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Published in:
22nd CIRP Conference on Life Cycle Engineering 2015

DOI:
10.1016/j.procir.2015.01.026

Published: 01/01/2015

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Sihvonen, S., & Ritola, T. (2015). Conceptualizing ReX for aggregating end-of-life strategies in product development. In S. Kara (Ed.), *22nd CIRP Conference on Life Cycle Engineering 2015* (pp. 639-644). (Procedia CIRP ; Vol. 29). Elsevier. https://doi.org/10.1016/j.procir.2015.01.026

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 29 (2015) 639 – 644

www.elsevier.com/locate/procedia

The 22nd CIRP conference on Life Cycle Engineering

Conceptualizing ReX for aggregating end-of-life strategies in product development

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Abstract

Efforts towards a circular economy are accelerating and gaining more attention. Since product's lifecycle is mostly determined during early product development phases, it is crucial to support those phases with explicit strategic directions. This paper examines the possibility to aggregate various definitions of end-of-life (EoL) strategies in a visually compelling way. We propose a taxonomy for communication between multidisciplinary product development teams using *ReX,* an abbreviation for alternative EoL strategies starting with prefix *'Re'*, such as reduce, reuse, repurpose, repair, remanufacture, recycle, and recover. We construct our taxonomy based on a) EU Waste Directive, b) a systematic literature review, and c) relevant theoretical constructs. Then we discuss whether ReX allows assessing potential EoL alternatives, and steering the product development efforts. Finally, we suggest ReX for supporting decision-making when several stakeholders are involved, common language is sought for, and significant EoL related decisions are made at the early phases.

Peer-review under responsibility of the scientific committee of The 22nd CIRP conference on Life Cycle Engineering

Keywords: End-of-life; end-of-life strategies; product development; decision-making; reduce; reuse; recycle; recover; remanufacture; resynthesize

1. Introduction

Valuable materials are lost and hazardous substances are released to the environment via landfills. This is partially due to the unbalanced metabolism of our societies resulting from the appetite for economic growth and the increased use of materials [e.g. 1]. In Europe, a new zero-waste program introduces new recycling targets and envisions a *circular economy* where products and materials serve multiple lifecycles in various formats, and where economic growth is decoupled from the environmental degradation [2]. Moreover, amendment proposal for the EU's Waste directive 2008/98 [3] further emphasizes the need for better understanding the phases occurring after the first use of products. Namely the proposal demands member states to actively promote e.g. designing technically durable, reusable and recyclable products suitable for multiple uses.

In the organizational context, unambiguous communication facilitates strategic decision-making, including environmental considerations. Along with the lack of technical capabilities, dynamics between internal organizational factors may hinder this communication and implementation of environmentally conscious practices [4], [5]. Product development process is a set of activities in organizations resulting in an artifact ready for commercialization [6]. While decisions made in the early stages of these activities dominate product's costs and environmental impacts during its lifespan [7]-[9], these phases appear to seldom include product designers' perspectives [8]. Unambiguous communication could facilitate multidisciplinary work in this fuzzy front end.

Baumann et al. [10] encourage linking environmental tools with other business processes, and even beyond the boundaries of organizations to avoid normative suggestions isolated from the overall decision context. They argue that such approach facilitates system thinking including interconnections between various processes. For instance, while manufacturers may not themselves participate in the recovery processes, they need to understand their products'

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doi:10.1016/j.procir.2015.01.026

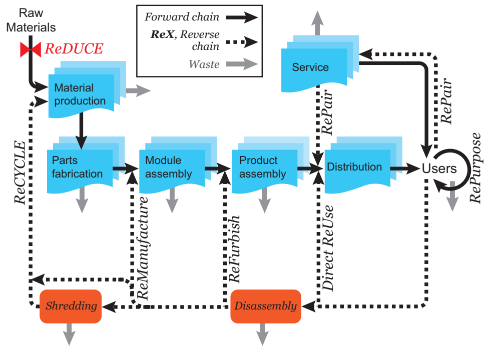

Figure 1. Eol strategies (adapted [11])

prospective alternatives reaching such stages [12]. This is stipulated also via legal instruments such as extended producer responsibility.

