Aalto University
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Technology

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Jussi Kilpeläinen

RECYCLABILITY OF EXTERIOR COMPONENT MATERIALS IN WEARABLE SPORTS INSTRUMENTS: AN EVALUATION PROTOCOL

Master's thesis for the degree of Master of Science in Technology submitted for inspection, Espoo, 19th December, 2016.

Supervisor	**Assistant Professor Rodrigo Serna Guerrero**
Instructor	**M.Sc. (Tech.) Erika Rautavaara**

Aalto University
School of Chemical
Technology

Aalto University, P.O. BOX 11000, 00076 AALTO
www.aalto.fi

Abstract of master's thesis

Author Jussi Kilpeläinen

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The increasing scarcity of resources has acted as a transformational global driver for companies to develop new recycling methods, as well as re-think the design of products to enable better recyclability. In addition, the political consensus around the world calls for environmentally friendly technologies. Companies can manage their resource efficiency by conducting environmental research, or by using tools developed for such purposes, both of which can lead to savings in related operations. The purpose of this thesis is to study the recyclability of sports instruments, in order to propose a method for evaluating the recyclability of materials used in such products manufactured by Suunto. This was approached by examining the recyclability of exterior material components. All internal components were excluded from the scope of this thesis as miscellaneous electrical and electronic equipment scrap. The study was carried out as a literature review, which examined current commercially available recycling technologies for relevant materials. Furthermore, the current and up-and-coming regulatory drivers were examined in an effort to create a comprehensive result.

Based on these findings, each material received a recyclability rating, which indicated the most viable end-of-life option for the material, which were: landfilling, energy recovery, downcycling, recycling, reuse after processing, or reuse as such. Furthermore, a set of criteria for material assessment was produced, which sets the underlying framework to assist in comprehensively evaluating the suitability of exterior materials.

This framework was developed into an evaluation protocol, which was implemented into Microsoft Excel to create a usable tool for Suunto. The output of the tool is a recyclability overview for the materials of a product. It displays the combined weight of all materials in a product which has the same end-of-life option. A product was tested with the tool and the results as weight percentages were: 16.2 % recyclable, 19.6 % downcyclable and 64.2 % miscellaneous WEEE. The tool can be further used during a design phase of a new product to assess the impacts of different material choices. Future work includes adding additional criteria, such as product disassemblability and remanufacturability, recyclability of internal components, and physical separation of components and materials from one another, in order to produce a more comprehensive evaluation tool.

Keywords recycling, materials assessment, recyclability evaluation tool, WEEE

Aalto-yliopisto
Kemian tekniikan
korkeakoulu

Aalto-yliopisto, PL 11000, 00076 AALTO
www.aalto.fi

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Luonnonvarojen alati nopeutuva ehtyminen vauhdittaa uusien kierrätystapojen kehitystä sekä pyrkimyksiä suunnitella tuotteita kierrätettävämmäksi. Poliittiset tahot ovat alkaneet vaatia vuosien saatossa yhä ympäristöystävällisempiä teknologioita. Yritykset voivat vastata tähän hallitsemalla luonnonvarojen käyttöään tekemällä ympäristötutkimusta tuotteistaan, mikä pidemmällä aikavälillä tuo myös säästöjä yrityksen kuluihin. Tämä diplomityö tutki puettavien urheilulaitteiden kierrätettävyyttä, ja loi arviointimenetelmän Suunto Oy:n tuotteiden materiaalien kierrätettävyydelle. Työ rajattiin tarkastelemaan ulkoisia komponentteja ja niiden materiaaleja. Kaikki sisäiset komponentit rajattiin ulos diplomityöstä sekalaisena sähkö- ja elektroniikkalaiteromuna. Tutkimus tehtiin kirjallisuuskatsauksena, jossa selvitettiin tämänhetkiset kaupallisesti käytössä olevat kierrätysmenetelmät ulkoisten komponenttien materiaaleille. Lisäksi aiheeseen liittyviä nykyisiä säännöksiä ja niiden tulevia kehityssuuntia tarkasteltiin kokonaisvaltaisemman näkökulman aikaansaamiseksi.

Näiden tulosten perusteella luotiin kriteeristö arvioimaan materiaalien uusiokäytettävyyttä tuotteissa. Lisäksi jokaiselle materiaalille annettiin kierrätettävyydestä arvosana, joka ilmaisee kannattavimman vaihtoehdon materiaalin elinkaaren lopussa. Vaihtoehdot olivat: kaatopaikkajäte, energian talteenotto, kierrätys huonompilaatuisena, kierrätys samanlaatuisena, uudelleenkäyttö käsittelyn jälkeen ja uudelleenkäyttö sellaisenaan.

Näiden tulosten pohjalta kehitettiin arviointimenetelmä, joka muunnettiin työkaluksi Suunto Oy:lle Microsoft Excelin avulla. Työkalu esittää yleiskatsauksen tuotteen kierrätettävyydestä perustuen tuotteen komponenttien materiaalien saamiin kierrätettävyysarvosanoihin ja näiden yhteenlaskettuun painoon. Työkalua testattiin tuotteella ja tulokseksi painoprosentteina saatiin: 16,2 % kierrätettävää samanlaatuisena, 19,6 % kierrätettävää huonompilaatuisena ja 64,2 % sekalaista sähkö- ja elektroniikkalaiteromua. Työkalua voidaan käyttää tulevaisuudessa tuotteiden suunnitteluvaiheessa arvioimaan eri materiaalien vaikutusta tuotteen kierrätettävyyteen. Työkalun kehitystyöhön tulevaisuudessa kuuluu muiden tässä työssä tarkasteltujen kriteerien, kuten tuotteen purkamisen, korjaamisen, materiaalien toisistaan erottamisen ja sisäisten komponenttien kierrätettävyyden vaikutuksen arvioinnin lisääminen työkaluun kokonaisvaltaisemman arviointityökalun luomiseksi.

Avainsanat kierrätys, kierrätettävyys, materiaalien arviointityökalu, SER

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Preface

This thesis was assigned to me by Suunto Oy, and I am grateful for this opportunity.
I would like to sincerely thank my instructors Erika Rautavaara, Ossi Lehtinen and Antti Virtanen from Suunto for their exceptionally active participation and valuable advice throughout the process of writing this thesis.
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Also, I want to thank all my friends who were standing in the way of my graduation during all these years of studying.

My final thanks belong to my family for their invaluable support throughout my life.

This thesis is dedicated to the memory of my father, who inspired me to pursue a career in engineering.

Vantaa, 24.11.2016

Jussi Kilpeläinen

Glossary

Circular economy	Industrial economy, in which every product is reused and no waste or pollution is created.
Downcycling	Nonfunctional recycling. The recycled product or material loses functionality, value or quality during recycling processes.
Feedstock recycling	Reusing waste materials as process input during the production of another material.
Functional recycling	Recycling as same quality as the original. Keeps the functionality, value and the quality of the recycled material or product intact.
New scrap	Scrap generated during a manufacturing process.
Nonfunctional recycling	See downcycling.
Old scrap	Scrap generated from end-of-life products
Platinum group metals	Iridium, rhodium, ruthenium, osmium, palladium and platinum
Primary material	Material made from raw materials newly extracted from the environment.
Pyrometallurgy	Production of metals under very high temperature processes.
Refurbishing	Reselling returned products which have been repaired and tested to work by the manufacturer.
Refuse-derived fuel	Shredded and dehydrated combustible solid waste used as a fuel.
Remanufacturing	Disassembling a product and rebuilding it with reused, repaired or new components.
Reverse logistics	Comprises all required steps in returning products back to the manufacturer.
Secondary material	Recycled material
Thermoplastic	A type of plastic that is moldable when heated.
Thermoset	A type of plastic that cannot be molded when heated.
Virgin material	A material that does not contain recycled materials

Abbreviations

AA	Aluminum Association
ABS	Acrylonitrile butadiene styrene
AFP	Anti-fingerprint
AISI	American Iron and Steel Institute
AR	Anti-reflective
ASTM	American Society for Testing and Materials
BPA	Bisphenol-A
CF	Carbon fiber
CFRP	Carbon fiber reinforced polymer, or plastic
ECHA	European Chemicals Agency
EEE	Electrical and electronic equipment
EOL	End-of-life
EPR	Extended producer responsibility
FOC	Free-of-chrome
GFRP	Glass-fiber reinforced plastic
IUPAC	International Union of Pure and Applied Chemistry
MB	Masterbatch
NBR	Nitrile butadiene rubber
OECD	Organisation for Economic Cooperation and Development
PA	Polyamide
PA12	Polyamide 12
PC	Polycarbonate
PC-ABS	Polycarbonate - acrylonitrile butadiene styrene alloy
PGM	Platinum group metals
PMMA	Poly(methyl methacrylate)
POM	Polyoxymethylene
PP	Polypropylene

PTFE	Polytetrafluoroethylene
PVD	Physical vapor deposition
rCF	Recycled carbon fiber
rCFRP	Recycled carbon fiber reinforced polymer
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RSL	Restricted substances list
RoHS	Restriction of Hazardous Substances
TPC	Thermoplastic copolyester elastomer
TPE	Thermoplastic elastomer
TPU	Thermoplastic polyurethane
WEEE	Waste Electrical and Electronic Equipment

1 Introduction

1.1 Background

Climate change and the ever decreasing amount of available natural resources have been globally recognized as limiting factors, which will affect everyday life on this planet in the future [1]. The current society is using resources excessively, which compromises the ability of future generations to meet their own needs [1]. However, it is still possible to make global development sustainable and meet the limitations imposed by the planet's ability to absorb the impacts of human activity [2]. Thus, political consensus calls for more environmentally friendly product manufacturing [3]. Furthermore, as consumer awareness in these environmental issues is simultaneously increasing, these aspects are becoming increasingly important as a competitive factor, and therefore the profits of a company may decrease if these environmental trends are not taken into account [4]. In addition, increasing amounts of customers are expecting that companies communicate their environmental activities transparently [5].

Environmental aspects of a manufacturing company can be managed by incorporating life cycle thinking to company-wide strategy [5]. A critical part of life cycle thinking is to consider environmental impacts happening outside the company's own premises [5]. Such impacts can be evaluated, for example, by conducting life cycle assessments of products [5]. Other methods include assessing environmental impacts through various tools, such as decision-making tools, which can optimize specific product manufacturing processes from an environmental point-of-view [6]. When properly used, the management of environmental issues may even support companies in terms of economic benefits [5]. For example, reusing, remanufacturing and recycling products brings value back to the company and reduces the need for newly extracted natural resources [2]. Evaluating products and their life cycle brings competitive advantages along with environmental benefits, because assessing the whole life cycle of a product allows to better manage production costs [5]. On a larger scale, the goal in these life cycle studies is to avoid situations, in which environmental impact decreases in a certain stage of the life cycle, while simultaneously rising in another phase [5].

One approach for a sustainable future is circular economy, in which waste would not exist as all products are designed for reuse [1]. Furthermore, ideas of a circular economy include that all fuel is renewable, and all biological nutrients complete their life cycle without contacting any toxics [1]. Accomplishing these goals would arguably lead to the creation of a steady ecosystem on this planet, which sustains the impact of consumption by humanity's current and future generations [1].

1.2 Working case: Suunto's wearable sports instruments

Suunto Oy is a Finnish manufacturing company producing compasses, sports watches and instruments, and dive computers [7]. Suunto was founded in 1936 when the founder, Tuomas Vohlonen, invented a process to mass produce liquid filled compasses [7]. Since then, Suunto has evolved into producing dive computers, for which it is the world leader, sports watches and other related accessories [7]. Suunto, as all manufacturing industries, is using part of this planet's natural resources in order to manufacture its products and bring value to its customers. Suunto wants to stay competitive in this field in the future, and therefore, it is conducting research on its products to address the increasingly relevant global environmental issues. This thesis is a part of the work done to prepare for these future requirements.

When the products manufactured at Suunto are no longer used by consumers, the products reach their end-of-life (EOL) stage. Then, the national waste legislation, which varies between countries, defines the treatment procedures of these EOL products, and the obligations of the manufacturer. For example, in the European Union, Suunto's products fall under the waste electrical and electronic and equipment (WEEE) legislation and end up in WEEE recycling facilities [8]. However, in order to keep the value of the materials and components used in these EOL products as high as possible, the possibilities of reusing and recycling these materials are explored in this thesis. The goal is to determine whether the environmental impact of products could be decreased by selecting appropriate materials for manufacturing, or by reusing and recycling currently used materials. Reusing materials and components decreases their environmental impact more than recycling [9].

The scope of this thesis is visually displayed in green color in Figure 1, which presents a flowchart for typical end-of-life sports watch recycling. This thesis aims to determine the recycling options for the exterior materials of disassembled products, and to create an evaluation protocol based on this acquired data.

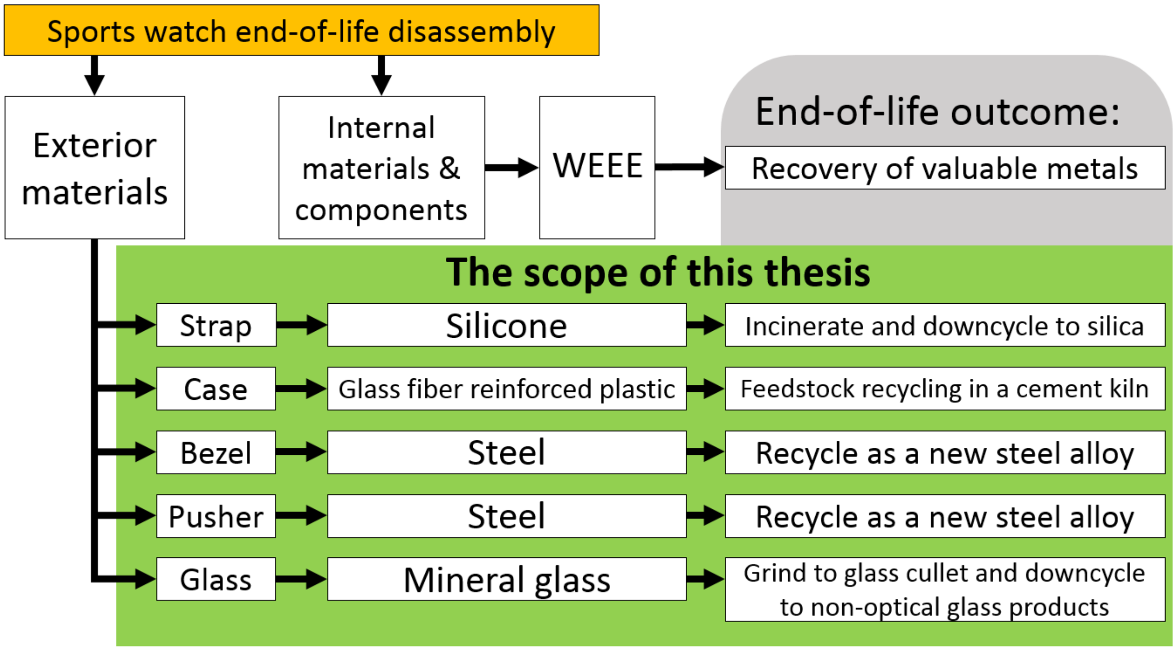


Figure 1. Possible recycling targets for an end-of-life sports watch with the scope of this thesis highlighted in green. (WEEE = waste electrical and electronic equipment)

1.3 Research objective

The objective of this thesis is to create an evaluation protocol for the exterior components materials of products manufactured at Suunto. In order to achieve such result, a literature review about the currently available recycling options of exterior component materials must be conducted first. Furthermore, to assess these materials from a larger perspective, such as legislative constraints and other environmental performance, a set of criteria for such objectives must be established. Based on these data, an evaluation protocol can be developed.

1.4 Structure of the thesis

This thesis will firstly examine the causes behind the drivers and trends of environmental issues to answer the question why this kind of research is conducted. This examination is done in the context of European Union’s legislation. After this, the theory of recycling is examined in order to comprehend which factors are of importance in this kind of research. Literature is then reviewed to find important criteria for the recyclability assessment to be conducted later in this thesis, and what similar research has accomplished. Next, the current commercially available recycling technologies for exterior component materials used by Suunto in their product manufacturing are presented. Furthermore, the impact of other factors, such as different grades, coatings and additives of materials are examined. After this theory part is completed, an evaluation protocol for Suunto is developed. This includes selecting the criteria for material assessment, defining recyclability indicators for all materials and describing the developed protocol and the equations used in it to calculate a recyclability result for a product. Furthermore, this evaluation protocol is implemented into Microsoft Excel 2013 spreadsheet in order to produce a usable tool for Suunto. This evaluation tool is then tested by conducting an assessment of an existing Suunto product. After this, the results and conclusions are presented and possible future directions for research are suggested.

2 Drivers for resource efficiency and recycling

In the last century, natural resource usage by humans has increased over the capacity of the earth [10]. In order to combat this increasing trend, policymakers have already enacted stricter environmental laws, which aim to address the use of animals, atmosphere, biodiversity, food, energy, land, mineral, waste, water and other materials through the context of resource efficiency [11]. However, resource efficiency as a term has not been explicitly defined, and therefore these policies vary between countries [11]. Nevertheless, recycling assists in managing natural resources more efficiently, and therefore, better recyclability for manufactured products should be pursued by companies [9]. In the future, the importance of resource efficiency and recyclability of products will arguably increase and have an increasingly severe impact on the feasibility of manufacturing companies and the whole industry [9]. Recycling has already been enforced by legislation in the European Union [11].

This chapter presents current economic trends in recycling, and also legislative drivers, which impact the feasibility of recycling. First, the concept of circular economy and the European Union's approach to it is examined. Next, producer responsibility schemes in the European Union regarding waste electrical and electronics equipment are presented. Furthermore, restrictions regarding substances in the European Union are explored. Finally, the impact of these concepts on a manufacturing company is evaluated. The concepts of this chapter establish the underlying framework and the reasoning for the subsequent research conducted in this thesis.

2.1 Circular economy

2.1.1 Theory

The current industrial society has generally not evolved from a linear "take-make-dispose" pattern. In other words, companies extract materials, manufacture and sell products to customers, who discard them when they no longer serve their purpose. Circular economy is a concept that addresses this problem by re-designing the whole global economy as a regenerative and restorative system that uses only renewable resources. It replaces the concept of end-of-life products with restoration, and the concept of a consumer with a user. The goal of circular economy is the complete elimination of waste by designing products from which their component materials can be efficiently harvested, thus providing a reliable source of recycled raw materials. The sustainability of manufacturing processes can be further supported with the use of renewable sources of energy. Furthermore, infrastructure, businesses and economic systems need to be re-designed in order to accommodate this concept, because any system based on consumption instead of restoration will inherently cause losses during the life cycles of products. High transparency in such business operations is also essential to achieve sufficient performance which enables a circular economy. The current linear economic system arguably increases business risks and resource costs, lengthens supply disruptions, intensifies competition, stagnates demand and causes unpredictability in prices. Furthermore, new incentives, regulations, and standards for businesses should be developed. The European Union has already begun the development of such standards for businesses to create a more circular economy [3], [1]. These new standards, along with other circular economy incentives of the European Union, are examined in the next subchapter. [1]

The Ellen MacArthur Foundation, for example, is a charity organization and a widely recognized authority dedicated to accelerating global transition to circular economy [1]. The foundation publishes reports about circular economy and works with businesses, governments, and education institutes to promote circular economy [1]. In a circular economy, virtually every resource, material and product is kept at their highest value as long as possible [1]. Thus, merely recycling a product does not contribute to the circular economy, if the value of the recycled material decreases significantly during these recycling processes [1]. However, recycling reclaims value from end-of-life products that contain materials originally extracted from natural stocks [9]. Consequently, recycling should not be seen as a goal, but rather, a method that allows to manage natural resources more efficiently and meet the needs of increasing consumption [9]. In theory, circular economy strives to achieve completely efficient life cycles for products [1].

However, this is not entirely possible due to the laws of thermodynamics, which set a physical limit to the efficiency of recycling [9].

Circular economy introduces two cycles which govern natural resources: biological and technical. These cycles are presented in Figure 2. On the left side of this picture, is a biological cycle for consumables and nutrients. In this cycle, all organic matter re-enters the biosphere safely after usage. The goal is to reach a level, where this biological cycle is sufficiently sustainable to enable the earth to produce all required nutrients for all inhabitants without the need for any toxic substances, and furthermore to allow sustainable growth with increasing population. The second cycle, on the right side of Figure 2, is a technical cycle for durable materials, products and components, which are kept at their highest utility and value at all times. This is enabled firstly through designing products for longevity, and secondly by enabling the products to go through maintenance and other operations, which further increase their usable lifetime, such as repairing, reusing and refurbishment. Furthermore, diversifying reusage options for products decreases the need to produce virgin materials. Effective collection and redistribution are also required to increase the eco-efficiency of these operations. The more compact this reverse technical cycle is, the less embedded energy and labor are lost and more material is preserved. Further concepts which increase resource efficiency through product longevity are standardization, modularization, upgradeability of products and design for disassembly. [1]

Currently, major advances have been made in improving resource efficiency and utilizing renewable energy sources in the current economy [1]. In contrast, less significant advances have occurred in designing out material leakage and disposal [1]. Except in certain fields, such as forest industry, which arguably recognized the need for sustainable growth a century ago [12]. For example, in Sweden the forest industry represents a circular economy, because they can produce energy required for their processes from their own byproducts, and can even distribute excess energy to other parts of the society [12]. Currently, this bioenergy usage is on average at 96 % in the forest sector, and furthermore, the volume of forests in Sweden has increased ever since 1920 [12].

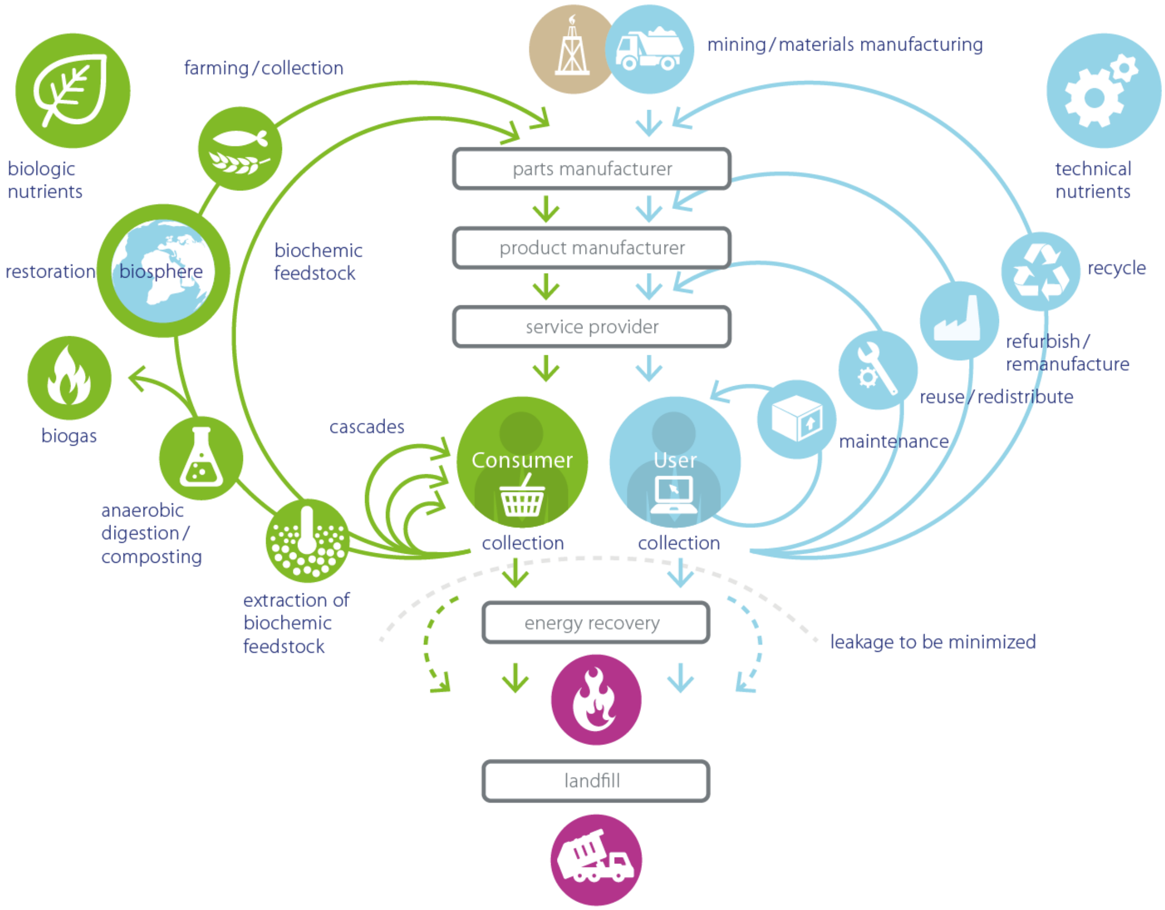


Figure 2. Circular economy system diagram [13].

The shift to a more circular economy has already begun as multiple indicators of this exist in current society. Resource scarcity has been recognized globally [1]. Consequently, stricter environmental laws have been enacted in many countries, along with policies that reward companies for resource efficiency [11]. The current shift in consumer behavior is to prefer access before ownership, which indicates that global culture is changing to a more sustainable structure, as businesses are changing more and more to renting and leasing instead of ownership based transactions [1]. Furthermore, information technology is already sufficiently advanced so that materials could be tracked through their whole life cycle [1]. However, achieving a circular economy requires more education that assists in creating the required skills and drives further innovations [1].

