker	6 900 000	Assumption of 100GBP per unit
(Rookley, 2016)	Ergo chair	30 000	Personal Contact with Aeron Chair

Table A3
Recycling rates for the United Kingdom.

Source	Product	UK Recycling Rates (%)	Note/Assumptions
(ERP, 2012)	Car battery	90	Wet Battery, Published in 2014
(OnRecycle, 2012)	Mobile phone	11	50% reuse
(Date, 2013)	PET bottle	52	Plastic bottle recycling rates
(WRAP, 2012)	DVD-R	38	Selected WEEE products/ 75% reuse
(WRAP, 2012)	Desktop computer	38	Selected WEEE products
(Halliwell, 2006)	Wind turbine 20 kW	2	UK Composites Recycling Rates
(Halliwell, 2006)	Wind turbine 100 kW	2	UK Composites Recycling Rates
(Halliwell, 2006)	Wind turbine 330kw	2	UK Composites Recycling Rates
(Cantrill and Barnett, 2012)	Refrigerator	98	Envicom-brand/ company based
(ETRMA, 2012)	Tire	98	–
(Eurostat Database, 2013)	Coffee maker	22	WEEE Products %
(WRAP, 2012)		38.40	–
(Halliwell, 2006)	Wind turbine 5 kW	2.00	UK Composites Recycling Rates
(Alfed, 2012)	Ergo chair	75.00	Based on aluminium recycling %

Table A4
Recycling rates for the United States.

Source	Product	US Recycling Rates (%)	Note/Assumptions
(SmithBucklin Statistics, 2014)	Car battery	99	Wet Battery
(ETBC, 2014)	Mobile phone	11	–
(APR, 2014)	PET bottle	31.2	–
(ETBC, 2014)	DVD-R	29.2	–
(ETBC, 2014)	Desktop computer	40	–
(Unser, 2001)	Wind turbine	0	**based on non-available recycling centre
(US EPA, 2014)	Refrigerator	40.4	–
(US EPA, 2014)	Tire	44.6	–
(ETBC, 2014)	Coffee maker	29.2	E-waste recycling rates
(US EPA, 2014)	Ergo chair	54.6	Based on aluminium recycling rates

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