For the past two decades, a large body of research has advanced our knowledge of various aspects in extending the useful lifespans of products, components and materials, e.g. in the domains of disassembly techniques, reverse supply chain strategies and remanufacturing. Fewer papers [13]-[16] seem to combine these multidisciplinary perspectives, albeit crucial for the implementation [17], [18] (Fig.1.).

Terms have also evolved in academia, industry and in legislation during the last few decades. In the literature, e.g. reuse, recover and, even recycle are terms sometimes used interchangeably. In legislation, for instance, a term *disposal* contained all waste management aspects from treatment to disposal in the European directive 75/442/EEC in 1975, but by 2008, the same term was used only as a least prioritized option in the EU Waste directive 2008/98/EC [19], [20]. Our aim is to facilitate shared understanding of the concepts, and provide a basis for a multidisciplinary framework for EoL strategies with direct links to legislative priorities.

This article is organized as follows. We start with an overview of our conceptual aggregation, *ReX*. This if followed by explaining our research methodology. We then present the results of the literature study and conclude with a discussion, and our plans for continuing the research.

2. Background for conceptualizing ReX

In this paper, we present a taxonomy aiming to unambiguously aggregate definitions for EoL strategies and their relationships.

Our taxonomy, *ReX,* consists of the 3R basics: *ReDUCE, ReUSE*, and *ReCYCLE*, complemented with *ReCOVER*. *ReUSE* is further divided according to refining processes needed. In *ReX* (Fig.2), potential EoL strategies are visualized according to their anticipated first impact space during the lifecycle of a product. Visualization could highlight the overall context and related constraints in product development, such as compatibility of materials for recovery, groupings of assemblies and their fastening techniques for disassembly, or durability.

In practice, ReX combines EU waste priorities [19] with The 10 Golden Rules, eco-design principles by Lagerstedt & Luttropp [21]. The 10 Golden Rules visualize eco-design principles as a circle denoting phases during product's pre-life, use and after life to which design rules could be applied. This visualization targets to serve as an appetizer for more detailed inquiries by the product designers. Inspired by the approach we integrated the 10 Golden Rules with EU's waste hierarchy, assumed to originate from Lansink's ladder [22], resulting some adjustments and more focused scope (Fig. 3). Another similar concept, 3R, is often used in conjunction with the terms Reduce-Reuse-Recycle, although variations coexist, such as Reuse-Remanufacture-Recycle [13] or 6R including terms e.g. ReDesign [23]. Finally, *'Re'* (lat. 'again, back') is a prefix for afresh, anew [24].

3. Research methodology

For searching theoretical constructs, we targeted peer-reviewed articles indexed in SCOPUS database. We conducted searches in sequence; first one author sought for TOP10 most cited articles using keywords, titles and abstracts, and then other author replicated the search. In addition, a nonprobability sampling technique called snowball [25] was applied. After removing duplicates and listing available sources, our 42 term combinations yielded 167 articles. We then tried to aggregate existing terms by their relationships to one another. In other words, we sought to examine conceptually [26] whether they contained pairs, complemented each other, or whether they seemed to be rather identical or contradictory in nature. Articles tended to yield numerous combinations, which supported using EU's waste hierarchy as the basis already during the analysis, as opposed to referring to it after separate analysis of each definition. We cite articles to illustrate our concept aggregation only.

4. Strategies for extending product's useful life

4.1. Reduce as first priority

Waste hierarchy in [19] starts with prevention activities before a substance, material or product has become waste. In the directive, these prevention activities are expanded along the lifecycle phases with measures regarding harmful substances in materials and products, potential adverse impacts of generated waste, and volumes of generated waste. Furthermore, extension of lifespan of products and possibilities for reuse are pronounced.

Unfortunately, this broad definition in the directive makes it difficult to measure the potential improvements carried out, especially outside original equipment manufacturing (OEM) supply networks. Lansink [27] argues that this first priority is most challenging to reach due to various challenges, such as difficulties in measuring the actual progress with ambiguous boundaries, and the conflicting interests between the actors.

Notwithstanding, in the *ReX*, *reduce* should only include lifecycle phases before a product hits the market, 'at source' [28], [29], similarly to eco-design principles such as housekeeping summarized by [21]. For instance, connecting sustainable manufacturing practices with sustainable design is relevant, yet it has emerged in research somewhat recently [17].