2.1.2 The European Union's approach

The European Union (EU) has adopted a long-term goal to make a transition to a more circular economy in Europe. The EU aims to avoid the irreversible damage caused by exceeding the Earth's capacity to renew resources with a new economic system which is sustainable and resource efficient. A circular economy is considered to enable resilient growth and to reduce exposure to risks, as it shifts the balance away from energy-intensive materials and primary extraction. However, before a circular economy can flourish, a multitude of necessary conditions must be met, and therefore the EU is supporting research and innovation in this field. The EU has an action plan for years 2016-2019, which requires the EU member states to start preparing to a more circular economy. New directives will set requirements for production, consumption and waste management, which will ultimately lead to a more circular economy. The long-term goals also include a ban on landfilling in 2030. [3]

Another EU target is the quality of secondary raw materials, particularly plastics, which will have new quality standards, to ensure their quality and suitability for manufacturers. However, details about these future directives and standards have not yet been published. Furthermore, usable secondary raw material could no longer be legally considered as waste, except under specific conditions. For example, certain secondary raw materials, which have had a long lifetime, may contain substances that are currently restricted or prohibited by the EU regulations, but were allowed during the time of original manufacturing. Detection and removal of these substances can be very costly, which decreases the recyclability possibilities of these old products. [3]

The European Commission has multiple projects under development to decrease the environmental impacts of products, with emphasis on electrical and electronic products [3]. In order to raise the quality of recycling, the European Commission will propose minimum conditions on transparency and cost-efficiency of recycling to extended producer responsibility schemes in the future [3]. Currently, the Ecodesign directive (2009/125/EC) targets only the energy efficiency of certain products, such as lightning equipment, kitchen appliances, televisions, and air conditioning [14]. However, mobile devices are not currently included, but are expected to be added to the scope of the directive in the near future, as suggested by preparatory studies conducted by the European Commission [15]. In the future, repairability, durability, upgradability and recyclability will be included in the directive [3]. The European Commission will elaborate on the specifics and implementation of these new aspects of the Ecodesign directive during 2017 [3]. The European Commission also promotes voluntary environmental certifications for companies. For example, a voluntary EU Ecolabel is granted to products that have a reduced environmental impact through their whole life cycle. The EU Ecolabel is presented in Figure 3. In the future, a voluntary certification for electronic waste treatment facilities will also be introduced. [3]

Figure 3. The European Union Ecolabel, granted for products with reduced environmental impact [16].

In the future, the EU plans to introduce financial incentives for businesses, in order to reach a more circular economy [17]. Practical means consist of, for example, elimination of environmentally harmful subsidies and an environmental tax reform to move taxation away from labor towards pollution and resources [17]. Furthermore, a unified method of measuring environmental impact is being developed to better manage products and organizations [17]. Other future actions by the EU that may affect companies include: economic incentives for greener products, supporting recovery and recycling, requirements for full traceability of hazardous waste, gradually increasing charges on waste disposal, simplifying obligations for small and medium sized enterprises, and development of transparent unified data reporting schemes and electronic waste registries [3].

In conclusion, the current global economy is quite far from an efficient circular economy. Therefore, the EU is currently acting as a trendsetter and its future directives will require substantial increases in the resource efficiency from companies operating in the European economic area. These future changes must be adapted by companies in to their strategies if they want to stay competitive in Europe.

2.1.3 Potential of circular economy in Finland

Developing the current economy towards a circular economy imposes new challenges for companies. However, multiple opportunities for potential growth in new sectors are simultaneously unveiled. In Finland, Sitra, a future fund organization owned by the Finnish government, aims to ensure a sustainable future in Finland by collaborating with researchers and companies. Sitra has studied the potential benefits that circular economy could bring for Finland. According to a report published by Sitra [18], the net benefits of applying the principles of circular economy in Finland would amount to 1.5-2.5 billion euros by the year 2030. This sum was achieved by identifying individual business models used in Finland and evaluating their possibilities to apply the concepts of circular economy. In addition, their report presented concrete possibilities for companies in Finland to apply the concepts of circular economy currently. An existing example of this is the paper and forest industry in Finland, which has already achieved many goals of circular economy through efficient usage of by-products as an energy source and utilization of recycled raw materials. However, selling these by-products as chemicals, instead of using them for energy recovery on-site would contribute even more to the circular economy. [18]

The benefits of circular economy to Finland’s mechanical engineering industry sector were evaluated at 300-450 million euros by the Sitra report [18]. This sum could be achieved by incorporating remanufacturing and leasing based business models to this industry sector. This increased value stems from the fact that this sector is heavily based on exporting goods and these companies rarely utilize their products efficiently at their end-of-life stage. Consequently, much of the potential end-of-life value is lost. Thus, retrieving these products through reverse logistics and remanufacturing them, combined with remotely monitoring the status of these products creates significant potential for sustainable growth and assists in achieving a more circular economy. Furthermore, the leasing based business models decrease the investment costs for clients, and therefore increase the total sales, while also creating a more stable source of revenue for the manufacturer. In addition, leasing of products acts as a driver to improve service and maintaining of these products, because the product will be returned to the manufacturer for reselling or further leased to another company. Such business models require optimizing products for increased durability. The service and maintaining of products typically amounts to 30-50 % of the total sales in these companies. [18]

The first Sitra report, published in 2014, concludes that the most significant potentials for sustainable growth in Finland arise from increasing lifetimes of products by maintaining service, reuse and remanufacturing [18]. Concrete examples of such processes were proposed in two Sitra reports [18], [19]. The second report by Sitra, which was published in 2016, further emphasizes the application of these proposals by recommending that companies conduct experiments based on circular economy, and further aims to increase the competitiveness of Finland's economy globally [19]. Additional suggestions include that materials should be recycled only after the lifetime of a product cannot be feasibly increased, and the prevention of waste should be set as a goal, instead of only reusing waste efficiently [18]. In the private sector, sharing economy through secondhand sales has the greatest value-saving potential [18]. These proposals are similar to the general theory of circular economy [1], and the goals of the EU [3]. Furthermore, Tekes, the Finnish Funding Agency for Technology and Innovation, has begun to fund companies and projects which seek to achieve a circular economy in Finland, such as refining municipal waste to usable product feeds, producing bio-based energy from sludge generated during pulp production, and novel construction materials produced from previously unusable waste [20]. The application of these circular economy principles naturally increases the responsibility taken by the manufacturer in their products, since the revenues of the company increasingly rely on the possibilities of reusing and remanufacturing products [1]. Nevertheless, certain laws and regulations are an integral part of the current and future economies to ensure that environmentally friendly activities are practiced by companies [1]. Such obligations imposed on producers are examined in the next subchapter

2.2 Producer responsibility

2.2.1 Extended producer responsibility

Producer responsibility schemes have been introduced in many countries in order to define the extent to which a producer has to take accountability from their products. The Organisation for Economic Cooperation and Development (OECD) defines Extended Producer Responsibility (EPR) as “an environmental policy approach in which a producer’s responsibility for a product is extended to the post-consumer stage of a product’s life cycle” [21], [22]. The goal of EPR schemes is to charge the costs of waste handling from the original producers instead of the society. This is done by holding the producers responsible for the costs caused by their products after their end-of-life stage. This usually includes sorting, treating and recycling waste products. Although EPR is individually obligated from producers, it is common practice to collectively manage the responsibility between multiple companies. In such cases, a producer responsibility organization takes care of the collection, treatment and recycling on behalf of the producers while the producers pay to this organization according to the amount of products the producers have placed to the market. [22]

EPR schemes play a major role in resource efficiency strategies promoted in the EU. The EU has three directives which impose EPR. The end of life vehicles 2000/53/EC directive [23], the waste electrical and electronics equipment 2012/19/EU directive [24], and the batteries 2006/66/EC directive [25]. Furthermore, the packaging and packaging waste 94/62/EC directive [26], and the waste framework 2008/98/EC directive [27], also include EPR but do not enforce it. Out of these directives, the WEEE directive is of interest in the scope of this thesis, because the examined exterior materials in wearable sports instruments fall under its obligations. However, practically all EU member states have more EPR laws than these directives require. Prominently oils, tires, paper, and textiles are covered by EPR schemes in the EU member states. However, EPR policies are not designed similarly in different EU member states, which hinders comparison of their efficiency. These different implementations of EPR laws also have varying incentives for producers to act accordingly. Furthermore, there is a lack of comparable and transparent data to precisely evaluate the economic performance of different EPR schemes between EU member states. [22]

During the last decade, producer responsibility organizations have evolved from being merely a financial management to broadly managing all related recycling and operational functions. This has significantly increased waste recovery and recycling performance in the EU. Simultaneously, producer’s coverage of the cost of recycling has increased, and reaches up to 100 % in some schemes. [22]

2.2.2 Waste Electrical and Electronics Equipment Directive

Waste electrical and electronic equipment is defined by the OECD as “any appliance using an electric power supply that has reached its end of life” [21]. WEEE is the fastest growing waste stream currently in Europe, and therefore causes increasing amount of damage to the environment [9]. The European Union’s WEEE directive 2012/19/EU aims to reduce this environmental damage [28]. The WEEE directive currently applies to selected product categories, such as household appliances, but not to large-scale industrial machines [29]. The categories are presented in detail in *“Appendix* B*: Categories of the EU RoHS and WEEE directives”.* Furthermore, the directive sets an overall goal of 85 % recycling rate for products [28]. However, EU member states use different implementations on how to reach this goal, as the local waste legislation varies between countries [28]. A part of these different implementations stems from the fact that the goals of the WEEE directive may not be reached only through recycling because old products are not designed for recycling [9]. Achieving these EU goals requires designing new products in such way that their recycling and dismantling is made easier [9]. Furthermore, better infrastructure to enable high collection rates of end-of-life products and more efficient waste processing systems are required in order to reach these goals set by EU [9].

For electrical and electronic equipment producers in Finland, the most economical choice is to join a producer responsibility organization, which handles the obligations set by EU directives and the Finnish Waste Act [30]. Currently, a functional waste collection infrastructure exists throughout Finland, which companies can use for their recycling purposes [30]. The membership cost covers all the recycling fees of products put to business to consumer markets [30]. This enables all residents of Finland to return their WEEE free of charge to municipal waste collection centers, as obliged by the EU [30]. Furthermore, the WEEE directive requires all electrical and electronic equipment produced after 2005 to be marked with a WEEE symbol, presented in Figure 4 [8]. Depending on the size or functionality of the product, the symbol may also be placed on the packaging [8].

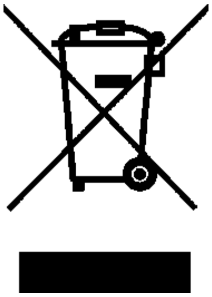


Figure 4. The symbol obligated in all WEEE [8].

Currently, one third of current WEEE recycled in the EU is officially reported. Part of the two thirds is suspected to be recycled otherwise without appropriate environmental care or shipped illegally to treatment sites outside of the EU. Despite stricter laws, WEEE is continued to be transported to informal waste recycling sites as long as the economic incentive exists. In order to develop solutions to this, it is important to understand how these informal recycling markets work. The recycling markets in developing countries are dominated by an informal waste management. This informal collection of WEEE causes very high collection rates of up to 95 %, which is substantially more than any EPR scheme in Europe has achieved. High material recovery rates of up to 80 % are also achieved in developing countries but this is often accomplished at the expense of human health. However, the causes include socioeconomical aspects as well, as up to 60 % of urban labor in developing countries work at the informal sector. [9]

However, this informal recycling can be seen as a way to develop recycling [9]. Wang et al. [31] have introduced a “Best-of-2-Worlds” philosophy that aims to achieve the most sustainable solution for developing countries. They propose a collaboration of manual dismantling at low-income countries to keep and generate local jobs, and delivering the hazardous recyclate fractions back to state-of-the-art recycling facilities [31]. A pilot in

Bangalore was conducted, which concluded that such operations with the informal sector are possible when personnel is sufficiently trained and financial incentives are presented [31]. Furthermore, such infrastructure for combining recycling operations between developing countries and Europe already exists as many small enterprises are currently shipping WEEE from Europe to developing countries [9].

2.3 Legislation concerning chemical substances

During recent decades, the consumer awareness on health effects of chemical substances has grown significantly. Furthermore, a globally uniform legislation for chemicals has been deemed necessary by companies operating across countries and continents. The EU typically has the strictest laws in the world concerning the use of chemical substances. Reducing the use of hazardous substances in products has benefits which reach beyond direct health effects. Hazardous waste from end-of-life products is reduced simultaneously, which increases the recyclability of products. This further reduces the need for primary extraction of materials from nature, which further reduces pollution and decreases global energy demand. The productivity of this whole product chain is affected positively, along with a positive impact on the environment in long term. However, the restrictions and requirements may cause negative short term financial consequences, if companies have to redesign products to ensure their recyclability. [32]

2.3.1 Registration, Evaluation, Authorisation and Restriction of Chemicals

Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) is a European Union regulation, which came into effect in 2007 [33]. The REACH regulation requires companies that produce or import chemical substances over one ton per year in the EU to register them to the European Chemical Agency (ECHA) [33]. Not registered substances are not allowed into the EU [33]. The reasoning for this legislation stems from the fact that chemical substances brought to markets before 1981 were never tested to be safe by any standard procedure [34]. Consequently, the REACH regulation inverted the responsibility for chemical safety. Instead of supervision by a national agency, the producers and importers must prove all chemicals to be safe before they are allowed in the EU [35]. Furthermore, the REACH regulation aims to improve the protection of human health and environment, enhance innovative capability in hazard assessment, ensure unobstructed transport of chemicals within the EU and enhance the competitiveness of EU's chemical industry [35].

The REACH regulation classifies products into three categories: substances, preparations and articles. A substance is a chemical element and its compounds, including necessary additives, but excluding separable solvents. A preparation is a mixture of two or more substances. An article is a product which has use beyond its chemical composition. For example, a polystyrene cup is not classified as a polystyrene substance. Therefore, a company that is not a chemicals manufacturer, could nevertheless have obligations set by the REACH regulation when importing articles which fall into one of the four categories presented in Table 1. [36]

Table 1. Article categories of the REACH regulation [36]

Category	Example
Articles accompanied by substances or preparations	Equipment packaged together with lubricants, reagents or gels
Articles which act as containers for release of substances or preparations	A printer cartridge releasing ink
Articles which act as a carrier materials for release of substances or preparations	A cloth impregnated with polish
Other intentional release of substances or preparations from articles	A scented product that releases perfume

Furthermore, a manufacturer operating in the EU may have to, in some cases, ensure that their suppliers from outside Europe comply with the REACH regulations, because the importer is held responsible that the materials, components and products imported from outside of the EU meet the REACH requirements [36]. However, some exceptions to the REACH regulation exist. For example, substances used only for research and development purposes are exempted from the REACH registration process [37]. A notification of usage to ECHA is sufficient to get a five year exemption for research and development [37].

Furthermore, producers must be aware that the ECHA governs a regularly updated candidate list of substances of very high concern (SVHC) [38]. The candidate list currently includes 169 chemicals which are classified as carcinogenic, mutagenic, toxic for reproduction or persistent, bioaccumulative and toxic [35]. The SVHC list is updated twice a year and these substances may be included in the future to an ECHA authorisation list, which, by default, restricts their use in the EU [35]. This authorisation list currently includes 31 substances, which have a sunset date, after which they are not allowed in products entering the EU markets [39]. Therefore, a strategic decision for companies is whether to design out these materials listed in the candidate list before they are restricted. Such decision may affect products and suppliers. Furthermore, certain chemicals not yet restricted by these EU regulations may already have been banned by local authorities in some countries [36].

2.3.2 Restriction of Hazardous Substances Directive

The European Union's Restriction of Hazardous Substances (RoHS) directive 2011/65/EU aims to improve the safety of electronic products and prevent the release of hazardous substances into the environment [40]. The goal is to replace the restricted heavy metals and flame retardants with safer alternatives, thus eradicating the use of hazardous substances [40]. Another goal is to increase the recycling rate of products which have contained these materials before [40]. Recycling rates are increased when the products do not contain any hazardous materials [40]. The RoHS directive currently restricts the concentration of substances presented in Table 2 in products on the EU markets [29].

Table 2. Substances restricted by the RoHS 2 directive [29]

Substance	Maximum concentration (ppm)	Restriction date
Cadmium (Cd)	100	1 July 2006
Hexavalent chromium (Cr^{6+})	1000	1 July 2006
Lead (Pb)	1000	1 July 2006
Mercury (Hg)	1000	1 July 2006
Polybrominated biphenyls (PBB)	1000	1 July 2006
Polybrominated diphenyl ethers (PBDE)	1000	1 July 2006
Bis(2-ethylhexyl) phthalate (DEHP)	1000	22 July 2019
Butyl benzyl phthalate (BBP)	1000	22 July 2019
Dibutyl phthalate (DBP)	1000	22 July 2019
Diisobutyl phthalate (DIBP)	1000	22 July 2019

The directive applies to all homogenous materials, which in practice means any single substance which can be theoretically separated from a product by mechanical means. The RoHS directive first came into effect in 2006 and it has been updated in 2011 and is now sometimes referred to as RoHS 2. It is closely linked to the WEEE directive, presented earlier in this thesis, since both these directives apply to same product categories, which are presented in detail in *"Appendix* B*: Categories of the EU RoHS and WEEE directives"*. Their scope currently includes practically all electrical and electronic products, with some exemptions, such as large-scale stationary industrial tools and military equipment. Furthermore, exemptions may be granted when no satisfactory alternative is available. [29]

The RoHS directive is reviewed on a regular basis [40]. Producers therefore must be aware that new restrictions are likely to be introduced in the next several years [40]. However, new substances will have a transition period before the restriction applies [40]. For example, as seen in Table 2, four phthalates will be restricted as of 22 July 2019 [29]. Environmentally aware producers should not hesitate to seek for safer alternatives before or during the transition period. Furthermore, the RoHS directive imposes several obligations for a manufacturer to ensure that all produced electrical and electronic equipment (EEE) is compliant [41]. These requirements include:

- Production control systems to check compliance must be implemented.
- EU declaration of conformity must be drawn up and signed.
- All technical documentation must remain available for 10 years after the EEE is placed on the market.
- A register of all non-compliant and/or recalled EEE must be kept.
- All EEE must be marked with the manufacturer's trademark and address.
- Must provide all the information required to demonstrate conformity if requested.
- Affix CE marking, which requires further compliance with other directives. [41]

Overall, the RoHS directive is a straightforward legislation which aims to ensure human health when using electrical and electronics equipment, and therefore taking great care in the handling of this directive correctly in manufacturing companies is essential.

2.4 Producer's outlook on resource efficiency

What was presented in this chapter demonstrates a current trend in society, which should not be dismissed by a manufacturer. Rejecting product recyclability design currently will arguably reciprocate with negative consequences eventually. The immediate gain in productivity by dismissing recyclability will be negated by the long term effects of reduced sustainability. Introduction of strict environmental laws may bring high costs of compliance to manufacturers operating in the affected countries. Manufacturers operating in countries with less strict laws may therefore gain an advantage in the markets depending on consumer behavior and the scope of the legislation. However, these legislative restrictions should not be seen as a burden and an increase in production costs, but as an opportunity to create competitive business strategies in a changing world. [1]

Increasing resource scarcity can be tackled efficiently by proactive actions, instead of acting at the last minute. If no pre-emptive measures are taken during a period of resource abundance, resource prices will soar when the society reaches a point of resource scarcity, as has arguably already happened with certain natural resources. When this tipping point has been reached, recycling has to be utilized with maximum efficiency in order to reach a sustainable level of consumption. Not preparing for this resource scarcity would arguably increase the occurrence of bankrupt businesses and collapsed societies. Therefore, recyclability of products should be pursued, not only for the immediate gain in lower manufacturing material prices, but for longer term sustainability of the manufacturing field and for the whole society in general. The principles of circular economy put to practice have been demonstrated in multiple case studies, conducted by the Ellen MacArthur Foundation, to decrease the risks of businesses, which should be a reason enough for companies to commit to sustainable decisions. [1]

Furthermore, an immense untapped market potential lies in products that could be manufactured without the need for extracting natural resources [1]. Such products would arguably decrease the manufacturing costs and environmental impact to a fraction of the current cost and impact [9]. Keeping a company on the verge of novel technology helps to amass the potential gains as soon as they realize [1]. This thesis is an example of work that companies may conduct in order to prepare for resource scarcity in the future. However, the sustainability theory and principles presented in this chapter should be carried out in practice to effectively combat resource scarcity [1]. Furthermore, the infrastructure of recycling is constantly evolving [9]. Products that cannot be presently recycled may still have the potential to be efficiently recycled in the future [9]. Current and future advances in technology constantly decrease the costs of logistics that currently cause a major part of the eco-efficiency of recycling [9]. A company that realizes the concepts presented in this chapter, for example, through efficient reverse logistics and refurbishment, creates increased market potential and adds value for itself [1].

3 Criteria for recyclability assessment

In order to comprehensively grasp the concept of recyclability in the context of this thesis, a general assessment for material recyclability needs to be established first. Thus, an understanding is created to acknowledge the impact of various factors to related recyclability. This chapter overviews recycling theory in order to comprehend what has to be taken into account when assessing materials. Literature is then examined to find important criteria related to evaluating the recyclability of materials. Furthermore, various tools developed for the purpose of evaluating recycling efficiency and other related aspects are examined. These tools typically also include the environmental aspects and legal obligations presented in the previous chapter.

3.1 Terminology of recycling

Recycling arguably affects all industries, however a uniform terminology regarding recycling across different fields has not been established [9]. Reuter and Worrell [9] propose that a uniform terminology and clear definitions for calculating statistics related to recycling would increase resource efficiency across all industries [9]. This subchapter presents those definitions for terms used in recycling. Furthermore, related to this terminology, a concept of product-centric recycling and the economics governing recycling processes are presented.

3.1.1 Recycling indicators and statistics

The following definitions are proposals for unifying recycling terminology, particularly promoted by Reuter and Worrell [9]. The terms presented in this subchapter are often used, but may not be fully understood. Furthermore, different indicators that are used to measure the efficiency of recycling should be clearly defined in order to achieve comparable statistics between companies and industries. These statistics can be calculated with the equations presented in this subchapter. The following seven definitions indicate different end-of-life options for materials. They are presented in a hierarchical order based on their potential for saving energy, which in this context, indicates the amount of energy saved by not having to produce a material or a product by extracting raw materials from natural resources. In this hierarchy, reduction of material usage is the best option, and landfilling of materials is the worst. [9]

Reduction or avoidance is achieved through minimizing the material amount needed to satisfy the material service. Alternatively, the need for service may be reduced. Reduction of material usage can be achieved also by lengthening the service lifetime of a product through design and repair. Furthermore, increases in manufacturing yield reduce material usage, as losses during production phase are diminished. It is important to remember that these methods simultaneously reduce the material available for recycling. Reduction saves the most energy in this hierarchy. [9]

Reuse is allowed by products which are designed for multiple uses, such as refillable bottles. Reusing products recovers more of the embodied energy from a product than recycling, because the manufacturing process of a similar product is avoided. In addition, a part of reuse comes through exchange markets for reusable goods. Product design is an integral part of possible reuse options. Therefore, products should be designed for multiple uses, or if possible, to have different functionality after its initial end-of-life stage. [9]

Refurbishment is the process of repairing and reselling products that have been returned to the manufacturer for various reasons [9]. Refurbished products are tested thoroughly to work, and any defects are repaired [9]. Other terms for refurbished products are also used, such as newly overhauled [42].

Recycling, or more precisely **functional recycling**, is reprocessing recovered waste materials back to their original quality and returning them to the supply chain. Recycling is also used as a broader term, denoting virtually any reprocessing of a material that is not landfilled. However, the term functional recycling indicates that the value and quality of the recycled material remains at the same level, thus keeping its initial functionality intact. Recycled materials are generally labeled as secondary materials, despite the fact that they may be of same quality as primary materials extracted from environment. Recycling typically saves substantial amounts of energy compared to producing primary materials. Future applicability of recycled materials generally depends on the purity of the material. [9]

Downcycling, or **nonfunctional recycling**, denotes products that are recycled as a lesser quality, reduced functionality or lower value than the original product. Downcycling should always be avoided if it is possible to recycle as a similar quality product. Downcycling causes loss of function to the material, and does not replace the primary or virgin material, which increases the need for primary extraction of materials from nature. Furthermore, downcycled materials may lower the quality of final products if they act as tramp elements or impurities in the recycling chain. However, downcycling still prevents material leakage to environment. In some cases, energy recovery may be more beneficial to the environment than low quality downcycling. [9]

Energy recovery, or waste-to-energy, is capturing the stored energy of a material as heat or electricity. This is done through incineration of the waste products. For example, if downcycling a product consumes excessive amount of energy, the recovery of their embodied energy is more beneficial to the environment. Plastics generally have very high energy content, and thus, plastics are often shredded to produce refuse-derived fuel. [9]

Landfilling is a waste treatment option to decrease adverse environmental effects and to control leakage of waste [9]. It is widely used when no economic incentives for recycling exist [9]. Landfilling is the main waste management method in many developing countries, but also prevalent in the United States of America [9]. Old landfills have been mined for resources, although it is rarely economically interesting [9]. Avoiding landfilled materials is relevant because the European Union plans to ban landfilling of all materials by 2030 [17].