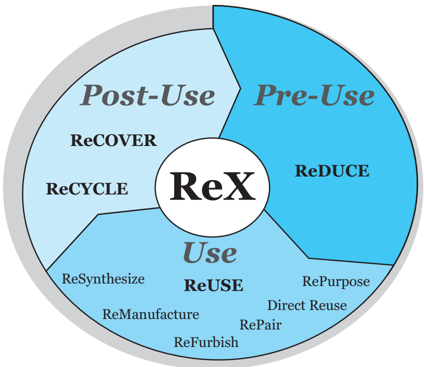

Figure 2. ReX strategies (inspired by [21])

Ways to extend lifespan before product reaches the market may take many forms. Multi-lifecycle as a design objective is proposed as one option to reduce environmental impacts [30]. For instance, Ardiente & Mathieux propose ways to examine and extend durability of specially energy using products [31]. Possibilities to enhance longevity of a product were also combined not only to consider possibilities to functionally extend the lifespan, but how to design emotional attachments to a product to make user unwilling to discard it. This option is called durable emotional attachment in [32]. One option suggested is to design products fostering sustainable behavior [33]. Solutions how to consider multiple-lifecycle in manufacturing process would also be needed [34].

This prioritized position for *reduce* allows seeking solutions such as recyclable and renewable materials, or extending the lifespan aiming at direct environmentally benign impacts before product is commercialized.

4.2. Reuse as second priority

Second ladder in the directive, 'preparation for reuse', is defined as *"checking, cleaning, or repairing recovery operations, by which products or components--can be re-used--*."[19]. In the directive, reuse is linked with originally conceived purposes. Interest is on products and components reuse instead of material reuse, as also embraced in [2].

Duflou et al. [35] assert that options usually applied in the industry include material recycling, incineration, and simply landfilling. Authors argue that industry seems to understand economic hierarchy options related to EoL treatments in different priority than the ecologically preferred hierarchy in which product's structural and functional parameters are preferably retained. As a way forward, Fleischmann et al. [36] suggest to assess the context in which reuse is likely to occur through evaluating forms of reuse, what in fact would be reused, what actors would be involved, and what would drive reuse as a strategy.

ReUSE strategy appears to usually contain minor or larger upgrading operations [11] with a purpose to stretch out the lifespan beyond the first lifecycle. Understanding terminology similarly enhances unambiguous choices e.g. for functional requirements including quality.

4.2.1. Resale or direct reuse

Product's functional performance may well expand beyond the emotional wear-out time. This allows for a possibility to reuse a product 'as-is' for the original purpose but in another type of market segment with usually lower price-levels. Reuse is described as second-hand trading [14] or direct reuse [11].

4.2.2. Repurpose

Using same product for new purposes without any adjustment would also divert a product becoming a waste. Ortiz et al. [37] provide *repurpose* with an example of a smartphone used 'as is' for environmental monitoring or educational purposes. So while neither this strategy is new [16], perhaps positioning it as an option could stimulate product developer's creativity.

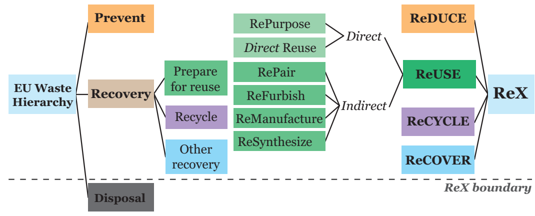

Figure 3. ReX taxonomy versus EU's waste hierarchy

4.2.3. Repair

Repair for reuse by the user or new user in a secondary market involves restoring the product into a 'working order' [11]. Usually a partial disassembly suffices for repair [38] in order to have an access to faulty components for rectifying activities [39]. *Repair* has been paired with remanufacture as an example of valued-added recovery when describing potential return flows [11], whereas in another definition it was combined with refurbishment under the *reuse* activities [40]. However, *repair* seems to be well placed in between *direct reuse* and *remanufacture* as part of extensions for the concept *reuse.*

4.2.4. Refurbish

Refurbishing a product is usually expected to demand somewhat more work than repair, but less than *remanufacture* [39] (Fig. 4). However, sometimes the borderline is subtle between the concepts [13]. It appears that *refurbish* is regarded as a step within remanufacturing process that sometimes merits its own place, if restoring a product does not alter it substantially [41].