Next, the indicators, which should be used to correctly demonstrate the effectiveness of different recycling methods and processes, are presented.

Recovery rate typically denotes the volume of material recovered from a waste stream. It can be defined as “amount of material recovered from a waste stream divided by the amount of material in the generated waste.” [9]

Recycling rate should be used to indicate the amount of material used in recycling processes divided by the amount of waste generated. However, it is often used when referred to the amount of material collected for recycling divided by the amount of waste generated, which is incorrect, because the amount of rejected material during recycling processes should be subtracted in order to acquire the amount of material actually used in recycling, and thus, an exact recycling rate. Different calculations and estimations methods of the amount of material available for recycling may cause further differences in recycling rates. [9]

Recycling efficiency is defined as output of the recycling process divided by the input. Material available for reuse after the recycling process is usually lower than the input of the recycling process. Losses happen in the recycling process itself due to quality and purity issues, which are caused by physics, thermodynamics and the chosen technology for each recycling process. [9]

The relation between the three previous indicators can be presented with the equation (1). [9]

$$Recycling\ rate = Recovery\ rate\ \times Recycling\ efficiency \tag{1}$$

These three previous recycling indicators are usually further combined with gathered data from a waste facility to assess the success of recycling schemes. However, there are other factors, which affect the success of recycling, such as collection of products, statistics and data. Furthermore, it should to be remembered that theft of recyclable material may also occur because of its high value. These unaccounted losses in the recycling chain can cause misjudgments, when the success of recycling is only calculated by the efficiency of processes in a facility. Therefore, the success of recycling schemes cannot be holistically measured in relation to these three indicators. [9]

In order to illustrate recycling efficiency and the calculation of recycling statistics, Figure 5 presents a simplified life cycle of any given metal. The life cycle of a metal is affected by choices made during different stages of manufacturing, product use and end-of-life stages. Furthermore, the letters used to indicate different process stages in Figure 5 can be used to present calculations of various recycling metrics and statistics. In relation to processes displayed in Figure 5, different scrap sources are defined as:

- New scrap is scrap recovered during the manufacturing process of products. An important notion is that high quantities of new scrap may be caused by an inefficient manufacturing process.
- Home scrap indicates new scrap recycled directly at own premises.
- Prompt scrap indicates new scrap which is sent to the supplier for reprocessing.
- Old scrap is scrap from end-of-life products. [9]

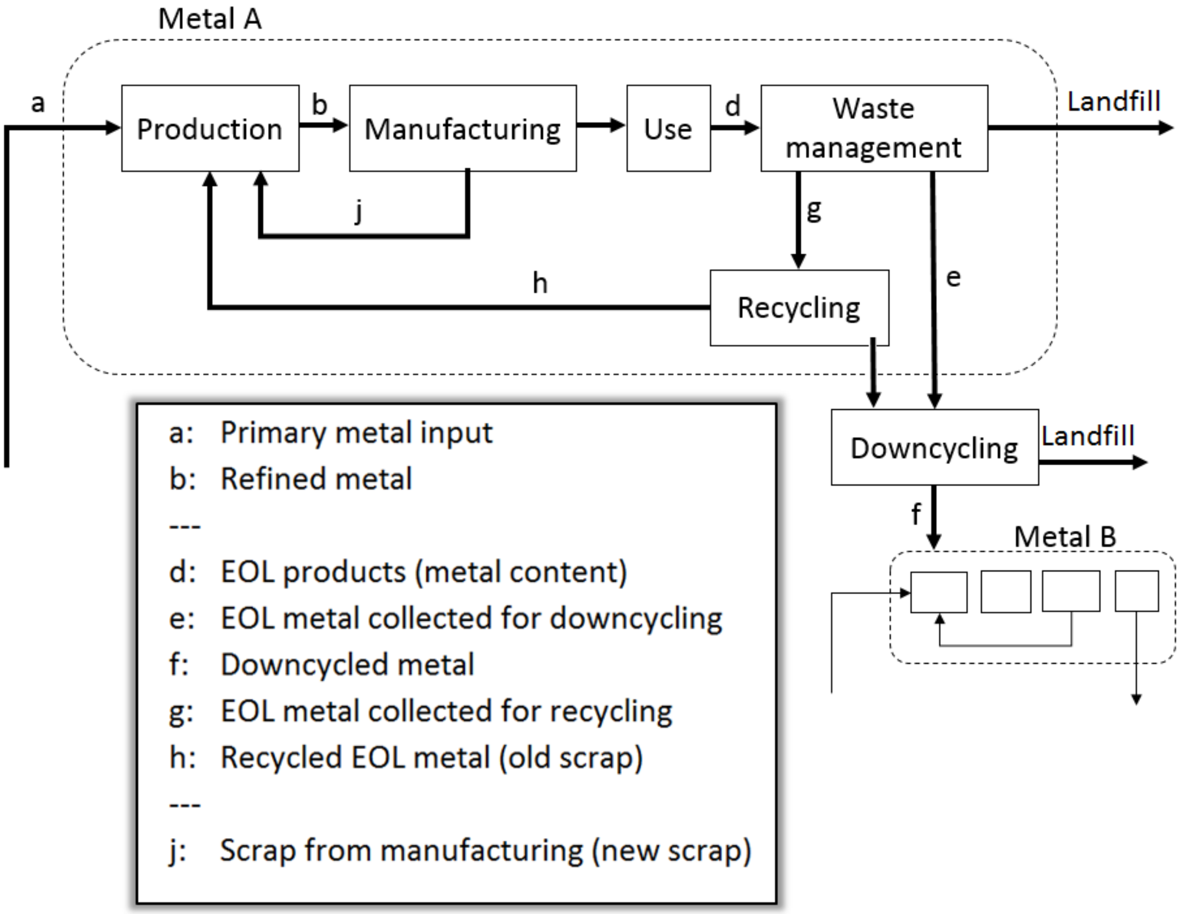


Figure 5. "Flows related to a simplified life cycle of metals and the recycling of production scrap and end-of-life (EOL) products" [9]. (Edited by Jussi Kilpeläinen)

Next, certain EOL metrics are presented and calculated with the help of Figure 5. These metrics are: recycling yield, metal specific recycling rate, old scrap collection rate, old scrap ratio, and downcycling rate [9]. Although these are presented in the context of metals recycling, similar metrics can be used for other materials also [9]. The inherent recyclability of metals, which causes this general simplicity of metal flow during its life cycle, is the reason for selecting them here as an example.

Recycling process efficiency rate, or yield, indicates the fraction of material that is recycled as same high quality products from products collected for recycling. It is calculated with the equation (2): [9]

$$Recycling\ yield = \frac{h}{g} = \frac{Recycled\ EOL\ metal\ (old\ scrap)}{EOL\ metal\ collected\ for\ recycling} \tag{2}$$

The recycling rate can be regarded as the most significant metric in EOL metals recycling, because it indicates the effectiveness of recovering and functionally recycling metals from discarded products. It is calculated with the equation (3). [9]

$$Recycling\ rate = \frac{h}{d} = \frac{Recycled\ EOL\ metal\ (old\ scrap)}{EOL\ products\ (metal\ content)} \tag{3}$$

A related metric is the downcycling, or nonfunctional recycling rate, which denotes the rate of successfully downcycled EOL products. Efforts which decrease this downcycling rate and simultaneously increase the recycling rate are beneficial to the environment. It is calculated with the equation (4): [9]

$$Downcycling\ rate = \frac{f}{d} = \frac{Downcycled\ metal}{EOL\ products\ (metal\ content)} \tag{4}$$

Furthermore, metrics for metal scrap are presented. The collection rate of old scrap indicates the amount of EOL metal, which has been collected and has entered the recycling chain, as opposed to landfilled metal. However, scrap discarded during recycling processes is not taken into account by this metric. It is calculated with the equation (5). [9]

$$Old\ scrap\ collection\ rate = \frac{g+e}{d} = \frac{EOL\ metal\ collected\ for\ recycling + downcycling}{EOL\ products\ (metal\ content)} \tag{5}$$

Old scrap ratio indicates the fraction of old scrap used in metal production. However, the model in Figure 5, may be insufficient to thoroughly assess metal recycling processes, as recycled metals can be reused in multiple different stages of metals production. Therefore, this metric may not present exact data. However, it is calculated with the equation (6): [9]

$$Old\ scrap\ ratio = \frac{h}{j+h} = \frac{Recycled\ EOL\ metal\ (old\ scrap)}{Scrap\ from\ manufacturing\ (new\ scrap) + Recycled\ EOL\ metal\ (old\ scrap)} \tag{6}$$

3.1.2 Product-centric recycling

The recycling industry typically focuses on the recycling of individual materials, and processes are developed in order to improve the efficiency of recycling a specific material. However, the overall efficiency of recycling would be improved, if this focus was shifted towards recycling products as a whole. Waste management facilities already process incoming waste on a product level. However, this classification to different products is lost during further recycling processes. This can be caused, for example, when the value of collected waste is estimated based on specific materials typically contained within this waste stream. A product-centric approach to recycling assesses the value of products beyond the price of individual materials contained within the products. For example, if certain components from a product were reused in a similar product, the value of these components would be higher than the individual materials separated from that component. This higher value is caused by the reduced need for extensive reprocessing of these products and materials during recycling. [9]

Furthermore, an important phase in recycling is separating interconnected materials from one another. However, depending on product design, materials may be interconnected to each other in such way, that recycling becomes unfeasible or even impossible. Therefore, this current material-centric approach to recycling is an insufficient model to comprehensively assess real life interactions between different products during recycling processes. In order to optimize these recycling processes, products should be quantified on the level of element, compound and alloy, because complex thermodynamics and physics interactions ultimately determine the recyclability of materials. This requires a deep understanding of physics and thermodynamics governing materials, products and recycling processes used during a products life cycle. Furthermore, recycling policies and laws should be based on this understanding. In summary, developing more efficient recycling methods requires a more comprehensive assessment of products than the recyclability evaluation of individual materials contained in the products. [9]

A key concept to such improvements in product recyclability is designing products for recycling [9]. This requires selecting materials based on the ways they are linked to other materials in the product, because the recyclability of a material is altered based on which other materials it is associated with [9]. However, product designers may not have sufficient knowledge of complex materials science [2]. Therefore, this design for recycling requires developing tools, which are based on rigorous application of thermodynamics, physics and process technology [2]. Such tools would assist designers to comprehensively estimate the impact of their material choices on recyclability [2].

According to Reuter and Worrell [9], three interrelated factors determine the outcome of recycling: “the way waste streams are mixed or pre-sorted during collection, the physical properties, and the design of the end-of-life products in those waste streams”. Furthermore, it is trivial to optimize only one of these factors without taking the others into account, as any one of these factors may ultimately determine the maximum possible value gained from recycling. Therefore, the whole chain of recycling has to be considered and optimized. [9]

Reuter et al. [2], have developed "The Metal Wheel", presented in Figure 6, which visually demonstrates these problems in recycling. It is an example of a typical EOL product, from which the possibility of recovering elements during different metals recycling processes is presented [2]. The Metal Wheel is presented at higher resolution in *"Appendix* C*: The Metal Wheel"*. It aims to help decision-makers grasp the inherent challenges of recycling products [2]. The elements which are usually lost during recycling, are marked as red circles, while the elements with yellow circles are probably lost, and green elements probably recovered [2]. Furthermore, the value of recovered elements decreases, the closer they are to the outer edge of the wheel [2]. In order to increase resource efficiency, the current focus can be set on the high-value, low-volume materials, which are essential for the development of future technology [9]. For example, elements such as gallium, indium, all rare earth elements and platinum group metals are typically lost during recycling, although their recovery is essential to sustainable growth [9].

In the current society, materials are firstly selected to fulfill a specific functionality in products and the consumer is satisfied with functionality and service, not by recyclability of products. Therefore, design for functionality overrides design for recycling. Drivers for product development emphasize on creating more value to the products, and therefore more complex products are developed. However, the more complex a product is the more interconnected, inseparable, and therefore unrecyclable material linkages it generally has. In order to reach a more sustainable future it is important to consider material linkages and design products for recyclability as well. [2]

🟦 **Society's Essential Carrier Metals: Primary Product** Extractive Metallurgy's Backbone (primary and recycling metallurgy). The metallurgy infrastructure makes a "closed" loop society and recycling possible.

🟦 **Dissolves mainly in Carrier Metal if Metallic (Mainly to Pyrometallurgy)** Valuable elements recovered from these or lost (metallic, speiss, compounds or alloy in EoL also determines destination as also the metallurgical conditions in reactor).

☐ **Compounds Mainly to Dust, Slime, Speiss, Slag (Mainly to Hydrometallurgy)** Collector of valuable minor elements as oxides/sulphates etc. and mainly recovered in appropriate metallurgical infrastructure if economic (EoL material and reactor conditions also affect this).

🟩 **Mainly to Benign Low Value Products** Low value but inevitable part of society and materials processing. A sink for metals and loss from system as oxides and other compounds. Comply with strict environmental legislation.

El **Mainly Recovered Element** Compatible with Carrier Metal as alloying Element or that can be recovered in subsequent Processing.

El **Mainly Element in Alloy or Compound in Oxidic Product, probably Lost** With possible functionality, not detrimental to Carrier Metal or product (if refractory metals as oxidic in EoL product then to slag/slag also intermediate product for cement etc.).

El **Mainly Element Lost, not always compatible with Carrier Metal or Product** Detrimental to properties and cannot be economically recovered from e.g. slag unless e.g. iron is a collector and goes to further processing.

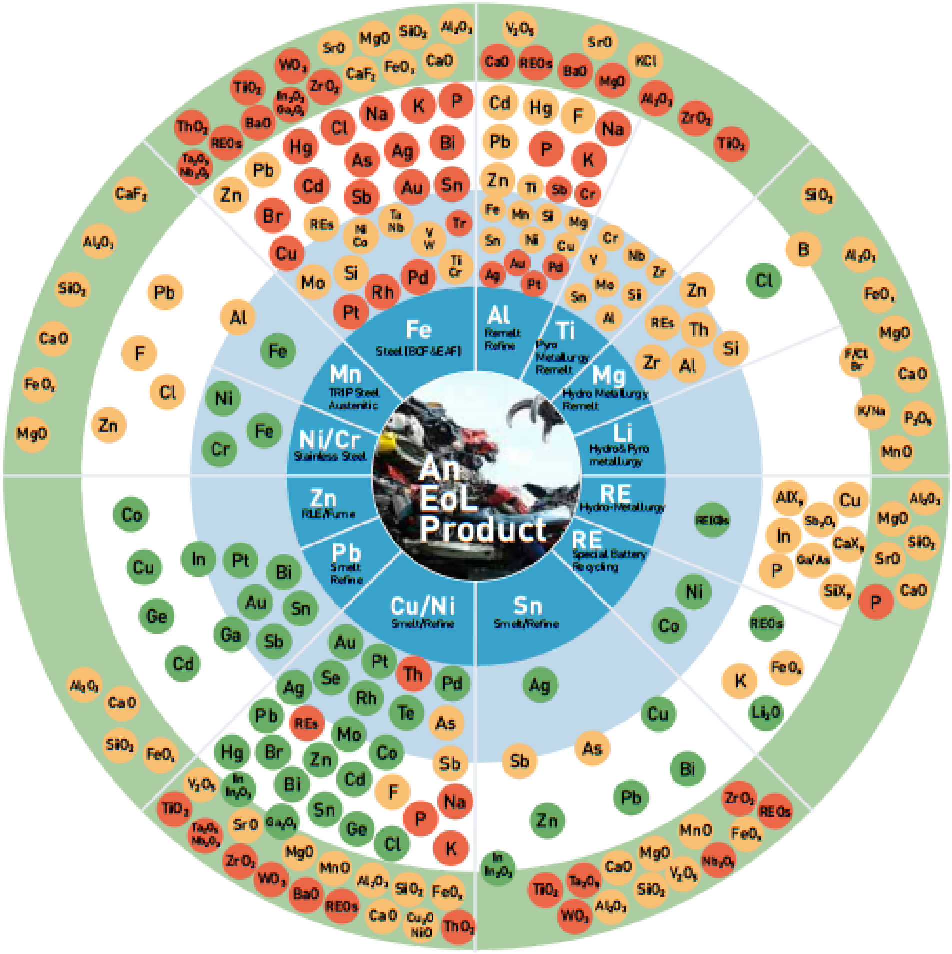


Figure 6. The Metal Wheel shows elements that are recoverable during end-of-life (EOL) recycling from society's essential carrier metals [2].

3.1.3 Economics of recycling

The feasibility of recycling is governed by global economics, and therefore losses in recycling may occur due to changes in raw material prices, which can make recycling commercially uninteresting [9]. Although the scope of this thesis does not include calculating the exact economic feasibility of recycling, it cannot be completely disregarded. Economic feasibility is, nevertheless, the underlying driver which pushes the development of all recycling technologies forward, and determines which recycling process is selected for a product [43].

The feasibility of recycling depends on various factors, such as the costs of components, collection, energy, processing, labor, and the value of products and materials. For example, a certain component in a product may be valuable, but the labor needed to disassemble the products may outweigh this value, and therefore the products are mechanically crushed and only the materials are recovered instead of specific components. Lee at al. [43] have developed a methodology to evaluate end-of-life options and disassembly of products. They propose the following eight equations to calculate the economic value of disassembled end-of-life products components. [43]

$$Miscellanous\ cost = collection\ cost + processing\ cost \tag{7}$$

$$Reuse\ value = cost\ of\ component - Miscellanous\ cost \tag{8}$$

$$\begin{aligned} &Remanufacture\ value \\ &\quad = cost\ of\ component - remanufacture\ cost - Miscellanous\ cost \end{aligned} \tag{9}$$

$$\begin{aligned}&\mathit{Primary\ recycle\ value}\\&\quad= \mathit{weight\ of\ component} \times \mathit{market\ value\ of\ material}\\&\quad- \mathit{Miscellanous\ cost}\end{aligned} \tag{10}$$

$$\begin{aligned}&\mathit{Secondary\ recycle\ value}\\&\quad= \mathit{weight\ of\ component}\ \times \mathit{scrap\ value\ of\ material}\\&\quad- \mathit{Miscellanous\ cost}\end{aligned} \tag{11}$$

$$\mathit{Incinerate\ value} = \mathit{energy\ produced}\ \times \mathit{unit\ cost\ of\ energy} - \mathit{Miscellanous\ cost} \tag{12}$$

$$\mathit{Landfill\ cost} = -(\mathit{weight\ of\ component} \times \mathit{cost\ of\ landfill}) - \mathit{Miscellanous\ cost} \tag{13}$$

$$\begin{aligned}&\mathit{Special\ handling\ cost}\\&\quad= -(\mathit{weight\ of\ component} \times \mathit{cost\ of\ special\ handling})\\&\quad- \mathit{Miscellanous\ cost}\end{aligned} \tag{14}$$

This special handling cost presented in equation (14) indicates, for example, the handling of hazardous materials, and therefore always has a negative value [43]. Similarly, the cost of landfilling products is always negative [43]. Afrinaldi et al. [44] have further developed these proposals of Lee at al. [43], and have developed a software for end-of-life disassembly analysis. They propose an equation to calculate the suitability of materials for recycling [44]. Furthermore, they propose that materials receiving a rating of under 80 % from the equation (15) would not be suitable for economic recycling [44].

$$\begin{aligned}&\mathit{Suitability\ for\ recycling}\\&\quad= \frac{\mathit{Cost}\ (\mathit{equivalent\ new\ material} + \mathit{disposal})}{\mathit{Cost}\ (\mathit{dismantling} + \mathit{reprocessing} + \mathit{logistics})} \times 100\ \%\end{aligned} \tag{15}$$

To improve the economic feasibility of recycling, Villalba et al. [45] propose a concept of recyclability index, which determines the economic feasibility of disassembling a product. Their methodology is to determine the amount of materials with high recyclability potential in a product, and calculate a profit-to-loss margin, which determines whether the materials should be disassembled and recovered from the products. Furthermore, they propose that corrective actions during manufacturing should be taken if this margin is negative, in order to ensure recyclability of products in the future. [45]

3.2 Criteria for recyclability

A simple method to support decision making is to create a set of criteria, which accomplishes a certain goal by excluding undesirable options from a larger group of options. For example, selecting materials for a product based on the desired properties the product should have. Such criteria for the recyclability of materials can be found from literature. These findings are examined and presented in this subchapter, in order to comprehend what has to be taken into account when developing such criteria for Suunto. Such criteria have been developed by denkstatt [46]. They present multiple criteria for efficient plastic recycling and waste management [46]. Their list includes the following criteria:

- Environmental impacts of collection, treatment and related recycling processes must be lower than the impact of producing substituted virgin materials or fuels.
- No recycling if products contain restricted substances.
- Effect of recycling must be evaluated according to existing or future CO_2 targets.
- Calorific value of plastic waste.
- Quality of waste stream.
- Concentration of all environmentally relevant substances.
- Emission control equipment available in local recycling facilities.
- No landfilling; prefer municipal solid waste incinerator for energy recovery.
- Social aspects, such as working conditions and consumer health, safety and convenience.
- Understanding and commitment of stakeholder groups. [46]

In order to classify materials and products to certain categories, the different possible end-of-life options need to be defined and clear criteria needs to be presented, which defines the reasoning for a material or product to end up in a specified category. For example, a study by Lee at al. [43] used the following six end-of-life categories, from which a specific option was selected, based on whether the objective was to minimize the environmental impact or to maximize the economic gain for the company:

1. Reusing a component, either directly or indirectly.
2. Remanufacturing a product, either by refurbishing or repairing.
3. High grade recycling, in which the material is used in same quality product.
4. Low grade recycling, in which the material is used in lower quality product.
5. Incineration of waste material to produce heat and electricity.
6. Landfilling of waste material. [43]

Furthermore, Lee et al. [43] also proposed the following recommendations for selecting an end-of-life option for the components of a disassembled product:

1. Recycling for metals without alloys and suitable polymers.
2. Downcycling for alloyed metals, polymers not suitable for recycling, ceramics, elastomers, and composite materials.
3. Incineration for energy recovery for polymers and composites not suitable for downcycling.
4. Landfilling for materials not suitable for other end-of-life options.
5. Special handling for hazardous and toxic materials. [43]

Although these end-of-life options are usually presented in a hierarchical order, some exceptions exist. For plastics, especially, a general hierarchy cannot be established because the net environmental benefits of different recycling options typically overlap. This is caused by the fact that plastics have a maximum profitable recycling rate. After reaching this level, the recycling costs increase, while the quality of recycled plastic decreases. Therefore, other forms of recycling for plastics, such as energy recovery, become more efficient. In such cases, recycling plastics to low quality products cannot be justified.

Therefore, individual life cycle and costs-benefit analyses may be required in order to determine the optimal process for plastics recycling. [46]

Furthermore, other plastic specific recyclability criteria exist, such as the calorific value of the waste, and which fuels this incinerated plastic waste substitutes. These two factors, together with general criteria, such as cost of logistics, determine whether plastic incineration is feasible [46]. Generally, plastics have gross calorific values comparable to or higher than coal [47]. Another criterion for plastics recycling, is the ratio of up to which percentage recycled material can be mixed with virgin material without affecting the mechanical properties significantly [48]. The cost of collection and sorting is still a considerably high factor in plastic recycling, which may cause on-site recycling options to have the highest eco-efficiency, such as energy recovery and feedstock recycling [46]. In contrast, the impact of logistics is lower in metals recycling [9]. Nevertheless, even low levels of high quality plastic recycling contribute significantly to resource efficiency compared to landfilling or energy recovery [46]. Furthermore, future innovations may reduce the costs of collection and sorting, which makes recycling more feasible [9], [46].

3.3 Tools for evaluating recyclability

Recycling is not a single process, but a sequence of multiple phases [9]. The entire efficiency of a recycling system suffers if any one phase is completed inadequately [9]. The significance of each step in recycling processes varies between different materials and products [9]. Furthermore, every material and product has a specific recycling range, which is constantly altered by technology, innovations, infrastructure and the costs and the environmental impact of collection and sorting [46]. Equivalent theory is that waste should be regarded as waste only when it cannot be reused again economically in any form [9]. Current state of recycling technologies and the inherent properties of materials determine the most efficient recycling method for a material [9]. The impact of all these factors may be difficult to grasp, for example, during the design phase of a product, and therefore the development of various tools which evaluate recyclability is encouraged [9]. This subchapter presents selected tools, such as computer software, which have been developed to support decision-makers assess the impacts of their decisions.

A significant amount of research has been conducted in order to assess the sustainability of recycling and related processes [49]. These methods usually include mathematical models to evaluate different aspects affecting recyclability [50]. Some methods have been further developed into computer software applications [50]. Generally, methods classified as multiple criteria decision analyses, can be used to evaluate various criteria, which have excessive amount of factors to be evaluated without the support of computers [50]. These methods allow weighing of different criteria to create different scenarios and evaluate, for example, the environmental benefits of various decisions [50]. One such method is an analytic hierarchy process (AHP) which is typically used to solve complex decision making problems in waste management industries [50]. The AHP weighs input criteria as pairs by forming a comparison matrix, and thus, identifies the most optimal outcome [49]. The AHP has been used to optimize recycling, waste management, remanufacturing, reuse, and product design and disassembly [49]. As an example, a study conducted by Yu et al. [51] used an AHP in order to determine the feasibility of recycling electronic scrap. Their proposed methodology is presented in Figure 7, along with the recycling plant material flows [51]. The input for their method was component information of disassembled products, which included component name, material content and mass [51]. The output of their method was optimal recycling plans for these components [51]. The process was further divided into three stages: material screening to group similarly recycled materials together in the collection bins presented in Figure 7, recycling process identification for these groups, and finally environmental decision making, which evaluated environmental impacts, costs and recoverable materials [51]. This, or a similar, method could be used to evaluate the recyclability of products at Suunto.