Quality is expected to become better in refurbishing a product than when repairing one. Purpose is to reach a specified quality and functional state for the refurbished components and parts, not the whole product. [11]. Through *refurbish* all critical modules are checked, fixed and replaced as needed [42].

Understanding these subtle differences may have an impact on the business models applied. If users are expected to regard refurbished products rather as an extension of repaired ones then it is understandable that pricing is expected to be more advantageous as well [39]. However, if refurbishing of a product results a level of 'like-new' quality as proposed in

[43], a willingness to pay for such quality might remain low due to perceptions of lower quality.

4.2.5. Remanufacture

Remanufacture is positioned within pre-use phases in [2] but we suggest locating it under *reuse* instead. Objective is to reach the quality of a new product, if not beyond [41] with descriptions such as 'like-new' [41] or 'as new' [11] used.

Processes included in *remanufacture* depend on the product complexity and the domain. *Remanufacture* is seen as a comprehensive process of restoring activities, and thus consequently also affecting the related reverse flow strategies. Restoring activities are likely to contain inspection, test, full disassembly, part replacement or refurbish, clean, reassembly, and re-inspection [14]. During *remanufacture*, the core identity of a product is assumed to remain the same [41].

Thierry et al. use term cannibalization when reusable parts are injected back to manufacturing processes [11]. We suggest combining it under *remanufacture*, as any suitable actor could take part in the preferably in concert with OEMs, for instance, due to warranty reasons. E.g. new and innovative parts could be mixed with refurbished parts while conducting the remanufacturing activities, thus supporting innovation instead of delaying it [13]. This exemplifies how strategic question pursuing remanufacturing is.

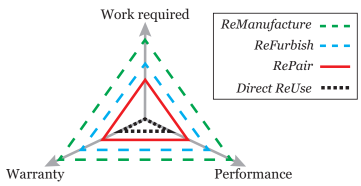

Figure 4. Differences in ReUSE strategies [39]

A product designed for remanufacturing should last minimum two useful functional lifecycles; e.g. material thickness and thus strength could be increased for longer life span [44]. But it might lead to an increased weight, and thus contradicting *ReDUCE* strategy, where smaller volumes of materials are of primary interest. In sum, although *remanufacture* may contain both *repair* and *refurbish* processes, it results in a product with warranties at least to the level of the new ones (Fig 4.).

4.2.6. Resynthesize

Using components for distinctly other purposes than originally planned is presented in [45]. Kang et al. place *resynthesize* at par with disposal, reuse, remanufacture, and recycle. Form and function of current products and assemblies are synthesized across multiple domains toward creating a new artefact different from original purposes. Resynthesizing necessitates disassembly of needed components from potentially multiple products in order to assemble them into a new application.

4.3. Recycle as third priority

Recycling is defined as*" any recovery operations by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes*" [19]. Definitions similar to EU categorization focus on material recycling*: "Possibility to disassemble products into recyclable fractions and the issue of material quality preservation is the heart of the matter in optimal recycling."* [46]. Recycling is seen as process in which material would either restore its original or downgraded purity, and consequently would be suitable for different purposes [42], [47]. Sometimes it is understood that before recycling activities sorting, separating, and disassembly needs to occur [16]. Yet automatic or manual disassembly could also be included as part or recycling in order to separate valuable material fractions, and hazardous materials or contaminants [14].

According to Mangun & Thurston [48] *remanufacture*, *recycle* or using the virgin materials are design related decisions that should be tackled in the product development. They provide a decision design model to assess alternatives with an example of a PC. While Villalba et al. [47] propose a recyclability index for assessing the potential economical value from recovered materials. Huisman [49] extends to include also the potential environmental value regained from recovered products using his QWERTY method.

4.4. Recover as fourth priority

Recover (lat. 'recuperare' to gain or find again something that has been lost [50]) is word with ambiguous meanings. Both generic and narrow meanings are used in the directive: *reuse* and *recycle* are sub-concepts to a generic term recovery (Fig 3.), whereas fourth priority 'other recovery' contains among others, energy or metal and metal compound recovery processes [19]. General perspective is taken by most of the articles we found, with various combinations of more than one potential *ReX* strategy included [11], [17], [51].

In the late 1990's, recovery was defined to consist of added-value and material recovery [36]. Added-value recovery contains e.g., repair and remanufacturing of products and components, while material recovery seeks to retrieve valuable or hazardous materials during the post-use phase [4]. Quality of recyclates including their purity levels, are under the scrutiny for instance, by [46], [52].

We suggest to only include solutions related to final material or substance recovery processes under *recover* within *ReX*. For instance, guidelines should be placed under *ReCOVER* if target for product design is to consider the metal's liberation characteristics [52] to ensure compatible recyclates using metallurgical process at EoL.

5. Discussion and conclusions

In the midst of myriad definitions for EoL, both researchers and practitioners are advancing the understanding of wicked waste problem. So why should these EoL options be combined under yet another term? For instance, due to our research methodology, terms may not be exhaustive and different groupings could have emerged. Nevertheless, our results suggest multiple meanings attached to terms and elaborate the need for their unambiguous definition.

Choosing a suitable *ReX* option is a strategic decision and should be carefully considered in the fuzzy front end. Preferred strategies vary depending on industry and overall context. *ReX* is intended to visualize such strategies (Fig.2) before requirements are set. Things to comprehend include the dynamic systems in which processes vary according to geographical location, time delays between interconnected processes, and established strategies by various actors [53].

This aggregated view could facilitate actively deciding on a single strategy, as it may not be viable to choose all possible alternatives due to their potentially inherent trade-offs [54], [55]. For instance, striving towards both automated and manual disassembly techniques in product development leads likely to sub-optimization [56]. Besides, decisions made later may result only one *ReX* option remaining viable even without consciously deciding.

Arguably, many papers seem to propose solutions for product development and design by using terms recycling and recovery interchangeably. Within *ReX,* our suggestion is to consider the outcome of the product design solution: if it targets for a result that is further forwarded in the reverse channels, it is about ReCYCLE but if the expected outcome is the 'end-result' – *ReCOVER* would be a suitable position. In practice, *ReX* could be used for instance, to determine which strategy is being considered or implemented by examining a product's identity (Table 1).

Table 1. Summary of ReX strategies (adapted from [11], [42])

ReX scenarios	**Level of disassembly**	**Expected quality**	**Identity**
ReDUCE	None	New	Original
ReUSE			
• RePurpose	None	'As-is'	Original
• Direct ReUse	None	'As-is'	Original
• RePair	Product/down to faulty part	Working order	Retain
• ReFurbish	Module	Specified level	Retain
• ReManufacture	Part	'Like-new'	Retain
• ReSynthesize	As needed	Low-high	Lost
ReCYCLE	Material	Low-high	Lost
ReCOVER	Substance	Low-high	Lost

Co-operation with various stakeholders could be enhanced with *ReX*. For instance, directive on Waste Electric and Electronic Equipment WEEE 2012/19/EC targets *"to promote the design and production of EEE in view of facilitating the reuse, dismantling and recovery of WEEE, its components and materials*" [57]. Reusing electronic components could be more profitable than material recovery when these modules contain most of the residual value [15]. Unambiguous communication between actors could facilitate to realize such benefits.

Few differences exist with the scope of our proposal and EU's waste hierarchy. Disposal would be regarded as a *no-ReX* strategy. Also the use of products for other purposes than originally conceived, namely *repurpose* and *resynthesize,* fails to meet scope for 'preparation for reuse' but they are aligned, e.g. with the principles of circular economy.

Our plan is to complement *ReX* with classifying existing guidelines. Such classification could be validated with a survey to understand whether product design constraints in a given context are leading to contradictory *ReX* strategies, and whether it is possible to group them according to *ReX*. For instance, results could be visualized with a radar chart in which product development team's results are located according to *ReX*.

We admit that it would be timely to consider sustainability at large instead of focusing at EoL. Yet understanding the implementation challenges of EoL may enable integrating other sustainability topics into product development practices.

Acknowledgements

This work is partly funded by Koulutusrahasto and Tekes.

References

[1] UNEP Working Group on Decoupling, "Decoupling natural resource use and environmental impacts from economic growth," Nairobi, Kenya, 2011.

[2] European Commission, "COM(2014)398 final Communication from the Commission to the European Parliament, the Council, The European Economic and Social Committee and the Committee of the Regions, Towards a circular economy: A zero waste programme for Europe," Brussels, 2014.