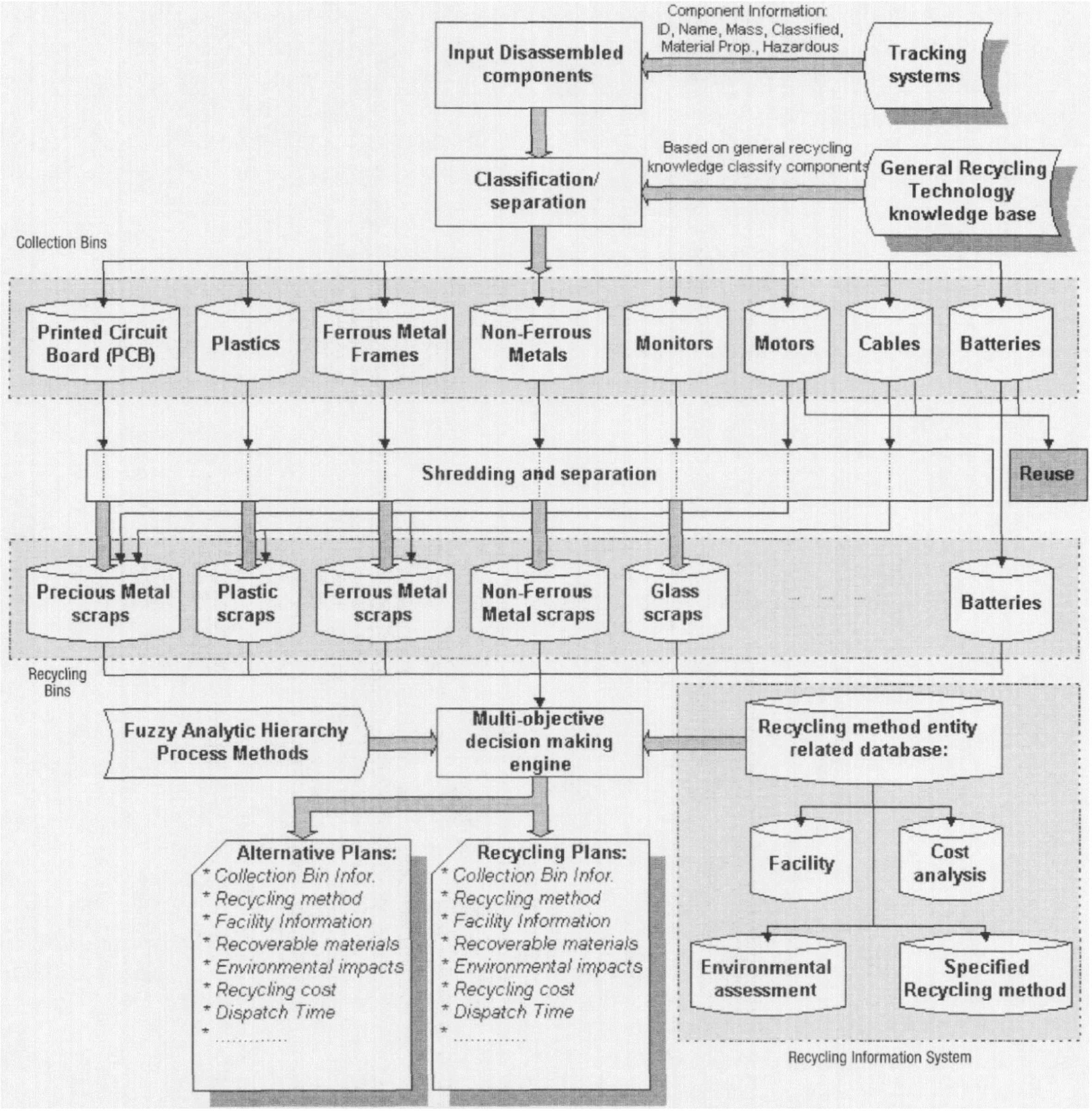


Figure 7. System architecture of recycling plant and proposed methodology for analytic hierarchy process [51].

Disassemblability is an important factor when evaluating the recyclability of products [9]. However, disassembling products leads to increased labor costs, which may discourage companies to take part in such actions [9]. Therefore, a need exists for a tool that optimizes product disassembly [9]. However, disassemblability of products is not in the scope of this thesis. All materials are assumed to be disassembled when they arrive to the evaluation procedure developed in this thesis. Nevertheless, a tool for evaluating disassemblability operations is presented here, because it is an essential part of recycling. Afrinaldi et al. [52] present a tool for designers to determine the impact of design choices on the disassemblability on the products. Input for their proposed tool is component information, such as mass, material, value, and connection types of the components, and also the cost of end-of-life operations [52]. The output is a disassemblability evaluation report, which provides feedback for product designers and suggests improvements for structure, disassembly sequence and material content of the product [52]. Figure 8 presents their proposed methodology. They have further developed this method to identify whether a single component is reusable, recyclable, or remanufacturable [53].

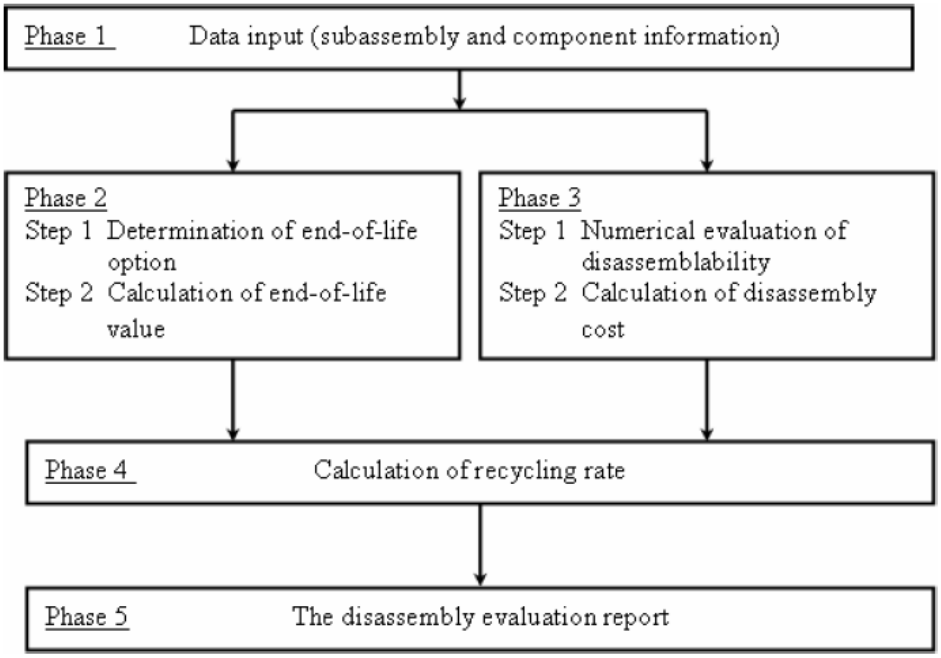


Figure 8. Proposed methodology for a computer-based end-of-life product disassemblability evaluation tool [52].

Afrinaldi et al. [44] have further developed their methodology, and created an end-of-life disassembly analysis software. This tool is meant to support designers to comprehend the effect of their decisions on the disassemblability of products. This software determines an end-of-life option for a product, numerically evaluates product disassemblability and searches for the optimal disassembly sequence. [44]

Remery et al. [54] propose another evaluation method to determine an optimal end-of-life scenario. Their hierarchical evaluation method is presented in Figure 9. It includes four main criteria for end-of-life evaluation: income generated from sales, treatment costs, compliance with regulations, and environmental performance. These criteria further contain multiple sub-criteria. Remery et al. [54] tested their recyclability evaluation method for a vehicle engine. They concluded that remanufacturing was the most viable end-of-life option. Reusing the engine as such was the second most feasible, and recycling without disassembling was the third. An important remark was that recycling with prior disassembling was concluded as having only slightly higher benefits than landfilling. This demonstrates the extensive impact disassembling products by manual labor force may have on the feasibility of recycling. [54]

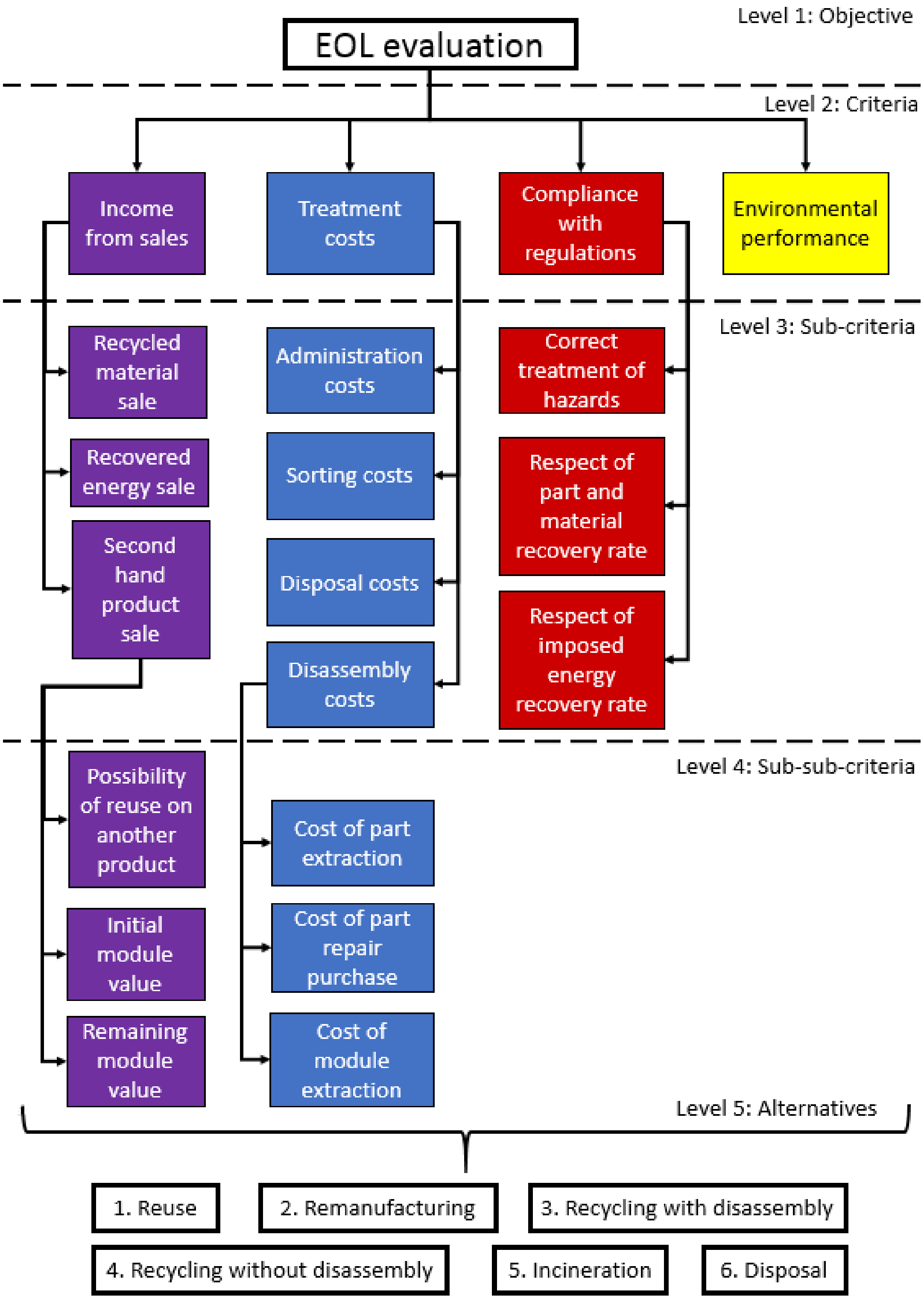


Figure 9. End-of-life (EOL) evaluation with five levels of hierarchy: objective, criteria, sub-criteria, sub-sub-criteria, and alternatives [54]. (Edited by Jussi Kilpeläinen)

This significant impact on costs due to manual labor has been taken into account in a study by Renteria et al. [55]. They propose a methodology presented in Figure 10 for optimizing the handling of waste electrical and electronics equipment. Their method is to simulate an automated disassembly facility for WEEE, which can then further be built and tested in a small scale facility, or a pilot plant. Their method was tested by disassembling television sets in a recycling facility. Their proposed future developments include: "research on new technologies for better material identification, automated learning capabilities of the disassembling system, and knowledge management embedded on the electronic devices". [55]

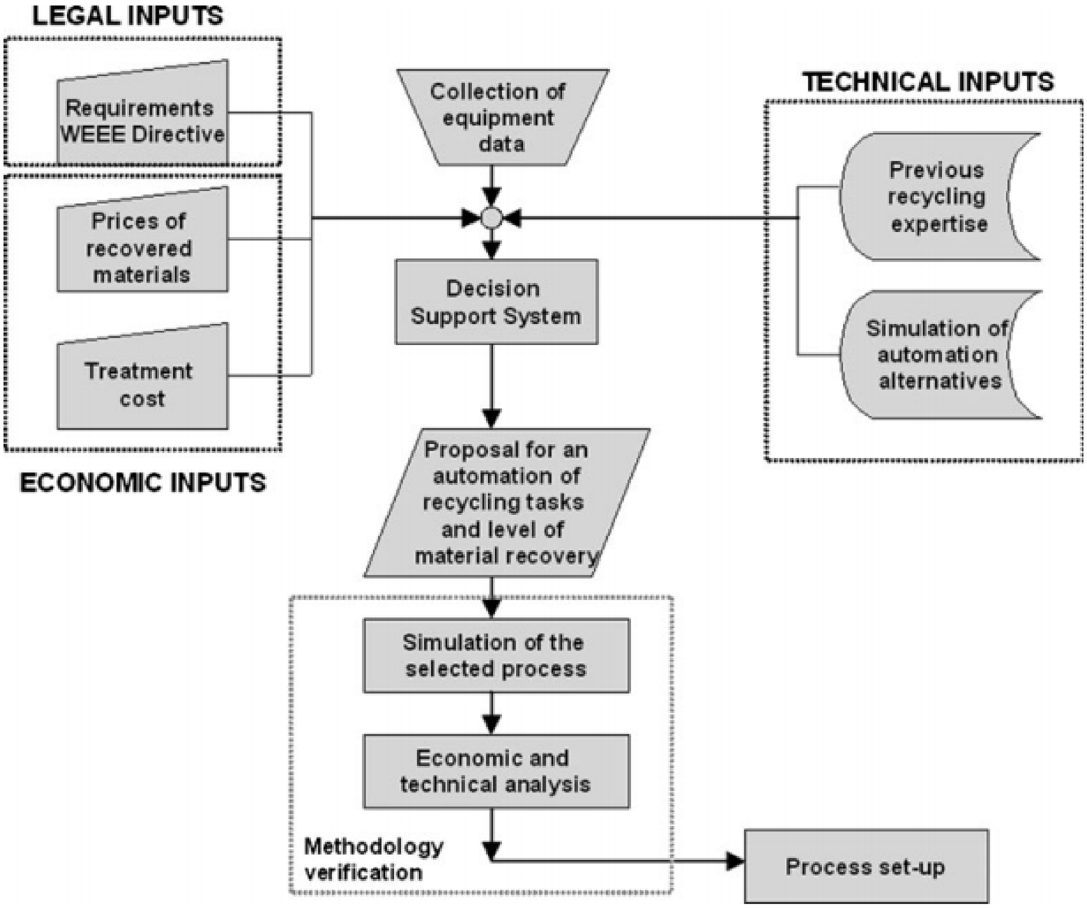


Figure 10. Inputs and methodology which evaluate waste electrical and electronic equipment (WEEE) recycling [55].

The tools presented in this chapter include more aspects than is included in the scope of this thesis. However, they present the requirements of a comprehensive evaluation tool. The factors included in these tools should be taken into account when making company decisions [9]. Furthermore, the rise of artificial intelligence and automated systems with learning capabilities, together with the possibility of embedding disassemblability data to the products themselves pose intriguing possible future developments for recycling facilities [55].

4 Wearable sports instruments' exterior materials

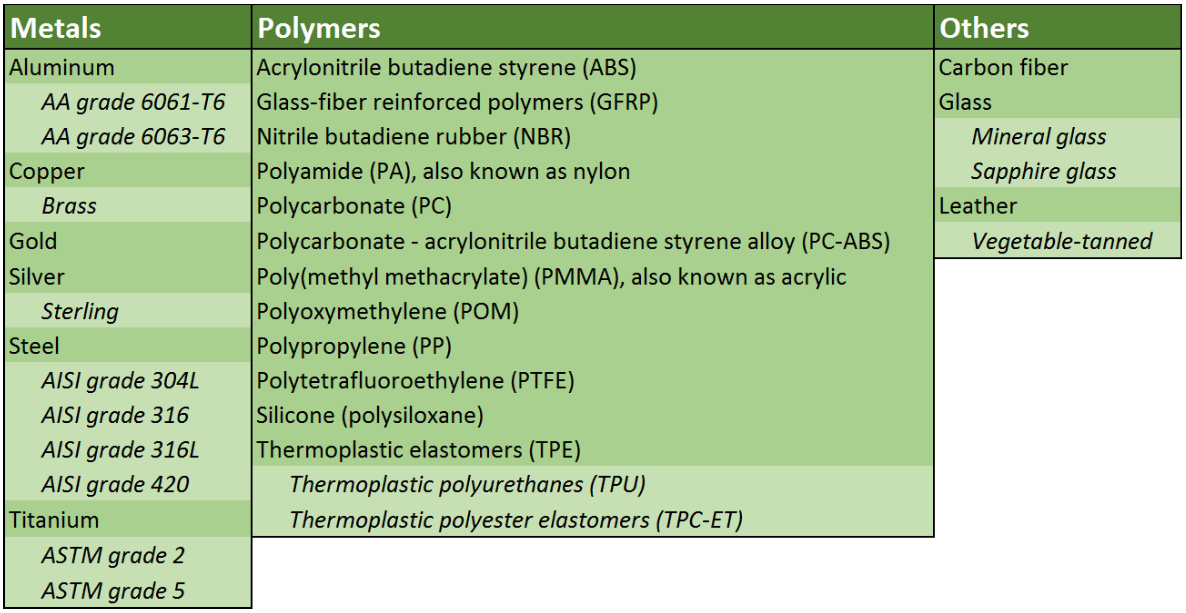
Suunto Oy is a manufacturer of compasses, sports watches, dive computers, precision instruments and related accessories. This thesis focuses on the exterior materials of Suunto's products. These exterior materials are the materials which can be seen on the outer surface of a product, as presented for example in Figure 11, which displays a selected Suunto watch. Only these exterior materials on the surface of the products, which are mainly the straps and cases of products, are examined in this thesis. All inner components such as electronics are excluded from the scope of this thesis.

Figure 11. Suunto Core Alu Pure White [56].

The exterior materials in a product are generally more susceptible to deterioration during use. Even a small dent on a surface of the product can make a product unsellable to customers, who demand a high quality product, even though the visual defect does not affect the functionality of the product. Therefore, exterior materials are visually protected by coatings or additives when needed. For example, some plastics change color when exposed to prolonged periods of sunlight, therefore additives which act as ultraviolet inhibitors and reduce this visual effect, provide customers with a more positive experience about the product, even though its functionality is not changed.

4.1 List of materials and material grades

Materials listed below, in Figure 12, are the exterior components' materials used by Suunto in their products, for example, in bezels, cases and straps of sports watches and dive computers. Different material grades are indicated by a lighter green color in the list and are related to the material above them. It must be noted that, while these different grades of materials are mentioned, the specific trade names of materials and their grades have not been disclosed by Suunto in this thesis.



Metals	Polymers	Others
Aluminum	Acrylonitrile butadiene styrene (ABS)	Carbon fiber
AA grade 6061-T6	Glass-fiber reinforced polymers (GFRP)	Glass
AA grade 6063-T6	Nitrile butadiene rubber (NBR)	*Mineral glass*
Copper	Polyamide (PA), also known as nylon	*Sapphire glass*
Brass	Polycarbonate (PC)	Leather
Gold	Polycarbonate - acrylonitrile butadiene styrene alloy (PC-ABS)	*Vegetable-tanned*
Silver	Poly(methyl methacrylate) (PMMA), also known as acrylic	
Sterling	Polyoxymethylene (POM)	
Steel	Polypropylene (PP)	
AISI grade 304L	Polytetrafluoroethylene (PTFE)	
AISI grade 316	Silicone (polysiloxane)	
AISI grade 316L	Thermoplastic elastomers (TPE)	
AISI grade 420	*Thermoplastic polyurethanes (TPU)*	
Titanium	*Thermoplastic polyester elastomers (TPC-ET)*	
ASTM grade 2		
ASTM grade 5		

Figure 12. Exterior component materials. Lighter color indicates a different grade of the above material.

An important notion is that polymers typically have multiple names. All polymers have a standardized name defined by the International Union of Pure and Applied Chemistry (IUPAC). However, these names are rarely used, because they often are excessively long. The purpose of this IUPAC nomenclature is to unambiguously indicate the polymer's chemical structure. Commonly used names for polymers are either shorter versions or abbreviations of these standardized names, or common trade names coined by a company. In contrast, the names of different metal grades cause less confusion generally as metal grades have been standardized by various historical associations. The grade names used here were originally designated by the Aluminum Association (AA) [57], the

American Iron and Steel Institute (AISI) [58], or the American Society for Testing and Materials (ASTM) [58], although the composition of metal grades are no longer supervised by these associations, these metal grade names are still most commonly used. The chemical compositions of standardized metal grades are also presented. Furthermore, coatings and additives used in these materials are examined in this chapter, because they may affect the recyclability of materials considerably [9].

4.2 Conventional recycling methods for exterior materials

During the last decades, the advantages of recycling have been recognized globally as energy costs for raw materials production increase steadily. Current trends in materials science and engineering increasingly emphasize the development of sustainable materials. Presumably, vast untapped market potential lies within materials which currently cannot be fully recycled. Therefore, novel recycling methods are constantly under research and countless organizations reward achievements and fund endeavors which develop more sustainable materials and processes. Although these novel recycling methods are of interest when designing future strategies, the focus of this thesis is on the current commercially available recycling methods, which have been implemented on a large scale and an infrastructure exists globally. This subchapter presents current commercially available recycling methods for the exterior materials listed in Figure 12. However, certain materials currently are not recyclable on a large commercial scale. In such cases, alternative end-of-life options and the state of current research concerning recycling of those materials are examined.

4.2.1 Metals

Metals are inherently recyclable because their mechanical properties do not degrade during reprocessing and therefore they are generally classified as 100 % recyclable. Furthermore, the energy required to melt metal scrap is usually only a fraction compared to mining ores. However, the need for mining metals may never be completely eliminated as recycling cannot be 100 % effective due to the second law of thermodynamics.

Furthermore, certain material linkages, alloys and combinations made for functionality of products may decrease the recyclability of these products and metals. [9]

4.2.1.1 Aluminum

Aluminum usage has increased during the last decades, as products are manufactured increasingly from aluminum to provide light weight components and corrosion resistance. Although aluminum is currently fully recyclable, this increased usage is expected to cause considerable impacts, which may decrease aluminum recyclability. Mainly, because the sustainability of these recycling processes becomes more difficult to ensure as the volume increases. This reduced recyclability is caused by neglecting the pre-sorting stage when large amounts of different aluminum alloy scraps are recycled in the same facility. To ensure high recycling rates, aluminum products should be sorted according to their alloys, and reused to produce similar alloys. [59]

Aluminum recycling is practiced globally because it consumes only 5 % of energy compared to the raw production of aluminum from bauxite ore [59]. This creates the key incentive for aluminum recycling, which is the substantially lower price of producing recycled aluminum, and thus aluminum scrap is highly valued and all aluminum scrap could be recycled without subsidies [9]. However, the total world average aluminum recycling rate is only 27 % [9]. Consequently, financial incentives for collection of aluminum exist in many countries, for example aluminum cans recycling has reached up to 98 % due to the introduced incentives in some countries [9]. Furthermore, aluminum creates an oxide film on its surface that makes the material impervious to deterioration, unless it is hit by particular chemicals or galvanic corrosion takes place [59]. Therefore, aluminum can be viewed as having a practically endless life cycle when proper recycling processes are used [59].

Over 300 different aluminum alloys exist and most of these aluminum alloys are designed to tolerate variations in compositions and impurities that are caused by the different products which end up to the recyclate scrap [59]. However, iron and silicon tend to accumulate with each remelting cycle, which is a rising issue in the production of rolled aluminum products, because these impurities decrease the aluminum’s physical, chemical and mechanical properties [59]. The aluminum grades examined in this thesis are 6061-T6 and 6063-T6. Their composition can be seen in detail in *“Appendix* A*: Chemical compositions of metal grades”*. These grades are common aluminum grade and they contain about 95-99% aluminum and their main alloying elements are magnesium and silicon. Furthermore, all grades of aluminum can be fully recycled with standard recycling processes, provided that they are not mixed with different grades which would decrease their recyclability rates [9], [59].

Highly oxidized and dirty aluminum scrap requires processes that consume more energy and require more stock materials during these recycling processes than the recycling of clean aluminum scrap. The recyclability of aluminum scrap is determined by its morphology, or in other words, the surface area of the aluminum scrap. Another issue in aluminum recycling is the use of coatings, which decrease metal recovery rate when these coatings create compounds with aluminum during processing. Furthermore, aluminum should be separated physically from all WEEE because it may decrease the recycling rates of other metals. If aluminum is present in recycling processes of other metals, it may end up to slag formed during this pyrometallurgical processing as alumina (Al_2O_3) or other compounds. In such cases, the aluminum is not only lost from the aluminum’s own recycling chain, but these formed aluminum compounds will disrupt other metals recycling processes by altering viscosity, flow, foaming and separation behaviors of these other remelted metals, which decreases metal recycling rates. [9]

4.2.1.2 Copper

Copper is one of the most important elements used in electronics industry, because of its excellent heat and electric conductivity [60]. The recyclability of copper and its alloy with zinc, called brass, are examined in this subchapter. Copper does not degrade or lose its physical or chemical properties during recycling processes [60]. Copper production relies heavily on the recycling of copper, since over 30 % of copper products are made from recycled copper globally [60]. The main factor affecting the efficiency of recycling processes is the purity of copper [61]. It is essential to verify the purity of the copper scrap to ensure the quality of products made from recycled copper [61]. This increases the costs of recycling significantly, but it is required to achieve high quality products [61]. Although copper by itself is already a highly valuable scrap metal, copper product scrap may also contain other valuable elements, such as bismuth, gold, silver, nickel, cobalt and platinum group metals [9]. Recycling processes have been developed in order to gather these valuable elements from copper scrap simultaneously with copper [9].

High grade copper of over 99 % purity is used in thin wires in which excellent surface quality is required [61]. Lower quality scrap copper is used for non-electrical products which tolerate more impurities, such as plumbing tubes [61]. However, all uncontaminated recycled copper can be electrolytically refined back to the same quality as high grade primary copper and used in products with high quality requirements [61]. Low quality contaminated copper scrap is sent to smelting and refining to achieve the desired purity [62]. High grade copper can be sent directly to the forming phase [62].

Brass

Brass is a metal alloy of copper and zinc. The properties of brass are altered by varying its zinc content, which typically falls between 5-50 % [58]. The cost of brass decreases as zinc content increases [58]. Different grade alloys may also contain other elements, such as tin, lead, or silicon [63]. These alloys are refined during the recycling processing by oxidizing these other elements [63]. Generally, brass scrap that is sorted based on its composition can be remelted without refining [9]. Copper and brass alloys are further classified, depending on their melting range, for example red brass melts over a range of 165 °C, therefore it is a wide melting range copper alloy [63]. These alloys can be recycled by remelting them in a furnace without the need to control the exact temperature, which decreases the costs of reprocessing [63]. Recycled brass products are generally made from brass scrap of similar composition [64]. During these processes excess zinc can be recovered along with other alloyed metals such as tin, antimony, lead, nickel and aluminum [61]. Virgin copper and zinc are further used during the manufacturing of these recycled brass products to adjust the final composition [64]. The cost of brass scrap is significantly lower than the production of similar products from raw materials [64].

4.2.1.3 Gold

Gold has a wide range of uses in today's society, ranging from jewelry to technological products [65]. Gold is a precious metal that is highly valuable, and since it does not decay, it is estimated that all gold ever mined still exists in products of some form [65]. Recycling of gold supply fluctuates rapidly with the economic situation [65]. The recycling rate is generally measured as a percentage of total gold supply and on average, recycled gold accounts for 30 % of global demand [65]. The long term trend is that the volume of recycled gold increases [65]. High value sources comprise up to 90 % of the recycled gold, the rest 10 % is from industrial sources [66]. Furthermore, gold is widely harvested from WEEE, which typically has gold content of about 200-350 grams per ton [67]. WEEE usually have up to 60 different elements, but gold can make up to 76 % of the total material value of a product [67]. Therefore, WEEE is often colloquially called an urban gold mine [67]. For comparison, in recycled mobile phones, silver, gold and palladium together make up to 93 % of the scrap value [67]. The biggest losses in gold recycling chain are caused arguably by its high value, because WEEE is often transported to low income countries, where the inefficient recycling processes achieve recycling rates of under 25 %, and therefore a major part of the gold is lost [67]. It is estimated that from the recyclable gold contained in European WEEE, up to 80 % is lost due to poor collection and poor recycling processes [67].

Gold is typically recycled by hydrometallurgical processes, which indicates processing metals in an aqueous phase [9]. In such process, gold can be recovered from this aqueous phase and refined chemically or with an electrolysis method [9]. Figure 13 presents recycling processes for gold (Au), silver (Ag) and platinum group metals, referred to as PGM in the figure [9]. The process to electrolytically refine gold to 99.9999 % purity for high quality industrial uses is called the Wohlwill process [68]. The Miller process is another process named after its inventor [68]. It produces 99.95 % pure gold with relative ease and it is therefore used when ultra-high purity gold is not required in products [68].

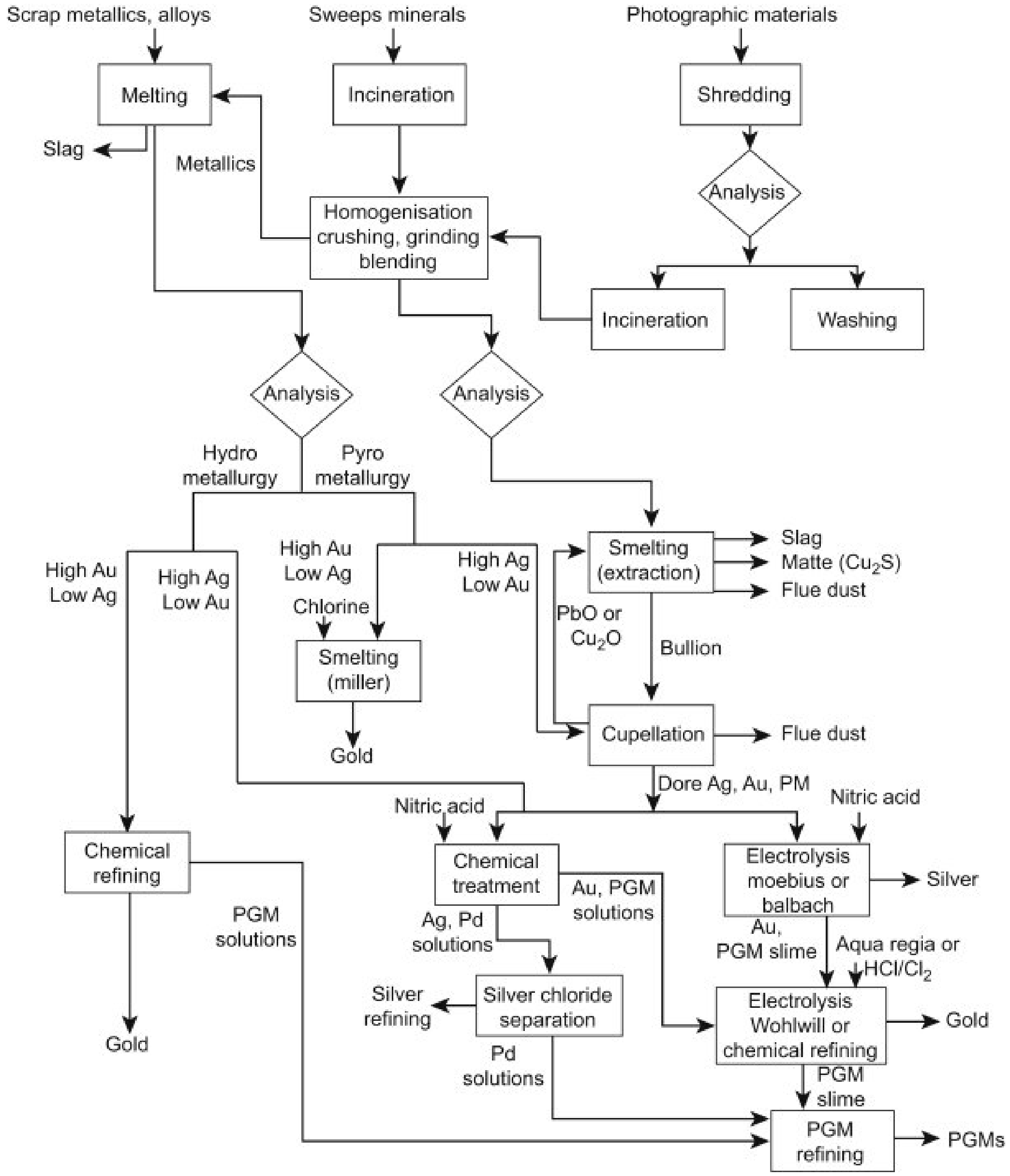


Figure 13. Metallurgical processes for precious metal recovery [9].

4.2.1.4 Silver

Silver has been classically used in jewelry, however, during the last century, industrial and technical uses have surpassed these aesthetic uses [69]. Currently, silver is used widely in photography and mirrors because it has the highest optical reflectivity of all metals [9]. Furthermore, silver has the highest thermal and electrical conductivity of all metals [69].

Despite these properties, silver is the least expensive precious metal [69]. Silver is typically refined to 99.9 % purity [58]. However, pure silver is too soft for many practical uses, therefore silver is often alloyed with other metals [58]. For example, sterling silver is the most widely used alloy in jewelry, it is an alloy comprising 92.5 % silver and 7.5 % other metals, usually copper, which gives the silver alloy the needed strength for practical uses [58].

Silver production relies heavily on the production of copper [9]. In total, 55 silver minerals are known, most of which are associated with copper, gold, lead or zinc [69]. Only a small portion of global silver demand can be mined from ores in which silver is the primary product [69]. Silver scrap sources include old photographs, films, photography processing equipment, electronics, jewelry, catalysts and manufacturing waste [69]. Figure 13 presents silver recycling processes, for example, a process starting from photographic materials can be seen in the right corner. Silver scrap recycling efficiency has been estimated at 97 % [69]. All-metal silver jewelry scrap can be recycled directly by melting it in a furnace without any preprocessing [69].

4.2.1.5 Steel

Steel is widely used in many industries due to its low cost combined with favorable properties. In the global economy, it is a dominant material and the most recycled metal in the world by weight. Recycling steel saves 33 % energy compared to producing steel from iron ore. Steel does not lose the inherent physical properties it has when it is recycled. Therefore, steel is widely regarded as having a practically endless life cycle. [70]

Steel scrap is generally shredded and then recycled either by an electric arc furnace, which uses 100 % steel scrap, or by basic oxygen furnace, which uses about 20 % of steel scrap. Figure 14 presents a schematic steelmaking process from ores and scrap. [9]

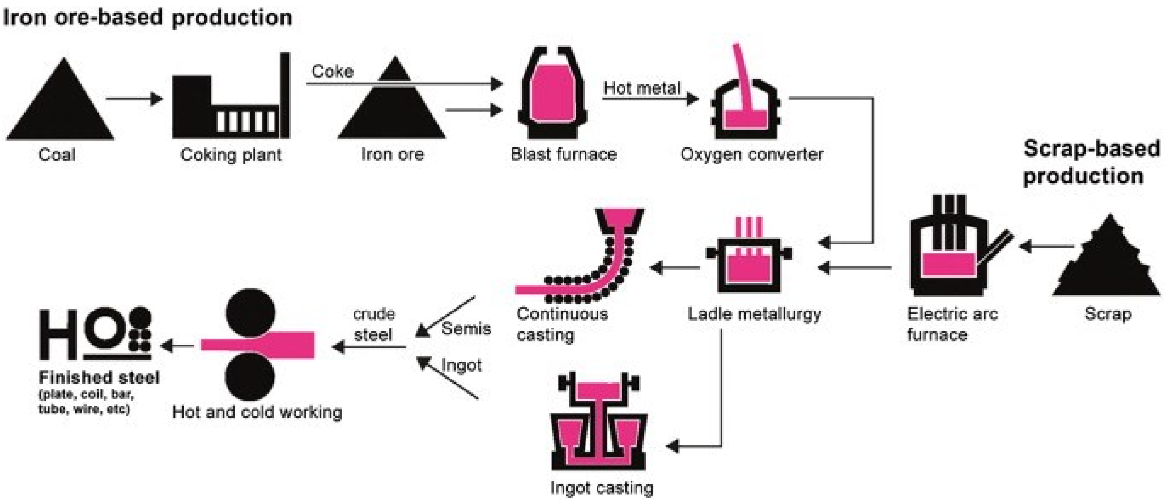


Figure 14. Schematic process of steelmaking from ores and scrap [9].

Recovering steel scrap from mixed waste streams is relatively easy because magnetic separation can be used to separate iron and steel [70]. Steel recycling processes of steel have different options which deal with different purity recyclates [70]. Main factor affecting the purity is the concentration of residual elements [70]. Generally, steel recyclate is mixed evenly from different sources to avoid these unwanted residual elements appearing in final products [71]. Steel can be recycled in original quality or downcycled into lower grade products if it is contaminated [70].

Different grades of steel can be blended in recycling and different steel grades can be produced from them depending on the current demand [71]. The composition of steel is measured after it is melted [72]. Molten iron is then added as a diluent if required to reach tolerable levels in residual elements for further processing [72]. Different alloy elements present in steel are not removed because they can reduce the need for additives [72]. Nearly all steelmaking methods use some amount of steel scrap [72].

It is notable that steel always contains some impurities, which however do not affect its mechanical properties significantly. Some of the impurities evaporate during conventional steelmaking processes due to extreme heat of the electric arc furnace, where the electric arc reaches temperatures of 4000-6000 °C. However, some impurities still dissolve to the steel products. No commercially feasible methods exists for the removal of all these unwanted residual elements because iron is not a noble metal. Current trend is that the purity of steel is constantly lowering as these residual elements gather over time to recycled steel. To combat this increasing loss in purity of steel, possible approaches which improve the quality of steel scrap include: product design for recycling, improvements in steel plant processing and shredder plant sorting, developing new steel alloys which take into account the inherent impurities, and diluting steel scrap with ore-based iron. Furthermore, understanding of steel flow in society is essential for recyclers in order to assess where the impurities come from. [9]

Four steel grades are used in the exterior components manufactured by Suunto, as listed before in Figure 12. These steel grades are 304L, 316, 316L, and 420, which are all common grades of steel. The *"Appendix* A*: Chemical compositions of metal grades"* contains detailed compositions of these different steel grades. The 300-series steels are stainless and austenitic, which is a very versatile type of steel because they can be formed and welded into many forms of products, and therefore they are the most common type of steels, accounting for 70 % of steel produced globally. 304L is a low carbon steel designed for severely corrosive conditions. 316 is an austenitic stainless steel which contains molybdenum to increase resistance against corrosion and chloride and to provide greater strength and 316L is a low-carbon variation of this 316 grade. The 420 steel belongs to a series of martensitic stainless steels, which typically have very high strength but less resistance to corrosion. All these steel grades can be recycled with standard recycling processes. [70]

4.2.1.6 Titanium

Titanium has the highest strength to density ratio of all metallic elements [73]. Different titanium alloys are mainly used in specialized applications such as critical parts in military, aerospace and marine industry and in high class consumer products such as bicycles and watches [73]. In such products it is important to have the desired mechanical properties such as proper strength and high corrosion resistance [73]. When compared to other metals, recycled titanium has very strict quality requirements regarding refining and homogenization [63]. Titanium scrap must be segregated based on chemical purity and sorted by physical form and all contaminations must be purified from the scrap, such as oils, grease and tool bits that may mix in with the scrap during machining [63]. In order to remove these undesirable inclusions and defects, pyrometallurgical processes such as electron beam or plasma cold-hearth furnaces are used [63].

While the recycling of titanium requires strict refining processes, the costs of these processes are substantially outweighed by the low cost of scrap material compared to the raw production of titanium. One advantage of recycling titanium alloys is that the scrap may already include the alloy components required for manufacturing. However, unwanted alloy elements can only be removed if their vapor pressure is significantly higher than the other elements in the alloy. Titanium scrap can also be used to produce other metal alloys in which the titanium additions greatly improve material properties, such as ferro-titanium or aluminum-titanium. The downside of this procedure is that the titanium is permanently lost from the titanium cycle. Therefore, only low quality scrap should be used for these alloying processes. Currently, an issue in titanium recycling is that its recycling methods have very restricted techniques for the removal of oxygen from titanium, which limits the amount of scrap available for products, which require low oxygen concentration. Another issue is that virtually all titanium remelting processes currently can melt only small amounts of titanium at a time, which increases processing costs. One exception is an induction skull melting process, which can be used to recycle titanium more quickly, however, it is very cost-intensive. [74]

Two grades of titanium are used in manufacturing: namely, “grade 2” and “grade 5”. The exact chemical compositions are presented in *“Appendix* A*: Chemical compositions of metal grades”*. Titanium grade 2 is unalloyed 99 % pure titanium. Titanium grade 5 contains 6 % aluminum and 4 % vanadium, and it provides inherent workability and processability combined with good mechanical properties. Due to this, the popularity of grade 5 has increased, and it has caused the grade 5 to become a widely applied material. The grade 5 dominates the titanium markets with its 45 % share. Its position as the standard alloy is reinforced even more due to proven manufacturing experience of many producers, which reduces the risk of defected products and makes the grade 5 a solid choice for many products. Therefore, titanium grade 5 is currently the standard to which other alloys are compared when selecting which titanium grade should be used. [73]

4.2.2 Polymers

Polymer is a substance composed of macromolecules. This definition includes plastics, as well as rubbers, and even animal proteins. Both natural and synthetic polymers are created by polymerization of monomers. Plastics can be subdivided into two categories, thermoplastics and thermosets, based on how they react when heated. Thermoplastics can be molded again when heated, while thermosets cannot be remolded. During the production of a thermoset plastic an irreversible reaction makes the solid state permanent. Heating a thermoset can make it burn, but not melt. Therefore, recycling thermoset plastics is inherently more difficult than recycling thermoplastics. [9]

Plastics should be recycled when the energy required to make new materials is higher than the amount of energy consumed in the recycling process [47]. Recycling options for plastics are mechanical recycling, feedstock recycling or chemical recycling [9]. If recycling is not feasible or sustainable, energy recovery is an option to avoid landfilling [9]. Furthermore, plastics usually have high calorific values, comparable to that of coal, which makes their usage in energy recovery feasible [47]. Mechanical recycling is the most commonly used to recycle plastics [9]. Mechanical recycling typically comprises the following process steps: sorting, shredding, washing and drying, and finally melting and reprocessing the plastic in to pellets or directly to products [9]. Feedstock recycling is an option for low purity mixed plastic waste and thermosets [9]. An example of feedstock recycling is using plastic waste as a reducing agent in iron and steel industry [9]. In this process, the plastics are converted via pyrolysis into syngas and used as a replacement to coke or mineral oils [9]. In chemical recycling the polymers are depolymerized to monomers, which are then polymerized again to virgin polymers [9]. However, chemical recycling is not widely used on commercial scale, due to its high costs, except for polyethylene terephthalate bottle and textile recycling, because it is currently the only recycling method to achieve the same quality as virgin polymer [9].

Separation of different plastic types is challenging, but it is a necessity in order to achieve high quality recycled material. Multiple different separation methods exist and they can be used for different plastics and plastic compositions. For example, sink-float separation can be used to roughly separate the plastics based on their specific weight. However, these sink-float separated plastics will require further processing to achieve a more complete separation based on the exact plastic type. Near-infrared sensor combined with an air jet is currently the preferred process to accurately separate polymers. This sensor distinguishes materials based on how they reflect light. An air jet then blows the recognized polymers apart from mixed waste. [9]

Society of the Plastics Industry developed a resin identification code system in 1988 to simplify the recycling of common plastics. The system is currently administered by ASTM International. Figure 15 presents these symbols. [75]

Figure 15. The ASTM International Resin Identification Coding (RIC) System [75].

1. Poly(ethylene terephthalate)
2. High-density polyethylene
3. Poly(vinyl chloride)
4. Low-density polyethylene
5. Polypropylene
6. Polystyrene
7. Other [75]

4.2.2.1 Acrylonitrile butadiene styrene (ABS)

Acrylonitrile butadiene styrene (ABS) is a thermoplastic polymer. ABS is a terpolymer, meaning it consists of three distinct monomers: acrylonitrile, butadiene and styrene. Concentration of these three monomers has to be balanced accordingly, as acrylonitrile provides polarity, butadiene provides elasticity and styrene provides glassiness to the alloy. Copolymerization is a process where multiple monomers unite together and form a polymer. The monomers can arrange in varying orders and form different structures to the polymers. ABS can be manufactured by such copolymerization process of acrylonitrile, styrene and polybutadiene, or by mechanically blending butadiene-acrylonitrile with styrene-acrylonitrile. [76]

A recommended recycling method for ABS is mechanical recycling in order to preserve the value of the material [77]. ABS can be recycled without any significant loss in quality, although changes in its color may occur [76]. The most common recycling processes are mechanical recycling by shredding and thermal recycling [76]. The latter process may cause the aforementioned yellowing of the ABS material [76]. Contamination by other plastics, especially polystyrene, decreases the quality of recycled ABS considerably [76]. Therefore, ABS waste should be handled carefully in order to avoid these unnecessary reductions in its value.

4.2.2.2 Glass-fiber reinforced polymers (GFRP)

Glass-fiber reinforced polymers or plastics (GFRP) denotes all polymers, which have been reinforced with glass fibers. Another commonly used name for GFRPs is fiberglass. The addition of glass fibers to polymers increases their strength. An important notion is that recycling glass fibers differs from recycling GFRP products. Only the recyclability of GFRP composites that contain glass fibers are examined in this thesis, since glass fiber as an individual material is not in the scope of this thesis. Examples of polymers, which are incorporated into GFRPs, include polyamide, polypropylene, and polycarbonate and its alloys.

Currently, glass-fiber reinforced plastics cannot be recycled without decreasing their value [78]. For example, incineration of GFRP waste leaves about 50-70 % of the material left as mineral ash, which then would have to be landfilled [78]. Multiple approaches to address these recyclability problems of GFRP have been proposed [79]. One approach is to reuse waste GFRPs in a cement kiln, in which the polymer is burnt for energy recovery, and the leftover inorganic material, which comprises glass and calcium carbonate, provides feedstock for the cement clinker [78]. However, this method decreases the value of GFRP significantly, since its functional value in such process, is that of calcium carbonate [78]. Currently, this method is commercially used in Germany [80]. Another approach is to grind the GFRP waste and multiple uses for grinded GFRP waste have been proposed and demonstrated [81]. However, the commercial usage options for this ground recyclate are still limited [81]. Commercially available products, which can partly use this ground GFRP, include concrete, roofing sheets, and molding compounds for car parts and similar products [81]. For example, a company in Belgium is manufacturing manhole covers from GFRP waste [81]. Another possibility to handle grinded GFRP waste is a pyrolysis process conducted under very high temperatures in an inert, oxygen-depleted, atmosphere [82]. This process degrades the polymers in GFRP to gas and oil, while leaving the glass fibers recoverable as solids [82]. Microwave pyrolysis has been proposed as an effective method to create oil, which was subsequently converted into syngas [82]. Furthermore, the glass fibers recovered after this pyrolysis process were determined to be usable reinforcing material in plastic composites, when mixed up to 25 % with virgin material [82]. Further work and research is required in many of these GFRP recycling applications before they are commercially efficient enough for widespread use. Thus, the local GFRP waste recycling possibilities should be explored in order to avoid landfilling of GFRP waste.

4.2.2.3 Nitrile butadiene rubber (NBR)

Nitrile butadiene rubber (NBR) or more precisely, acrylonitrile butadiene rubber, is also known as nitrile rubber. NBR has gained widespread use recently because it is non-allergenic, unlike natural rubber [83]. Numerous commercial recycling options for rubbers exist [84]. Rubbers can be grinded to powder, crumb or shred for downcycling purposes [84]. This rubber crumb is widely used in construction, for example in concrete, roofing, asphalt, and sports and recreational surfaces and thermoplastic rubbers can be produced from this powder [84]. Of current interest is the possibility of recycling rubber as same quality products, since virtually all current rubber recycling is downcycling or energy recovery [84]. Devulcanization of rubber transforms the products back to reactive polymers, which can be used to replace virgin polymers with comparable properties [84]. However, none of these current processes cannot fully reclaim rubber products back their original quality [84]. Several studies have examined blending recycled NBR with other rubbers. For example, blending NBR with styrene butadiene rubber, which is used in car tires [83]. These approaches may be a future direction for the recycling of NBR.

4.2.2.4 Polyamide (PA)

Polyamide (PA) is more commonly known as nylon, which is a group of synthetic polymers first introduced by DuPont in 1935 [85]. Polyamides are used in a wide range of products, such as films and textiles, and these products are generally fully recyclable as new textiles after use [9]. Recycled polyamides, which do not have sufficient quality for clothing, can be shredded and processed into other textile products, such as carpet underlays, blankets, sound deafening products, ropes, padding, stuffing, and yarns [9]. Solid PA products are commonly recycled by making granulates from the products [9]. It is also possible to chemically recycle polyamides back to monomers [76]. A recent study found that using recycled polyamide 12 (PA12) used in additive manufacturing, or 3D-printing, causes no significant difference to the quality of products compared to manufacturing from virgin PA12 [86]. Furthermore, glass fiber reinforced PA grades are used at Suunto to increase heat stability and UV resistance. Their recycling methods are examined in Chapter 4.2.2.2.