[3] European Commission, "COM(2014)397: Proposal for a Directive of the European Parliament and of the Council for amending Directives 2008/98/EC on waste, 94/62/EC on packaging and packaging waste, 1993/31/EC on landfill of waste, 2000/53/EC on end-of-life vehicles, 2006/66/EC on," Brussels, 2014.

[4] M. A. Ilgin and S. M. Gupta, "Environmentally conscious manufacturing and product recovery (ECMPRO): A review of the state of the art," *J. Environ. Manage.*, vol. 91, no. 3, pp. 563–591, 2010.

[5] M. Lenox and J. Ehrenfeld, "Organizing for effective environmental design," *Bus. Strateg. Environ.*, vol. 6, pp. 187–197, 1997.

[6] K. Ulrich and S. Eppinger, *Product Design and Development, 5th edition*, 5th intern. Singapore: McGraw-Hill International, 2012, p. 415.

[7] N. Bey, M. Z. Hauschild, and T. C. McAloone, "Drivers and barriers for implementation of environmental strategies in manufacturing companies," *CIRP Ann. - Manuf. Technol.*, vol. 62, no. 1, pp. 43–46, Jan. 2013.

[8] T. C. McAloone, T. A. Bhamra, and S. Evans, "Success in environmentally conscious design: how is it achieved and maintained?," *in Proceedings of the 1998 IEEE International Symposium on Electronics and the Environment. ISEE - 1998*, 1998, pp. 171–175.

[9] K. Ulrich and S. Pearson, "Assessing the importance of design through product archaeology," *Manage. Sci*., vol. 44, no. 3, pp. 352–369, 1998.

[10] H. Baumann, F. Boons, and A. Bragd, "Mapping the green product development field : engineering, policy and business perspectives," *J. Clean. Prod.,* vol. 10, pp. 409–425, 2002.

[11] M. Thierry, M. Salomon, J. Van Nunen, and L. Van Wassenhove, "Strategic issues in product recovery management*," Calif. Manage. Rev.,* vol. 37, no. 2, pp. 114–135, 1995.

[12] K. Goggin and J. Browne, "Towards a taxonomy of resource recovery from end-of-life products," *Comput. Ind.,* vol. 42, pp. 177–191, 2000.

[13] A. Gehin, P. Zwolinski, and D. Brissaud, "A tool to implement sustainable end-of-life strategies in the product development phase," *J. Clean. Prod.,* vol. 16, no. 5, pp. 566–576, 2008.

[14] C. M. Rose, A. Stevels, and K. Ishii, "Method for formulating product end-of-life strategies for electronics industry," *J. Electron. Manuf.,* vol. 11, no. 2, pp. 185–196, 2002.

[15] M. Kwak and H. M. Kim, "Evaluating End-of-Life Recovery Profit by a Simultaneous Consideration of Product Design and Recovery Network Design," *J. Mech. Des.,* vol. 132, no. 7, p. 071001, Jul. 2010.

[16] A. Kriwet, E. Zussman, and G. Seliger, "Systematic Integration of Design-for-Recycling into Product Design," *Int. J. Prod. Econ.,* vol. 38, pp. 15–22, 1995.

[17] K. Ramani, D. Ramanujan, W. Z. Bernstein, F. Zhao, J. Sutherland, C. Handwerker, J.-K. Choi, H. Kim, and D. Thurston, "Integrated sustainable life cycle design: a review," *J. Mech. Des*., vol. 132, no. September 2010, pp. 091004–091004–15, 2010.

[18] V. Krishnan and K. Ulrich, "Product Development Decisions: a review of the literature," *Manage. Sci*., vol. 47, no. 1, pp. 1–21, 2001.

[19] European Union, *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives*. 2008, pp. 3–30.

[20] European Union, "Council Directive 75/442/EEC on 15 July 1975 on waste," *Official Journal 25/07/1975*, 1975.

[21] C. Luttropp and J. Lagerstedt, "EcoDesign and The Ten Golden Rules : generic advice for merging environmental aspects into product development," J. Clean. Prod., pp. 1–13, 2006.

[22] S. Watson, "Making the waste hierarchy: just Ad Lansink," *Isonomia blogs,* 2013. [Online]. Available: http://www.isonomia.co.uk/?p=2556. [Accessed: 20-Oct-2014].