4.2.2.5 Polycarbonate (PC)

Polycarbonate (PC) is often used in products which require reliable performance over a long lifetime, due to its high durability and strength [77]. PC can also be reinforced with glass fibers to further increase its properties. Recycling methods for such products are examined in Chapter 4.2.2.2. PC can be fully recycled by all typical plastic recycling methods: mechanical recycling, feedstock recycling, or energy recovery [77]. Furthermore, chemical recycling methods for PC have recently developed significantly [87]. These methods depolymerize polymeric PC scrap back to monomers that are used in subsequent process to form new PC polymers [87]. These chemical methods can achieve 100 % monomer recovery [87]. However, chemical recycling is rarely used on a commercial scale [9], [87]. Because PC can be fully recycled, the most environmental recycling method for

PC may vary locally, as its eco-efficiency depends on the cost of logistics and the processes used in local recycling facilities [77].

One ingredient for polycarbonate synthesis is bisphenol-A (BPA) [88]. BPA was proposed to the REACH SVHC candidate list by France in 2016, which could lead to restricting its use in Europe in the future [89]. Although BPA release from polycarbonate products is extremely low, less than 5 parts per billion, consumers may avoid these products [90]. Figure 16 presents a hydrolysis process where polycarbonate is converted to bisphenol-A, and further to phenol in an aqueous medium [87].

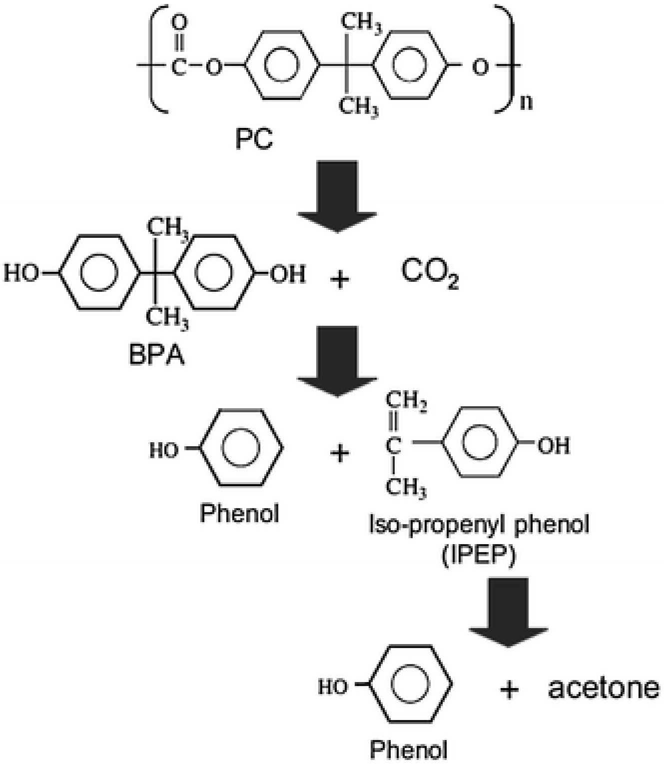


Figure 16. "Mechanism of polycarbonate (PC) hydrolysis for the synthesis of bisphenol-A or phenol" [87].

4.2.2.6 Polycarbonate - acrylonitrile butadiene styrene alloy (PC-ABS)

Polycarbonate is commonly alloyed with other plastics. PC alloyed with ABS is a thermoplastic alloy, in which the PC provides good mechanical properties and heat resistance, while ABS provides better processability and chemical stress resistance [91]. While plastic alloys often have superior properties, the downside is that their recyclability is decreased simultaneously, as the structure of polymers becomes more complex [9]. Glass fiber reinforced PC-ABS is also used at Suunto, and its recycling methods are examined in detail in Chapter 4.2.2.2. Recycled ABS tends to perform more poorly than recycled PC [92]. A study shows that up to 15 % of recycled PC-ABS of 99 % purity can be safely mixed with virgin materials without significantly affecting the mechanical properties of the alloy [92]. The same study proposes an optimized PC-ABS product which contains 40 % recycled PC, 10 % virgin PC and 50 % virgin ABS, which was seen as the best option to obtain first-rate mechanical properties, high recycle content and low cost [92]..

4.2.2.7 Poly(methyl methacrylate) (PMMA)

Acrylic is also known, and precisely noted, as poly(methyl methacrylate), and generally abbreviated as PMMA. It is a transparent thermoplastic polymer and therefore often used as a substitute for glass [77]. Current technologies allow PMMA recycling to reach 99 % purity, thus, recycled PMMA can be used with virgin materials [77]. However, functionality of PMMA may be lost during recycling, for example, the transparency in thin liquid crystal displays [93]. Therefore, highly functional PMMA products should be assessed to find possible reuse options, before recycling them [93]. Another option for high quality PMMA recycling is chemical recycling, which is presented in Figure 17. It presents a pyrolysis process for waste PMMA with four distinct phases: depolymerization, liquid recovery, purification of monomer and heat recovery from residue [93]. This process reaches 99.8 % purity, thus, making it usable in every application, even in optical devices when mixed with virgin polymers [93]. Therefore, chemical recycling may be the future direction of polymer recycling, however, it is not yet widely used on a large commercial scale due to high costs [93].

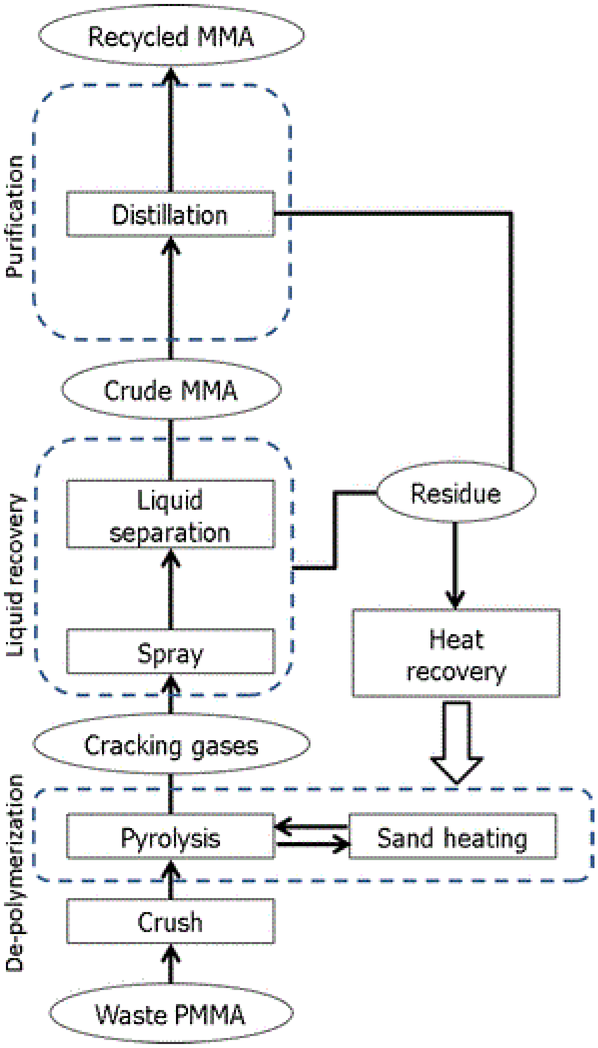


Figure 17. Chemical recycling of PMMA through pyrolysis [93].

4.2.2.8 Polyoxymethylene (POM)

Polyoxymethylene (POM) is a thermoplastic used in many engineering applications due to its excellent stability, high stiffness and low friction [94]. Other names for POM include acetal, polyacetal and polyformaldehyde [94]. POM can be recycled mechanically, however, it usually leads to some amount of degradation, and since POM is a specialized engineering polymer, it cannot be regarded as a viable option [94]. Other studies have also concluded that recycling of POM causes a slight degradation of the polymer [95]. Specifically, the mechanical properties of POM tend to decrease with each reprocessing cycle [95]. Suitability of recycled POM should therefore be evaluated based on the individual application [95]. Degradation of quality can be seen in the vividness of color and the surface quality: recycled polymers showed less reflectivity and a yellow tint [95]. However, blending of under 35 % recycled POM with virgin POM could still be considered as a product with acceptable properties according to the same study [95]. Furthermore, chemical recycling methods can produce virgin quality material [94].

4.2.2.9 Polypropylene (PP)

Polypropylene (PP) is a relatively inexpensive material, first introduced in the 1950s, and currently used mainly in packaging and more recently in laundry appliances to replace stainless steel [77]. Glass fibers are commonly incorporated in to PP to create GFRPs, which increase mechanical properties and heat resistance of PP [77]. Recycling methods of such products are examined in Chapter 4.2.2.2. PP can be fully recycled, and usually products such as battery cases, brushes, brooms or ice scrapers are made from recycled PP [77]. According to the resin identification code system, which was presented earlier, the designated number for PP recycling is 5, as seen before in Figure 15. However, recycling rate of PP is low, about 5 % [77]. This low recycling rate originates from the fact that PP is commonly used as a packaging material, typically disposed of in municipal waste facilities by incinerating or landfilling [77]. Furthermore, transporting end-of-life PP products to a recycler is currently not economically feasible as the cost of producing virgin PP is very low [77].

4.2.2.10 Polytetrafluoroethylene (PTFE)

Polytetrafluoroethylene (PTFE) is a fluoropolymer, which is commonly known by the trade name Teflon®. Fluoropolymers are typically regarded as inert materials, since their reactivity decreases as fluorine content increases [96]. PTFE has lowest reactivity of all fluoropolymers, it is therefore used in many demanding applications [96]. However, PTFE has severe limitations regarding high temperature, and the recommended maximum continuous service temperature is 260 °C, because PTFE begins to release mildly toxic substances when heated over 300 °C, and furthermore, a highly toxic perfluoroisobutylene is released at 475 °C [96]. Therefore, fluoropolymers should not be incinerated, unless the facility is equipped with hydrogen fluoride and hydrogen chloride scrubbers, which can remove these toxic combustion products [96].

Commercially large scale PTFE recycling is currently only practiced from scrap generated during the manufacturing processes of PTFE. In such cases, three factors may decrease its recyclability: other impurities in the scrap, degradation of resin during conversion, and oxidation. This PTFE acquired from scrap at the manufacturing site can be grinded to micropowder, known as fluoroadditive, which can be added to plastics, inks, oils, lubricants, and coatings to reduce their wear rate and friction. [96]

Recyclability research for PTFE is ongoing, because products manufactured from PTFE are not currently recyclable at their end-of-life stage [97]. Pyrolysis process has been proposed and demonstrated to be able to recover the tetrafluoroethylene monomer from PTFE scrap [98]. Currently fluoropolymers are commercially recycled only in Germany, where the world's first fluoropolymer recycling facility started operations in 2015 [99].

4.2.2.11 Silicone

Silicones, or polysiloxanes, are polymers which consist of repeating units of siloxanes [100]. Silicones have a broad range of applications and they are commonly formed as oil, rubber, grease, resin or caulk [100]. Typically, end-of-life silicones are thermally decomposed to generate silica (SiO_2) [100]. However, this is not ideal, since the functionality of the material is irretrievably lost [100]. A low temperature depolymerization process has been proposed for recycling silicones as new high quality polymers [100]. The process creates synthetic precursors from silicone waste [100]. These precursors can then be polymerized to new silicone polymers [100]. Figure 18 presents these chemical reactions of depolymerizing silicone, thus creating new polymers of similar quality [101]. However, creating cost-efficient chemical recycling techniques with current technology is still a challenge [101].

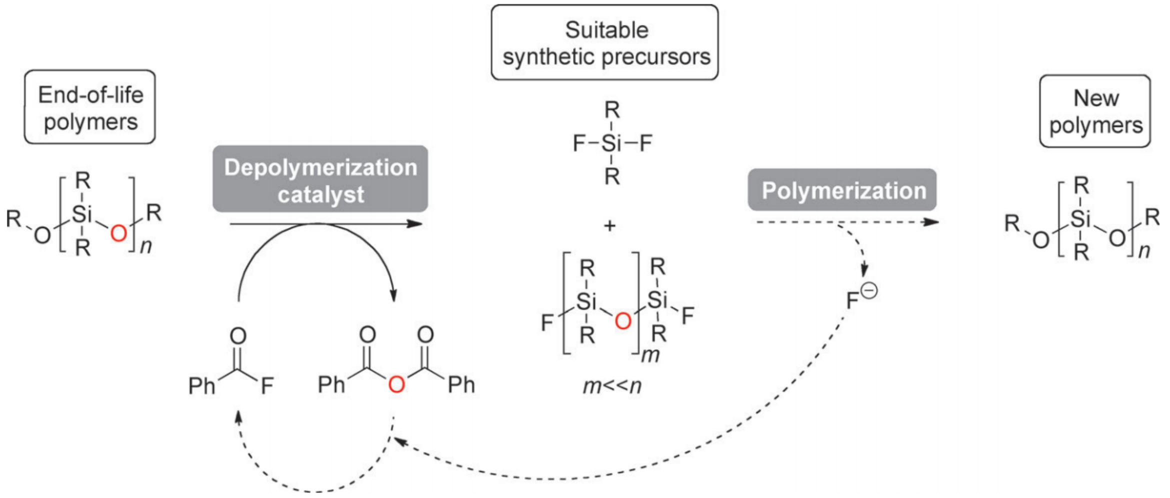


Figure 18. Depolymerization reaction scheme of silicones. [101]

4.2.2.12 Thermoplastic elastomers (TPE)

Thermoplastic elastomers (TPE) are polymers that have many similar properties as rubbers, such as flexibility, resilience and softness. Furthermore, all TPEs can be manufactured rapidly and they are inherently recyclable, unlike rubbers, which require slow vulcanizing manufacturing processes and are not functionally recyclable. These reasons cause the increased usage of TPEs throughout all industries, and they are currently used in many products, which used only rubber few decades ago, such as adhesives, footwear, wire insulation and polymer blending. However, TPEs cannot be used in as high temperatures as rubbers, which prevents their usage in certain applications, such as car tires. [77] The recyclability of TPE products cannot be generally assessed, because this plastic family comprises innumerable different types and blends of plastics. Therefore, the recyclability of the following two grades are examined closer.

Thermoplastic copolyester elastomers (TPC)

Thermoplastic copolyester elastomers (TPC) are polymers, which consist of alternating hard and soft blocks of polyester and polyether [102]. These TPC polymers are further divided to subgroups: TPC-ES, TPC-ET, and TPC-EE denoting whether the soft blocks consist of polyester, polyether or both, respectively [102]. However, TPCs are sold under many different trade names, and may contain some undisclosed additives, which are used to alter the properties of these plastics [77]. Therefore, the supplier of TPCs has to be consulted for recyclability data. Another possible approach is to treat these plastics as mixed plastic waste, which can be incinerated, or downcycled into low-cost products, for example, to produce floor tiles and plastic lumber [77].

Thermoplastic polyurethanes (TPU)

Thermoplastics polyurethanes (TPU) are a group of TPEs, which are created by polyaddition of diisocyanates and diols. TPUs can based on polyester, polyether or polycaprolactone, and further divided into aromatic or aliphatic TPUs. These polymers characteristically have alternating soft and hard blocks, which allow fine-tuning the polymer for desired applications. These blocks are formed from diisocyanates and alternating long or short chain diols or polyols or chain extenders. Virtually unlimited different possibilities can be formed by combining these blocks. Figure 19 presents the chemistry of forming thermoplastic polyurethanes. [103]

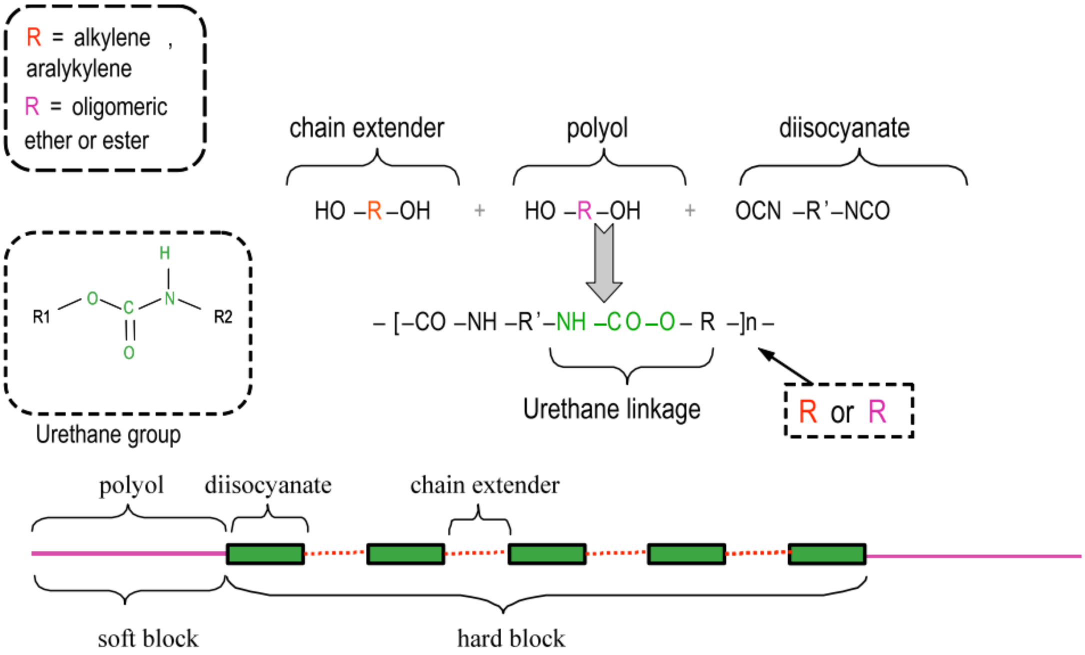


Figure 19. Chemical forming of thermoplastic polyurethane (TPU) [103].

Thermoplastic polyurethanes are generally recyclable by all recycling methods available for plastics: mechanical, chemical and feedstock recycling, or they can be used in energy recovery. TPU however deteriorates with each recycling cycle. Current solutions to this are either downcycling or blending the recyclate with virgin material. [104]

4.2.3 Other exterior materials

Other exterior component materials comprise carbon fibers and their composites, various mineral glasses and sapphire glass, and vegetable-tanned leather, which is used in straps. Their recycling methods and factors affecting their recyclability are examined in this subchapter.

4.2.3.1 Carbon fibers

The usage of carbon fibers (CF) and their composites, such as carbon fiber reinforced polymers (CFRP) has increased in product manufacturing across all industries during recent years, due to their excellent mechanical properties and light weight [105]. However, the infrastructure for recycling carbon fibers and the commercial recycling methods have not developed sufficiently quickly to address this increasing consumption [9]. Currently, over 90 % of carbon fiber products are landfilled at their end-of-life [105]. The reason for this low recycling rate of carbon fibers originates from the inherent difficulty in recycling composites [9]. Generally, such plastics composites have a complex structure comprising fillers, fibers and matrices, which may be further combined with other materials, such as metals or other composites, and furthermore, most composites cannot be remolded as they are thermosets [9]. For these reasons, the separation of different materials for recycling processes becomes difficult or even impossible [9]. This creates a driver for the development of novel recycling technologies, as untapped market potential lies in recycled carbon fiber (rCF) products [105]. Another driver for the development of novel recycling methods is that recycling laws will become stricter in the future [17]. Furthermore, producing recycled carbon fibers consumes only 10 % of the energy required to produce virgin carbon fibers [105].

Many recycling methods for carbon fibers have been developed in recent years, as aviation companies, such as Boeing have expressed interest in using recycled carbon fibers [105]. The first commercial CFRP recycling plant started operations in 2006 [105]. The current recycling processes for carbon fibers are classified either as mechanical or thermochemical, depending on the method of waste breakdown [9]. Figure 20 presents which type of carbon fibers are usable in these recycling processes, and to which products the rCF and the recycled carbon fiber reinforced polymers (rCFRP) are suitable [9]. Although these various recycling routes for carbon fibers exist, the only process used on a large commercial scale is pyrolysis, which can be seen on the right side of Figure 20 [9]. Pyrolysis is a thermochemical process in which heated organic molecules decompose thermally in an inert atmosphere [9]. During this process, the matrix of carbon fiber reinforced polymer volatilizes, while the carbon fibers themselves remain inert and can be recovered [9]. Furthermore, these volatilized matrices provide enough energy to keep the pyrolysis process self-sustainable [9]. However, recycled fibers from this pyrolysis process tend to be fluffy and aligned at random angles relative to each other, which decreases their strength in a composite [9]. Thus, these fibers need to be realigned with other processes, such as creating yarns and slivers, or by using a centrifuge, before reimpregnating them in to a new composite [9]. The highest demand in the industry is for straight fibers, but technology for efficiently producing such fibers through these recycling processes is still under research [9]. Perfectly aligned recycled fibers would have the same quality as virgin carbon fibers [9].

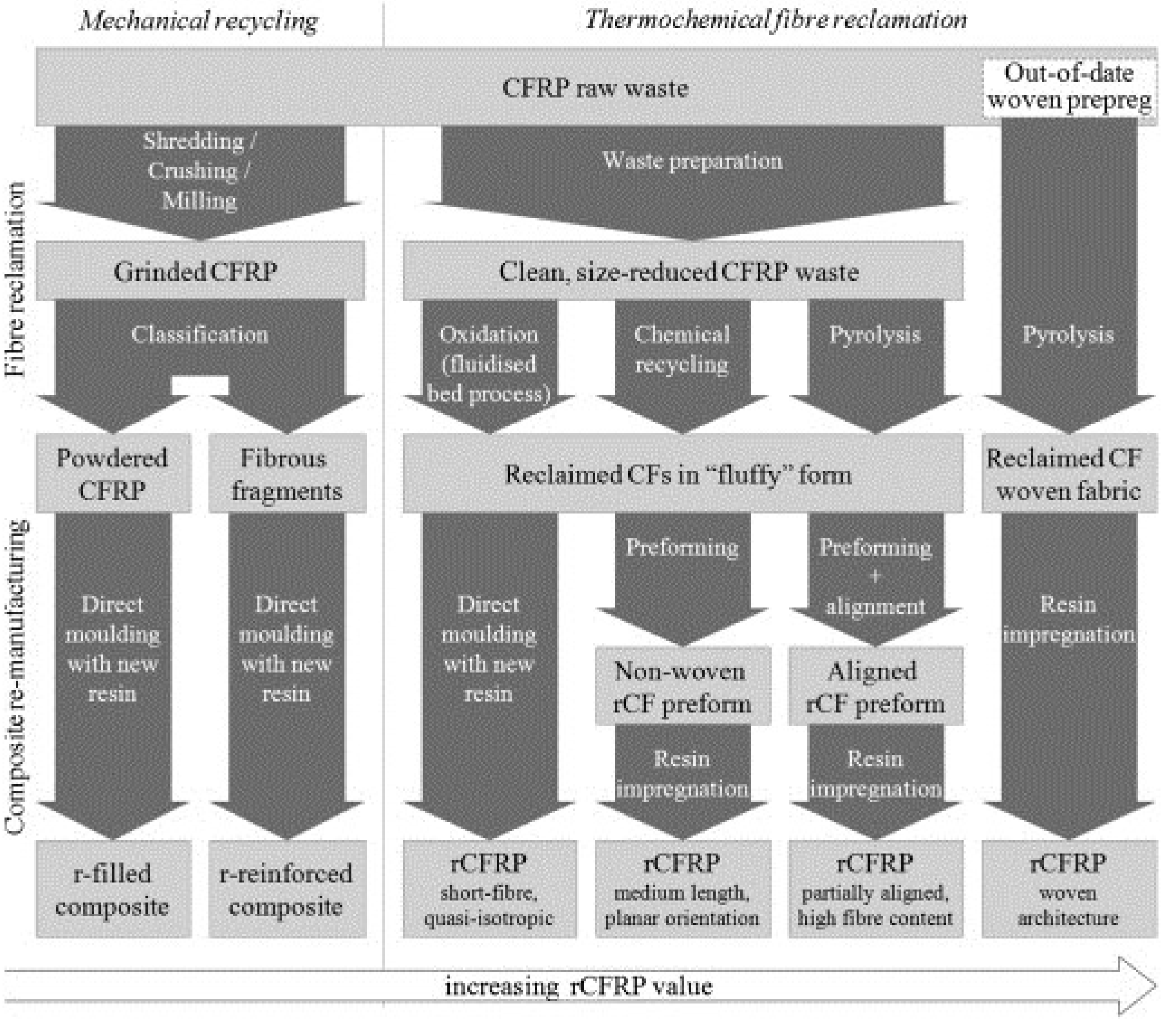


Figure 20. Overview of processes of recycled carbon fiber reinforced polymers (rCFRP) and remanufacturing processes [9].