[23] J. Yan and C. Feng, "Sustainable design-oriented product modularity combined with 6R concept: a case study of rotor laboratory bench," *Clean Technol. Environ. Policy*, vol. 16, no. 1, pp. 95–109, Mar. 2013.

[24] "Definition of re- in English," *Oxford Dictionaries*. [Online]. Available: http://www.oxforddictionaries.com/definition/english/re-. [Accessed: 20-Oct-2014].

[25] N. K. Malhotra, *Marketing Research - an applied orientation*, 4th ed. Upper Saddle River, NJ: Pearson, Prentice hall, 2004, p. 679.

[26] I. Niiniluoto, *Johdatus tieteenfilosofiaan: käsitteen- ja teorianmuodostus*, Second pri. Keuruu, Finland: Kustannusosakeyhtiö Otava, 1984, p. 314

[27] A. Lansink, "Reaching for the top rung: achieving waste prevention," *Isonomia blogs*, 2014. [Online]. Available: http://www.isonomia.co.uk/?p=2740. [Accessed: 20-Oct-2014].

[28] P. Deutz, M. McGuire, and G. Neighbour, "Eco-design practice in the context of a structured design process: an interdisciplinary empirical study of UK manufacturers," *J. Clean. Prod*., vol. 39, pp. 117–128, Jan. 2013.

[29] H. C. Zhang, T. C. Kuo, H. Lu, and S. H. Huang, "Environmentally conscious design and manufacturing: A state-of-the-art survey," *J. Manuf. Syst.*, vol. 16, no. 5, pp. 352–371, Jan. 1997.

[30] M. Zhou, R. J. Caudill, D. Sebastian, and B. Zhang, "Multi-lifecycle product recovery for electronic products," *J. Electron. Manuf.,* vol. 9, no. 1, pp. 1–15, 2000.

[31] F. Ardente and F. Mathieux, "Environmental assessment of the durability of energy-using products: method and application," *J. Clean. Prod.,* vol. 74, pp. 62–73, Mar. 2014.

[32] C. Fitzpatrick, S. Hickey, K. Schischke, and P. Maher, "Sustainable life cycle engineering of an integrated desktop PC; a small to medium enterprise perspective," *J. Clean. Prod*., vol. 74, pp. 155–160, Jul. 2014.

[33] J. Daae and C. Boks, "Towards an Increased User Focus in Life Cycle Engineering," in *CIRP LCE 2013*, 2013.

[34] A. Rashid, F. M. A. Asif, P. Krajnik, and C. M. Nicolescu, "Resource Conservative Manufacturing: an essential change in business and technology paradigm for sustainable manufacturing," *J. Clean. Prod*., vol. 57, pp. 166–177, Oct. 2013.

[35] J. R. Duflou, G. Seliger, S. Kara, Y. Umeda, A. Ometto, and B. Willems, "Efficiency and feasibility of product disassembly : A case-based study," *CIRP Ann. - Manuf. Technol*., vol. 57, pp. 583–600, 2008.

[36] M. Fleischmann, J. M. Bloemhof-Ruwaard, R. Dekker, E. van der Laan, J. A. E. E. van Nunen, and L. N. Van Wassenhove, "Quantitative models for reverse logistics: A review," *Eur. J. Oper. Res*., vol. 103, no. 1, pp. 1–17, Nov. 1997.

[37] P. J. Ortiz, J. Browne, D. Franklin, J. Y. Oliver, R. Geyer, Y. Zhou, and F. T. Chong, "Smartphone Evolution and Reuse : Establishing a more Sustainable Model," in *2010 39th International Conference on Parallel Processing Workshops,* 2010, pp. 476–484.

[38] A. Gungor and S. M. Gupta, "Issues in environmentally conscious manufacturing and product recovery : a survey," *Comput. Ind. Eng*., vol. 36, pp. 811–853, 1999.

[39] A. M. King, S. C. Burgess, W. Ijomah, and C. A. Mcmahon, "Reducing Waste: Repair, Recondition, Remanufacture or Recycle?," *Sustain. Dev*., vol. 14, no. online December 2005, pp. 257–267, 2006.

[40] F. Kimura, T. Hata, H. Suzuki, and P. M. Engineering, "Product Quality Evaluation Based on Behaviour Simulation of Used Products," in *CIRP Annals - Manufacturing Technology*, 1998, vol. 47, no. l, pp. 119–122.

[41] E. Sundin and B. Bras, "Making functional sales environmentally and economically beneficial through product remanufacturing," *J. Clean. Prod.*, vol. 13, no. 9, pp. 913–925, Jul. 2005.

[42] W. L. Ijomah, J. P. Bennett, and J. Pearce, "Remanufacturing : Evidence of Environmentally Conscious Business Practice in the UK University of Plymouth ," in *International Symposium on Electronics and Environment,* 1999, pp. 192–196.

[43] S. Behdad, M. Kwak, H. Kim, and D. Thurston, "Selective disassembly and simultaneous end-of-life decision making for multiple products," in *ASME2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE 2009*, August 30-September 2, 2009.

[44] S. Okumura, T. Morikuni, and N. Okino, "Environmental effects of physical life span of a reusable unit following functional and physical failures in a remanufacturing system," *Int. J. Prod. Res*., vol. 41, no. 16, pp. 3667–3687, 2003.

[45] S. Woo Kang, C. Sane, N. Vasudevan, and C. S. Tucker, "Product Resynthesis: Knowledge Discovery of the Value of End-of-Life Assemblies and Subassemblies," *J. Mech. Des*., vol. 136, no. 1, pp. 011004–1–14, Nov. 2014.

[46] L. Alting and J. B. Legarth, "Life Cycle Engineering and Design," in *CIRP Annals - Manufacturing Technology*, vol 44 (2), 1995, vol. 44, no. l, pp. 569–580.

[47] G. Villalba, M. Segarra, A. . Fernández, J. . Chimenos, and F. Espiell, "A proposal for quantifying the recyclability of materials," *Resour. Conserv. Recycl.*, vol. 37, no. 1, pp. 39–53, Dec. 2002.

[48] D. Mangun and D. L. Thurston, "Incorporating component reuse, remanufacture, and recycle into product portfolio design," *IEEE Trans. Eng. Manag.*, vol. 49, no. 4, pp. 479–490, Nov. 2002.

[49] J. Huisman, C. B. Boks, A. L. N. Stevels, I. Owing, E. Equipment, and E. Communities, "Quotes for environmentally weighted recyclability (QWERTY): concept of describing product recyclability in terms of environmental value," *Int. J. Prod. Res*., vol. 41, no. 16, pp. 3649–3665, 2003.

[50] *Oxford Dictionaries*, "Definition of 'Recover.'"[Online]. Available: http://www.oxforddictionaries.com/definition/english/recover. [Accessed: 16-Nov-2014].

[51] T. F. Go, D. A. Wahab, M. N. A. Rahman, R. Ramli, and C. H. Azhari, "Disassemblability of end-of-life vehicle: a critical review of evaluation methods," *J. Clean. Prod*., vol. 19, no. 13, pp. 1536–1546, Sep. 2011.

[52] A. Van Schaik and M. A. Reuter, "Dynamic modelling of E-waste recycling system performance based on product design," *Miner. Eng*., vol. 23, no. 3, pp. 192–210, 2010.

[53] F. Mathieux, D. Froelich, and P. Moszkowicz, "ReSICLED: a new recovery-conscious design method for complex products based on a multicriterial assessment of the recoverability," *J. Clean. Prod*., vol. 16, pp. 277–298, 2008.

[54] D. C. A. Pigosso, E. T. Zanette, G. Filho, A. R. Ometto, and H. Rozenfeld, "Ecodesign methods focused on remanufacturing," *J. Clean. Prod*., vol. 18, pp. 21–31, 2010.

[55] C. M. Rose, A. Stevels, and K. Ishii, "A New Approach to End-of-Life Design Advisor (ELDA)," in *International Symposium on Electronics and Environment,* 2000, pp. 99–104.

[56] P. Tanskanen and R. Takala, "A decomposition of the end of life process," *J. Clean. Prod*., vol. 14, pp. 1326–1332, 2006.

[57] European Union, Directive 2012/19/EU of the European Parliament and of the council of 4 July 2012 on waste electrical and electronic equipment (WEEE) recast, no. June. EU: *Official Journal of the European Union*, 2012, pp. 38–71.