Although many of these recycling processes work on a small scale, recycling carbon fibers on a commercial scale introduces additional issues, which often result in defected or damaged fibers. These problems arise from the fragile nature of carbon fibers. The two major problems currently are continuous processing and low quality scrap. Commercial feasibility of recycling plants requires continuous processing of incoming waste, instead of batch operations. However, as the throughput time is decreased in a continuous process, the risks of degraded fibers increases simultaneously. The other issue is that commercial recycling is conducted with scrap of unknown quality, and efficient reclamation of fibers requires extensive amounts of information in order to optimize the process. A close cooperation with scrap producers and recyclers assists in retaining the highest value possible from scrap, which further decreases the cost of recycled carbon fibers for producers. Thus, the ongoing research for new recycling methods of carbon fibers is much needed, as there clearly is a market demand for such technology. [9]

4.2.3.2 Glass

Glass is typically collected and sorted by color and reprocessed by crushing and smelting it. The crushed glass is called cullet, which is then melted in a glassmaking furnace. This process can be repeated indefinitely without losing any of the material’s properties. Contamination can be removed with hand sorting, eddy current sorting, magnetic sorting, sieving or vacuum sorting. However, due to the usually arbitrary handling of scrapped glass, high purity glass cullet cannot usually be guaranteed. For example, when accurate optical properties are desired for a high quality product. Glass can be downcycled into other products in such cases. Recycled glass is used in a large number of different applications, such as glass wool insulation, foamed glass, glass ceramics, abrasive materials, bituminous pavements, concrete compounds, water filters, or in reflective clothing and markings if grinded to small spheres measuring 1-60 µm. These applications typically utilize recycled glass ranging from 2-80 % depending on the requirements of the final product. [9]

It is notable that glass is an inert waste. It does not decompose in the environment because it is insoluble and chemically unreactive under normal conditions. No benefit is gained if glass is present in a waste-to-energy incineration process. The most significant environmental benefit of glass recycling is the reduction of energy demand and pollution compared to extracting and processing raw materials from the environment. Nevertheless, glass can already be manufactured and recycled sustainably. However, the economic viability of glass collection varies between countries, which creates the current main issue in glass recycling: ensuring the proper collection of glass and returning all recovered glass to glassmaking. Consequently, many countries have implemented legislation with financial incentives that drive the collection of glass containers. [9]

Mineral glass

Tempered mineral glasses are used as screens in virtually all modern consumer electronics, because they can withstand significantly more impacts and scratching than regular glasses. Mineral glasses are typically trademarked by the manufacturing companies and their compositions are kept as trade secrets. However, these mineral glasses typically are alkali-aluminosilicate glasses, because their properties are especially suitable for touch screens. These glasses are further toughened by an ion-exchange process, during which bigger alkali ions replace smaller ones on the surface, thus creating high compressive strength on the surface. [106]

Lithium aluminosilicate is a type of glass-ceramic. Glass-ceramics are created from glass by heat treatment, which creates a crystalline phase to the material. This process, called controlled crystallization, creates desired properties for the material, such as extremely low, near-zero, thermal coefficient. Glass-ceramics have very high melting points and therefore disrupt the standard glass recycling processes if mixed with standard glass waste. [107] Currently, glass-ceramics can only be downcycled via crushing and using in ceramic tiles or as abrasive media [9]. The most commonly used mineral glasses in consumer electronics is recyclable by standard glass recycling programs. However, by the definitions used in this thesis, this kind of recycling is classified as nonfunctional recycling or downcycling, since the functionality of these specialty glasses is lost during the standard glass recycling processes, because they do not return to the supply chain as a similar quality product, but end up in various other glass products.

Sapphire glass

Sapphire is a crystalline form of aluminum oxide (Al_2O_3) mineral, also known as corundum. However, the name corundum generally refers only to nontransparent or coarse gems [108]. Sapphires can be of any color, or colorless, depending on their impurities. Red sapphires are called rubies. Sapphire is extremely hard: second only to diamond on the classic Mohs scale of mineral hardness [109]. It is also more expensive to manufacture than mineral glasses, especially if made for touch screen applications. Therefore, it is seen only in high quality consumer products. Sapphire crystals can be created artificially by hydrothermal synthesis [110], which is a process in which aluminum oxide seed is grown to a single crystal [111], which is subsequently cut to wafers [112].

Recycling methods for sapphire have been developed. Residue sapphire can be reused during the production of sapphire as powdered material [113]. Other sapphire scrap can also be recycled in a similar fashion, if cleaned before crushing to powder [114]. Furthermore, corundum waste has been demonstrated to increase resistance to abrasive wear when used as a filler matrix in polymeric composite materials [115]. Fine-grained corundum in itself can also be used as abrasive material [108]. Due to the extreme hardness of sapphire, it can arguably also be reused in products of similar size if the product is designed in such way that the sapphire can be disassembled intact.

4.2.3.3 Leather

Leather has been used by humans a protective material since ancient times, and tanner as a profession was mentioned in early literature of mankind. Leather is still a desired material, although plastic, silicone, metal and other straps have become increasingly common in watches. Leather making process from raw skin or hide removed from an animal has three main stages: preparation, tanning and crusting. The preparation stage includes many different processes, which remove unwanted components, such as hairs and fats. This intermediate product before tanning is called pelt. Tanning is regarded as the most important step in leather making because it stabilizes the leather’s chemistry and structure permanently to a non-degrading state. After tanning the leather is colored and treated to achieve desired properties for the final product. Modern tanning processes generally utilize either chrome or different vegetables as a source of tannins. Typically, only tropical and subtropical plants provide sufficient amounts of tannins to enable feasible commercial use. Most common plants which are used to produce vegetable tannins are mimosa, quebracho, chestnut and tara. However, chrome tanning currently dominates leather production: it is used in about 85 % of leather products. The popularity of chrome tanning is caused by inexpensive and fast leather manufacturing, as well as consistent coloring options and resistance to boiling water. [116]

However, chrome tanning is currently losing popularity because of environmental issues: toxic and carcinogenic hexavalent chromium may form during the chrome tanning process, although chromium(III) is the only required complex in the chrome tanning process [116]. Another reason is that free-of-chrome (FOC) tanned leathers can be downcycled or incinerated without releasing any hazardous materials to the environment [116]. Although FOC leather products and FOC leather waste produced during manufacturing are recyclable, these vegetable-tanned leathers are not the end-all solution for environmental issues of leather production. Commercial vegetable tanning agents contain 15-70 % of vegetable extract, and 20 % or more non-tannins, such as gums, sugars, mineral salts, organic acids and other insoluble matter [117]. These contained non-tannins mostly remain in the solution and causes the waste water to be harmful to the environment when released, due to high chemical oxygen demand and low biodegradability [117].

Leather waste can be recycled as fertilizers, leather boards or biogas [116]. Furthermore, multiple studies propose using leather waste or recycled leather in polymer composite materials [118]. These composite materials can be manufactured by gluing dried, shredded and sieved leather scrap with resins with the help of catalyzers and then molding the final composite product with an extrusion process [119].

4.3 Coatings and additives

Recycling becomes increasingly difficult as the complexity of a product increases, as more process steps are required to separate the increasing amount of different interconnected materials from a product. Furthermore, separation of all material linkages in a product may require excessive amounts of energy, or may even be impossible in some cases with current technology. Such material linkages in a product decrease the recyclability of all interconnected materials, or in extreme cases make the whole product unrecyclable. This difficulty in separating different materials efficiently stems from the immense amount of different products in a typical recycling waste stream. For example, during a typical WEEE recycling chain, products are mechanically crushed and further separated based on material properties, for example by magnetic separation, to acquire different recycling fractions. In the optimal situation, these acquired recycling fractions would comprise only materials consisting of a single compound. However, current recycling technologies rarely reach such result, because individually inspecting every single component in a recycling stream would arguably require more energy than is gained from the recycling of these components. Thus, some of these separated materials may still have a coating on them, or contain additives, both of which may affect the material properties, and therefore decrease their value and recyclability. However, some coatings are removed during standard recycling operations. Typical examples of this are pyrometallurgical recycling processes, in which most coatings evaporate due to extreme heat. Furthermore, as coatings usually are extremely thin, and therefore contribute only insignificant amounts of added materials to the recycling chain, their effect on recyclability of products may be negligible. [9]

The goal of this subchapter is to assess whether coatings and additives affect the possible recycling options of the materials, which were presented at the start of this chapter, in Figure 12. A considerable obstacle in assessing the recyclability of used coatings is that coating manufacturers want to keep the recipes of their coatings as trade secrets. This same problem applies to additives used in plastics. However, this problem could be solved from another direction, for example, by consulting the supplier of such materials, and presenting them a list of unsuitable materials.

Coatings that are difficult to remove are preferred in virtually all industries. The factor that controls the difficulty of removal, is the adhesion between the coating and the substrate material, on top of which the coating rests. The possibility of removing a coating depends on the amount of force required to penetrate, push and remove the coating and the geometry of the substrate and the completeness of the coating process itself. Roughness of the substrate material increases adhesion, since a rougher surface has more surface area for the coating to adhere to. However, it simultaneously increases the risk of failure to penetrate all crevices on the surface, which leads to voids, and therefore, less contact area for the coating. Furthermore, purity of the substrate is a decisive factor, since any excess particles on the substrate decrease the chances of successful adhesion on the surface. Many coatings presented in this subchapter are classified as thin films, which indicates coatings that have a thickness ranging from few nanometers to few micrometers. A variety of processes have been developed to apply such thin films onto products, such as deposition, spraying, and dipping. The shape of the product usually determines the most convenient application method. [77]

Removal processes exist for many coatings, since they are used to test and correct coatings [120]. The process of removing coating may be called decoating or stripping [121]. Multiple methods exist for the removal processes, such as abrasion or using solvents [122]. Furthermore, coatings can be tested with numerous equipment, for example scratch tests or accelerated weathering devices, which expose the coatings to UV radiation, heightened temperatures and water sprays [120]. However, if the base material is not inherently suitable for some specific conditions, a thin coating may not fully protect it in all cases [120]. Coating processes on plastics or metals do not differ significantly, although plastics usually require more preparation, such as drying before the coating process [77]. Coatings from metals can be removed with heat, since metals generally withstand extreme heat, while the coating on the surface may evaporate long before reaching the melting temperatures of metals [9]. However, one of the criteria for selecting a recycling process for steels is the presence of coatings, according to the European Steel Scrap Association specifications [9]. Some coating removal methods for metals are: selective evaporation under a specific temperature, to evaporate a specific coating component, vacuum treatment to capture zinc coating from steel, and treatment of steel with sulfur containing gas to remove tin [9].

4.3.1 Physical vapor deposition

Physical vapor deposition (PVD) signifies different processes, which produce thin films onto a substrate with physical processes. Four main categories of PVD processes are sputter deposition, vacuum deposition, arc vapor deposition and ion plating. These PVD processes can transport atoms and molecules within a vacuum, low pressure inert gas, or plasma. The main limitation of most PVD techniques is the line-of-sight requirement between the source and the target. Figure 21 presents a sputtering PVD process. It is a process in which ionized atoms collide onto a target surface to eject target atoms. The sputtering target is the source material, from which the thin film coating is formed on top of a substrate. Furthermore, sputter deposition denotes the process in which these ejected atoms then condense as a thin film onto this substrate. These processes are common methods of applying thin films, since they can be used for any material. [123]

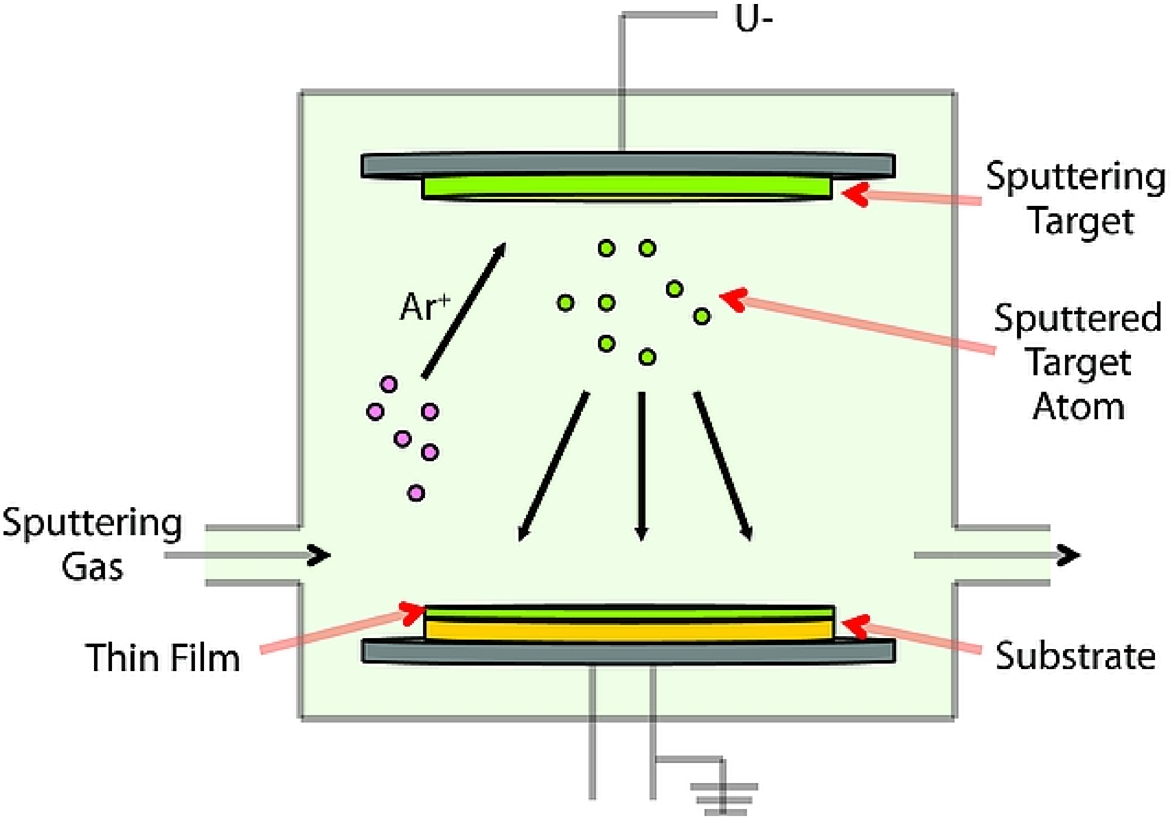


Figure 21. Sputter deposition, which is one of the physical vapor deposition (PVD) processes [124].

These methods can also be conducted in a vacuum, if an extremely low level of contamination is required for a product. Other PVD methods include arc vapor deposition and ion plating, which are used to deposit hard coatings, such as metals on to a substrate. Furthermore, it is possible to form multilayer coatings with consecutive PVD treatments. [123]

4.3.2 Ceramic coatings

Ceramic coatings are used to modify some of the material's properties, such as increased resistance to abrasion, scratching and temperature, imperviousness to gases and liquids, and being more chemically inert, without using solid ceramic products [120]. Furthermore, ceramic coatings do not wear off in normal use due to their extreme durability [120]. Ceramic coating materials include titanium carbides and nitrides [125]. Although ceramic coatings are rather expensive when compared to, for example, polymeric or organic coatings, these multiple benefits over the less expensive coatings justify their usage [120]. The method of application for a ceramic coating depends on the product on to which the coating is placed, but typically the ceramic coating is a powder, which is dispersed into a slip and applied with wet processes, for which the most common application methods are dipping and spraying [120]. In addition, ceramic coatings can be deposited with a plasma PVD process [126]. Ceramic coatings can be removed, for example, with sand blasting [121]. The typical reasons for removal are: remanufacturing components, reconditioning existing products or correcting quality problems with the ceramic coating [121].

4.3.3 Electroplating

Electroplating is a process, in which a metal or a conducting material is coated with another metal. It is done as with an electrodeposition method, in which the metal to be coated acts as a cathode while the source metal for plating acts as an anode and the current used provides electrons, which moves the process forward. This process has to be conducted in aqueous solution, in order to enable the freely moving ions to form an even surface on the cathode. Figure 22 presents an example of an electroplating process, in which iron is plated with nickel. Electroplating is usually done to achieve increased aesthetic, protection or special surface or mechanical properties. These coating processes provide properties such as increased corrosion resistance, conductivity, reflectivity or hardness, without the need to manufacture the whole product from the coating metal, thus, decreasing manufacturing costs. [127]

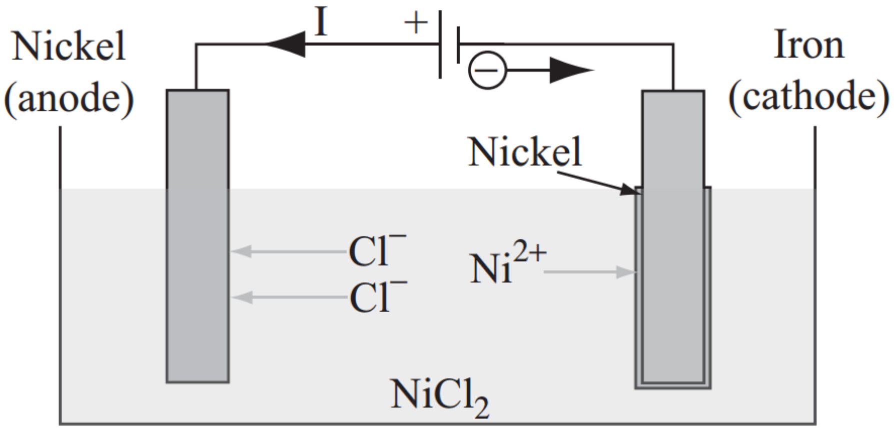


Figure 22. Electroplating nickel on iron [127].

The impact of metal plating on recyclability varies greatly between metals [9]. For example, coatings on aluminum may hinder their recyclability, while nickel plating does not affect the recyclability of steel products, as it is a part of certain steel alloys [9]. Many processes for removing steel coatings exists as mentioned before [9]. Coating removal processes are normally used during metals recycling if it is economically feasible to do so [9].

4.3.4 Functional coatings

Functional coatings signify coatings which have additional purposes apart from being decorative or protective. Functional coatings examined here have either anti-fingerprint, anti-reflective or anti-dust properties.

Anti-fingerprint (AFP) coatings are hydrophobic and oleophobic, thus, they repel water and oil. They are typically based on (per)fluoroalkyl-modified silanes, which exhibit high contact angels with water and oil. AFP coatings are used in glasses, electronic display screens and other consumer products to increase aesthetic appearance. AFP coatings can be applied on top of PVD or other coatings. AFP coatings can be applied with multiple methods, such as conventional spray, dip coating and chemical vapor deposition. Anti-fingerprint coating applied with a conventional spray is regarded as the watch industry standard, due to easy application. The spray coating is post-processed in a heated oven to increase durability. However, AFP coatings typically wear off during use due to rubbing. Therefore, they do not have an impact on the recyclability of products. [128]

Anti-reflective (AR) properties are required in nearly all optical glass products. Anti-reflectivity is achieved by changing refractive index of the materials, and thus causing destructive interference which eliminates reflections seen from the surface. AR coating can be applied, for example, by the aforementioned deposition processes. Typically, the material used in these AR coatings is magnesium fluoride, because of its suitable refractive index and transparency from ultraviolet up to infrared wavelengths. A possible method to achieve AR properties, is by applying a single-layer AR coating, in which the destructive interference of light occurs between the coated substrate and the air-coating interface. AR properties can also be achieved by increasing the porosity or roughness of another coating or the base material, since light then scatters to multiple directions. Since AR coatings are used in nearly all optical glasses, they cannot be assumed to have a significant impact on the recyclability. [129]

Silicone products require an anti-dust coating, otherwise they would become stained with particles floating in the air very quickly. Anti-dust coating is not a complex process, as anti-dust properties are achieved by spraying silica (SiO_2), which is basically sand [130]. However, silica is classified carcinogenic because microscopic dust is formed during this manufacturing process from a spray gun, and therefore the use of dust respiration filter is required during manufacturing. [131]. However, products with anti-dust coating are safe for consumers [130].

4.3.5 Colors

Some special colors are used in products for aesthetic purposes. Strontium aluminate is used in products to achieve glow-in-the-dark properties. It is a chemically and biologically inert material [132]. However, strontium aluminate needs to be activated with a suitable dopant to allow photoluminescent phosphorescence behavior [132]. Strontium aluminate waste can be used as a synthetic slag in steelmaking [133]. Laser marking pigments can be used in plastics when a product is too complex to print on with traditional methods

[134]. A colored marking is achieved with a polymer that contains two colorants with different sensitivities to laser light [134]. However, this method is not applicable to all polymers. Multicolored markings are not possible with current technology [134]. These and other colors are typically used in many consumer electronics, however their origin may not be always known. Therefore, one possible suggestion to have a list of allowed or restricted substances when ordering inks, pigments or paints from a supplier to ensure the environmental safety and recyclability of these products.

4.3.6 Masterbatches

Masterbatches (MB) provide colors or other additives with properties, such as UV resistance to plastics. MBs are concentrated mixtures of solid or liquid pigments or additives in a carrier resin. They are diluted with virgin polymer to add the desired qualities to the final polymer product. Masterbatches are used because they decrease production costs and allow producers to avoid weighing small quantities of additives. Figure 23 presents masterbatch color pellets. [135]

Figure 23. Masterbatch color pellets [136].

The carrier material in masterbatches must be compatible with the polymer of the product to avoid negative effects on mechanical and thermal properties [135]. The masterbatch can be the same polymer or a well-tolerated substance with a low melting point [135]. Some plastic additives may hinder recycling efficiency [9]. When additives are used in large amounts, it becomes difficult or even impossible to guarantee the purity of the recycled material [9]. Plastics which are difficult to recycle are recommended to be downcycled to construction materials or incinerated as refuse-derived fuel [9]. The impact of MB additives on recycling therefore must be consulted from the supplier. If the supplied polymer does not contain any lower quality polymer as a carrier or additives that degrade the quality of the product, it may be assumed that it will not affect recycling options.

5 Evaluating recyclability for Suunto

During the last decades, sustainability of global economic trends has gained a great deal of attention from consumers and politicians alike [1]. In order to keep the planet and its resources sustainable for future generations, manufacturing companies are increasingly required to produce recyclable products [17]. Suunto wants to stay competitive in this market situation, where recyclability of products can be expected to be increasingly important when consumers select their products. Therefore, it is of importance to assess the recyclability of Suunto's products. In order to evaluate the recyclability of Suunto's products, an evaluation protocol for assessing the recyclability of the exterior components' materials used by Suunto is developed in this chapter. During this procedure, every exterior material used by Suunto is given a rating which indicates the material's recyclability. Compiling these ratings allows to evaluate the recyclability of complete products.

This chapter presents which criteria from the literature review were selected for Suunto, within the scope of this thesis. Then, the database for material recyclability ratings is described and presented. Based on that, the developed evaluation protocol is defined, and finally a procedure for testing the protocol for a product is demonstrated.

5.1 Selected criteria for material assessment

Assessing whether materials are usable for creation of a specific product is an important step in the product design process. This step becomes necessary in order to ensure the recyclability when designing products for recycling [9]. The assessment conducted in this thesis uses a set of criteria, which acts as a checklist type of tool, in order to exclude unusable materials. The set of criteria for material assessment was produced based on the conducted literature review in this thesis. Chapter 2 provided the underlying framework for this assessment and also examined legislation related to these subjects, while Chapter 3 examined general criteria related to feasibility of recycling processes of products. The following criteria and sub-criteria were selected to assess exterior materials in this thesis:

1. Material cannot be hazardous.
    1.1. Compliant with the current European Union's Restriction of Hazardous Substances (RoHS) directive and its amendments.
    1.2. Compliant with the European Union's Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation.
    1.3. Not on the current REACH candidate list of substances of very high concern.
    1.4. No toxics are emitted during recycling processes.
2. Material has some reuse value at the product's end-of-life.
    2.1. Prefer components which can be reused.
    2.2. Prefer materials which do not deteriorate during recycling.
    2.3. Prefer functional recycling over nonfunctional recycling.
    2.4. Prefer plastics with high calorific value.
    2.5. Do not use materials which are landfilled at end-of-life.
3. Material does not cause any unnecessary environmental damage.
    3.1. Prefer materials with low environmental impact at their end-of-life stage.
    3.2. Ensure that the amount of material collected for recycling is high enough to outweigh the environmental impact of treatment and logistics.
    3.3. Ensure that downcycling a material causes less environmental damage than the manufacturing of materials which the downcycled material substitutes.

All currently used materials at Suunto already comply with the not hazardous criteria. These materials can be further assessed with the second and third criteria and their sub-criteria. Furthermore, future materials may be assessed with all these criteria.

5.1.1 Restricted substances lists used by the company

Due to the increased trend among companies to take more responsibility in environmental issues, many companies have begun to use and publicly release restricted substances lists (RSL) to promote their environmental awareness. Such list can be viewed as an additional list of criteria for the aforementioned materials assessment. Suunto is a brand of Amer Sports, which announced its RSL in 2013 [137]: "To ensure product compliance, Amer Sports developed its Restricted Substances List (RSL) policies, which were implemented throughout to the supply chain in 2013. Amer Sports Apparel and Footwear category further developed its Materials Compliance Program and extended it to the Group's core Tier 2 suppliers, so that fabrics and trims are proactively screened against emerging priority substances […] a solution for more sustainable textile production." [137] It is notable that this list is currently category-based, meaning that the RSL does not apply to all products, but instead the product category determines which materials are usable in a specific product.

These RSL's usually comprise globally recognized hazardous substances which have adverse effects on human health or the environment. However, a material supplier's commitment to circular economy could be increased if the recyclability of materials was included in such list as a criterion. The EU's REACH regulation together with the WEEE and RoHS directives, and national waste laws, typically already address the issues of hazardous substances. However, such substances may not be restricted in all countries yet, and such issues can be addressed by an environmentally aware company in their RSL.

5.2 Evaluation protocol database

An essential part of developing an evaluation protocol is a clearly defined database, to which the results are based, which furthermore allows all users to see what data affects the results. This subchapter acts as the database for the developed evaluation protocol. The recyclability rating is first defined and then the result for each material is presented. These recyclability ratings for materials are the core part in the development of the evaluation protocol, which compiled produce an overall rating for the recyclability of a single product. Reusable materials, however, need an individual assessment, to decide whether they are reused as such, reused after a repairing process, or recycled with commercial recycling processes. Furthermore, the impact of coatings and additives is assessed in this subchapter.

5.2.1 Definition of the recyclability rating

The recyclability rating indicates the current viable end-of-life option of a material. This rating is based on the current commercially available recycling methods and therefore should not be regarded as a constant value. The recyclability rating of a material should be changed if new recycling methods become prevalent for any given material. For example, when new technological breakthroughs occur and new recycling facilities, which recycle previously unrecyclable materials, are set up widely. Furthermore, reasons not related to recycling processes may change the rating, such as legislation concerning end-of-life products. Dividing materials to six different categories based on their end-of-life outcome was selected for this study. The six proposed recyclability ratings, and the reasoning why a material receives a specific rating are presented in Table 3. These ratings and justifications were determined based on the literature review presented in Chapter 3 and Chapter 4. Although the ratings are presented in a hierarchical order, the environmental benefit between energy recovery and downcycling may be in reverse order, especially in plastics recycling, depending on the impact of logistics and substituted materials. A rating from zero to five (0-5), with five being the most environmentally friendly, is given to all exterior materials. These recyclability ratings depend on which of the following end-of-life outcomes the material currently has. However, whether reusable materials are actually reused or recycled is not defined by this thesis, but rather, by the company’s decision.

Table 3. Recyclability rating definitions.

#	Recyclability rating	Justification for a material to receive this rating
0	Landfill	Material cannot be reused, recycled, or incinerated by any means, and therefore, the only option is landfilling.
1	Energy recovery	Material cannot be recycled as new products, however, it is possible and beneficial to the environment to incinerate the material, to recover the embodied energy in the material as heat and electricity.
2	Downcycle (non-functional recycling)	Material cannot be used to manufacture similar quality products, however, the material can be downcycled and used in manufacturing of products of lower quality, functionality or value.
3	Recycle (functional recycling)	Material can be used to manufacture similar quality products after recycling. The quality, value and functionality of the material remains intact.
4	Reuse after a process	Material can be reused after processing, such as repairing or polishing.
5	Reuse as such	Material can be reused as such without the need for extensive processing.

These recyclability ratings were further used together with the criteria presented in Chapter 5.1 in order to create the flow sheet presented in Figure 24. This flow sheet displays the evaluation procedure a material undergoes to determine its recyclability rating. The flow sheet is read by starting from the yellow area at the top, and then working towards the recyclability rating stage by answering the questions regarding the material recyclability.

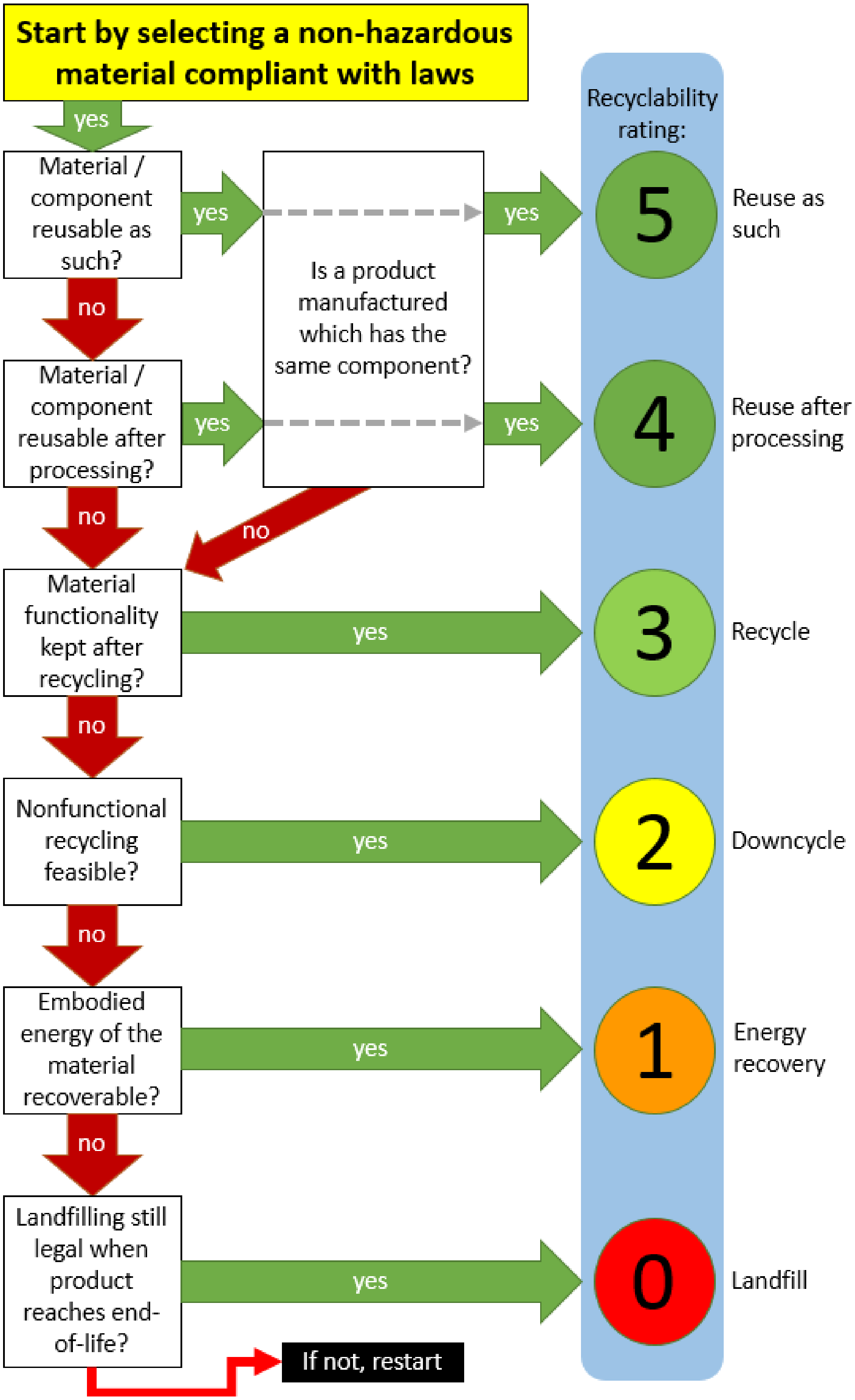


Figure 24. Material assessment flow sheet with criteria and recyclability ratings.

5.2.2 Recyclability ratings for exterior materials

The exterior materials which were examined in the literature review in Chapter 4, and presented in Figure 12, are gathered here, together with their recyclability rating, which indicates their current commercially available end-of-life option. The recyclability rating was given according to the definitions in Table 3. However, it should be kept in mind that the recyclability ratings can change in the future, when new recycling technologies are introduced and become commercially available.

Metals are generally straightforward to recycle because of their inherent properties which allow a high recycling rate, and the globally established metals recycling infrastructure [9]. Based on the data acquired from the literature review, all metals and metal grades used by Suunto in the exterior components can be recycled. Table 4 presents the recyclability ratings for metals and different metal grades. Furthermore, certain metal parts, such as bezels, may be reusable, depending on product design at Suunto. Generally, the functionality of unalloyed metals remain intact during recycling processes [9]. Alloyed metals should be recycled to produce similar alloys or used in smaller amounts to fine-tune the composition of other alloys [9].

Table 4. Recyclability ratings for metals

Metal	Do different grades used by Suunto affect the recycling options?	Rating	Recyclability
Aluminum	No	3	Recyclable
Brass	No	3	Recyclable
Copper	No	3	Recyclable
Gold	Not applicable	3	Recyclable
Silver	Not applicable	3	Recyclable
Steel	No	3	Recyclable
Titanium	No	3	Recyclable

Generally, polymers cannot be fully recycled as same quality products. However, certain recycled polymers can be blended with virgin polymers up to a certain percentage without affecting the quality significantly. Plastics which can be blended with virgin material are classified as recyclable in this thesis, if no other restraints are present. Furthermore, polymers generally have high energy content, which may cause recovery of the embodied energy from polymers by incineration to be more beneficial to the environment than downcycling to low quality polymers. Table 5 presents the recyclability ratings for all the examined polymers and important comments when applicable.

Polytetrafluoroethylene requires extra attention, as toxic fumes are emitted during incineration of PTFE products and handling of these toxic fumes requires properly equipped incineration facilities [97]. Therefore, it may be preferable to landfill PTFE products, because the fluorine compounds released from incinerated PTFE may deteriorate the incineration equipment [97]. Furthermore, recycling of PTFE end-of-life products is not commercially available on a large scale [97], although the world’s first PTFE recycling plant started operations in 2015 in Germany [99]. Therefore, PTFE recycling options should be closely monitored, as they are likely to change in the future.

Table 5. Recyclability ratings for polymers

Polymer	Rating	Recyclability	Comments
Acrylonitrile butadiene styrene (ABS)	3	Recyclable	Yellowing of material may occur during recycling [76]
Glass-fiber reinforced polymers (GFRP)	2	Downcyclable	Recycling under research [79], [82]
Nitrile butadiene rubber (NBR)	2	Downcyclable	Recycling under research [84], [83]
Polyamide (PA)	3	Recyclable	Multiple recycling methods exist [9], [76], [86]
Polycarbonate (PC)	3	Recyclable	Multiple recycling methods available [77], [87]
PC-ABS alloy	3	Recyclable	Blending with virgin polymer possible, up to 15 % [92]
Poly(methyl methacrylate) (PMMA)	3	Recyclable	Multiple methods exists [77], [93]
Polyoxymethylene (POM)	3	Recyclable	Blending with virgin polymer possible, up to 35% [94], [95]
Polypropylene (PP)	3	Recyclable	Resin identification code 5 [77] ♷
Polytetrafluoroethylene (PTFE)	1	Energy recovery	Incineration releases toxics, requires proper facilities [96], [97]
Silicone	2	Downcyclable	No commercially available recycling methods [101]
Thermoplastic copolyester elastomers (TPC)	1	Energy recovery	Unlikely to be recyclable in current applications [77]
Thermoplastic polyurethane (TPU)	2	Downcyclable	Low quality recycling possible [104]

The remaining exterior materials comprise carbon fibers, leathers and various glasses. Table 6 presents the recyclability ratings for the remaining exterior materials, which include all materials apart from metals and polymers. Sapphire glass receives a high rating because it can arguably be reused as such in same size watches, provided no visible scratches are present. Sapphire can be visibly scratched only by materials which are higher on the Mohs scale of mineral hardness, such as diamond [109].

Table 6. Recyclability ratings for other exterior materials

Material	Rating	Recyclability	Comments
Carbon fibers and their composites	2	Downcyclable	Recycling under research [9], [105]
Mineral glasses	2	Downcyclable	Functionality of specialty glass is typically lost during recycling processes [9]
Sapphire glass	5	Reusable as such	Downcyclable, if not reused [113], [114], [115], [108]
Leather (vegetable-tanned)	2	Downcyclable	Products with different functionality can be made [116], [118], [119]

The tables presented in this subchapter act as a material database for the recyclability evaluation tool which is presented later in this thesis.

5.2.3 Impact of coatings and additives on recyclability

Coatings are typically used for decorative purposes in Suunto, although certain coatings improve material durability when handling, transporting or using the products. The selected coating must nevertheless withstand all typical chemicals that the products are exposed during normal usage of Suunto products, such as seawater, ultraviolet radiation, mosquito repellents, and hand creams. Certain coatings may wear off during normal use, but the inherent corrosion resistance of a product must not be affected if a coating is removed.

The manufacturers of coatings reluctantly release exact information regarding the substances used in their products. The exact compositions are held as trade secrets to reduce the risk of competition by another companies which would produce the same product. However, Suunto could present a list of unsuitable materials to the suppliers, which allows Suunto to select coatings with recyclability as criteria. Another possible factor which may decrease the recyclability of plastics is plastic masterbatches, which contain additives. A product with masterbatch plastic is considered recyclable by standard methods if the masterbatch does not contain any lower quality polymer as carrier or any other additives, which would degrade the material quality. In order to ensure this, the recyclability of masterbatch plastics can be further consulted from the supplier. The conclusion from the literature review and from the data which was available to Suunto, is that the coatings used by Suunto do not have a significant impact on the recyclability of products, and therefore are not included in the evaluation protocol.

5.3 Description of the evaluation protocol

The development of the evaluation protocol to assess product recyclability based on exterior components' material data is presented in this subchapter. To evaluate a product, the weight of all exterior materials with the same recyclability rating in a product is combined and the percentage of product's weight for each corresponding rating is then presented. All internal components are assumed to be miscellaneous WEEE, from which valuable metals are recovered by a recycler. This evaluation protocol, including the equations presented in this chapter, are implemented into Microsoft Excel 2013 spreadsheet in order to create a tool, which assesses the recyclability of products with the current material selection, as presented in Figure 12 in Chapter 4. Input for the tool comes from Suunto's products bill of materials, which includes the required component weight data for the calculations presented in this subchapter.

The total weight of materials with the same recyclability rating is calculated with the equation (16).

$$W_n = w_{na} + w_{nb} + \cdots w_{nm} = \sum_{i=1}^{m} w_{ni}$$

(16)

Where:

$n = \{0,1,2,3,4,5\}$

$w =$ weight of component

$a, b, \dots m =$ different materials with same EOL option used in a product

$W_0 =$ total weight of **landfilled** materials in a product

$W_1 =$ total weight of materials in a product used in **energy recovery**

$W_2 =$ total weight of **downcycled** materials in a product

$W_3 =$ total weight of **recycled** materials in a product

$W_4 =$ total weight of materials in a product **reused** after processing

$W_5 =$ total weight of materials in a product **reused** as such

The percentage of a product's weight corresponding with each recyclability rating is calculated with the equation (17).

$$R_n = \frac{W_n}{total\ weight\ of\ the\ product} \times 100\ \%$$

(17)

Where:

$n = \{0,1,2,3,4,5\}$

$R_0 =$ percentage of product's weight sent to **landfill**

$R_1 =$ percentage of product's weight used in **energy recovery**

$R_2 =$ percentage of product's weight **downcycled**

$R_3 =$ percentage of product's weight **recycled**

$R_4 =$ percentage of product's weight **reused** after processing

$R_5 =$ percentage of product's weight **reused** as such

The percentage of internal components, classified as miscellaneous WEEE, or other electronics scrap, in the product is calculated with the equation (18).

$$Miscellaneous\ WEEE = \frac{total\ weight\ of\ all\ internal\ components}{total\ weight\ of\ the\ product} \times 100\ \% \tag{18}$$

5.4 Testing the evaluation protocol

The developed evaluation protocol is tested in a practical case to demonstrate its functions and test its reliability against real world data. The evaluation protocol is tested for a sports instrument, hereby referred to as “Product A” due to confidentiality. This test also requires exact weights of individual components and materials, which cannot be publicly disclosed, and therefore, only the general categories of materials are displayed in Table 7. The test is conducted with an implementation of the evaluation protocol into a Microsoft Excel 2013 spreadsheet. This implemented evaluation protocol is hereinafter referred to as the tool. Input for the tool is the composition and weight of used exterior materials, which are presented in Table 7. In addition, the total weight of “Product A” is 110 grams. After inserting the data from Table 7 into the tool, the tested product receives an overview of its total recyclability as an output from the tool. The exterior components weights are distributed between the six different end-of-life options accordingly, and the weight of the internal components is predetermined to the miscellaneous WEEE category. The results of this test are discussed in detail and presented in Figure 25 in the next chapter.

Table 7. Exterior component data of Product A

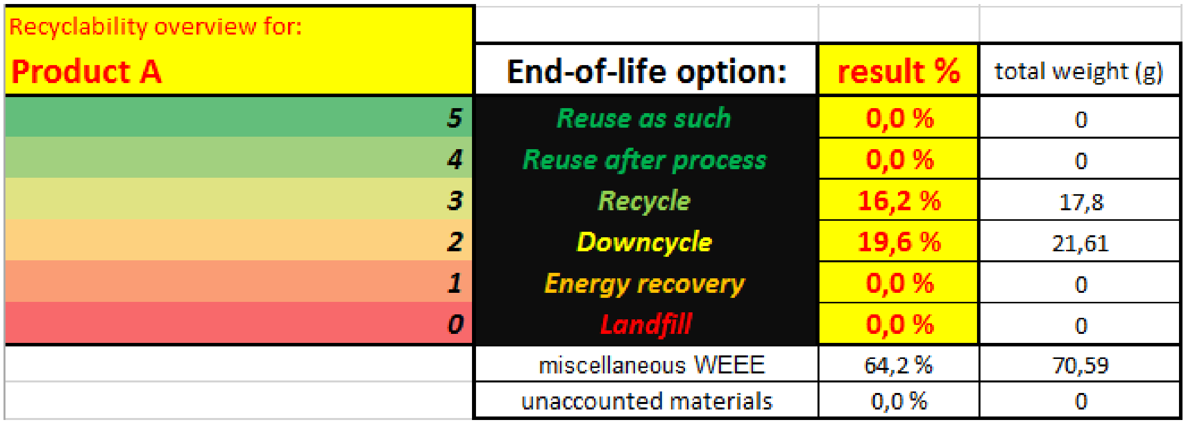
Exterior component	Quantity	Material	Recyclability	Rating	Weight (g)
Component A	1	Polymer A	Downcycle	2	3
Component B	1	Polymer B	Downcycle	2	1
Component C	1	Polymer C	Downcycle	2	5
Component D	1	Steel	Recycle	3	1
Component E	1	Steel	Recycle	3	0.2
Component F	1	Steel	Recycle	3	0.1
Component G	1	Glass fiber reinforced polymer	Downcycle	2	8.5
Component H	3	Steel	Recycle	3	0.1
Component I	3	Steel	Recycle	3	0.1
Component J	3	Steel	Recycle	3	0.1
Component K	3	Steel	Recycle	3	0.1
Component L	3	Steel	Recycle	3	0.1
Component M	3	Polymer D	Downcycle	2	0.01
Component N	1	Steel	Recycle	3	10
Component O	1	Polymer E	Downcycle	2	0.1
Component P	1	Polymer F	Recycle	3	6
Component Q	1	Mineral glass	Downcycle	2	4

6 Results and discussion

This chapter presents and discusses the results produced by the evaluation tool created for Suunto in this thesis. The goal of this thesis was to create a recyclability evaluation tool for Suunto based on the data available in literature. In order to develop this tool, the recyclability of exterior component materials used at Suunto's product manufacturing was studied from literature. These materials were presented before in Figure 12 in Chapter 4. Furthermore, related legislation, economic and environmental aspects were examined in order to generate a set of criteria for material assessment based on the information available in literature. The following data were presented in the previous chapter:

- A set of criteria was proposed for material assessment at Suunto. It was presented in chapter 5.1. These criteria consist of legal, economic and environmental factors, which should be taken into account when selecting materials for manufacturing.
- Six specific end-of-life options were proposed in order to categorize every material examined in Chapter 4 by giving them a specific recyclability rating. The justification why a specific recyclability rating is given to a material was presented in Table 3 in Chapter 5.2.1 and the recyclability ratings received by materials were presented in Chapter 5.2.2.
- An evaluation protocol, which calculates a recyclability overview for a product based on the recyclability ratings of materials and weights of the components in the product was described in Chapter 5.3.
- This protocol was implemented into Microsoft Excel 2013 in order to create an evaluation tool for Suunto.
- The component data presented in Table 7 in Chapter 5.4 was used to test this tool for a product manufactured at Suunto.

The evaluation tool output is presented in Figure 25 as a screenshot from the spreadsheet. The tested "Product A" contained only recyclable or downcyclable exterior components. The spreadsheet calculated the total weight of all products' exterior materials for each end-of-life option, and presented these results as a weight percentage of the product. All internal components were assigned to the miscellaneous WEEE category for the recovery of valuable metals. However, it must be noted that the whole product falls under WEEE category under the EU’s legislation, and the result does not indicate that the external and internal parts would be differentiated in any way by the legal requirements for their handling.



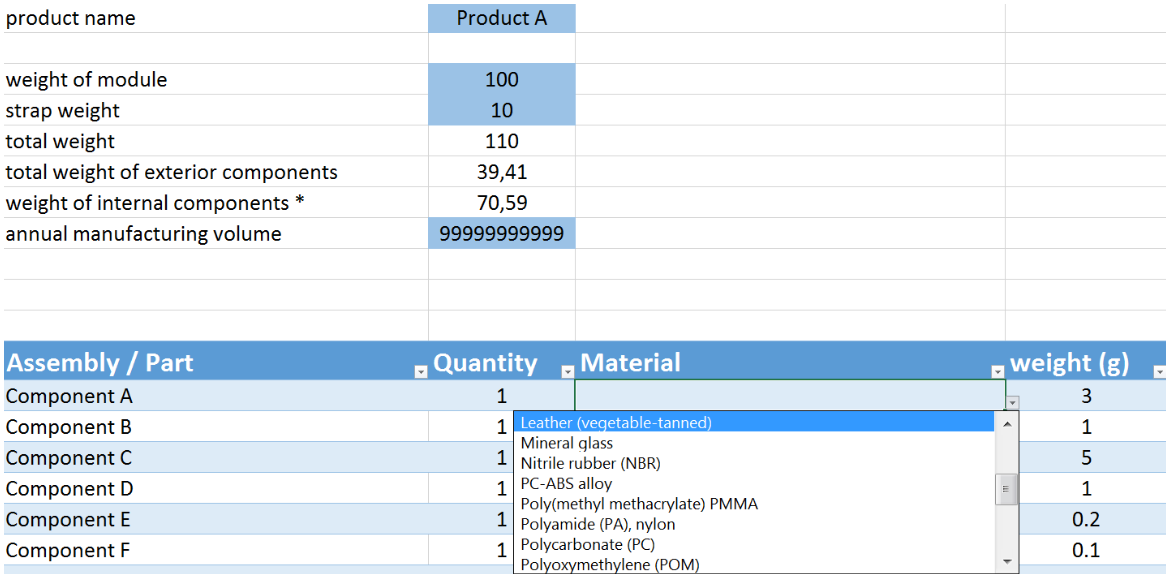
Recyclability overview for: **Product A**	**End-of-life option:**	**result %**	total weight (g)
5	*Reuse as such*	0,0 %	0
4	*Reuse after process*	0,0 %	0
3	*Recycle*	16,2 %	17,8
2	*Downcycle*	19,6 %	21,61
1	*Energy recovery*	0,0 %	0
0	*Landfill*	0,0 %	0
	miscellaneous WEEE	64,2 %	70,59
	unaccounted materials	0,0 %	0

Figure 25. Recyclability overview for Product A. (WEEE = waste electrical and electronic equipment)

The evaluation tool can be used, for example, by a designer to evaluate the impact of material choices to the recyclability of a new product. The spreadsheet contains individual sheets for:

1. Material recyclability ratings
2. Product and component data
3. Product overview
4. Annual production volume

Based on the data inserted into the first and second sheet, the “product overview” sheet calculated the result, which was presented in Figure 25. The “material recyclability ratings” sheet contains all the materials examined in this thesis and their recyclability ratings. New materials can be added to this list, if their recyclability rating is determined from literature by similar fashion as in this thesis. The tool then automatically adds these newly added materials to the list of possible materials selectable for products in the “product and component data” sheet, which is presented in Figure 26. It contains information about the product and all components used in the product. These data were gathered from a bill of materials of the tested Suunto product. The material of each component can also be changed from a drop down menu, as presented in Figure 26. This menu is automatically generated from the material recyclability ratings sheet. This allows the user of this tool to easily test how different material choices affect the recyclability of the whole product.



product name	Product A
weight of module	100
strap weight	10
total weight	110
total weight of exterior components	39,41
weight of internal components *	70,59
annual manufacturing volume	99999999999

Assembly / Part	Quantity	Material	weight (g)
Component A	1		3
Component B	1		1
Component C	1		5
Component D	1		1
Component E	1		0.2
Component F	1		0.1

Figure 26. The product and components data sheet of the evaluation tool.

The “product overview” sheet also displays the total weight of all individual materials used in the product and the recyclability ratings of these materials. This feature indicates which materials should be changed when a higher recyclability rating for the whole product is wanted. If the annual manufacturing volume is inserted, then the “annual production volume” sheet multiplies the weights of used materials by the annual production volume of that product. This sheet is used in order to assess the total amount of used materials, which have left the factory, and whether their collection for recycling could be feasible. The tool also contains detailed instructions so that any user can grasp how to use it. The main application for the current tool is to use it during the design phase of a new product.

The product overview sheet, which was presented in Figure 25, indicated that most of the weight in the tested “Product A” consisted of internal components, which were classified as other electronic scrap, or miscellaneous WEEE. Furthermore, the exterior components’ materials comprised only recyclable or downcyclable materials. From this test, it can be suggested that the usage of these downcyclable exterior materials can be re-evaluated in future products. The goal is to replace these downcyclable materials with materials that are fully recyclable without compromising the required mechanical properties of the product. Nevertheless, the current case of “Product A” can be already regarded as good, since materials, which cannot be recycled in any way were not used, and no part of the product should end up in landfill. However, because the evaluation tool is currently only a simplified method to evaluate the product recyclability, this result acts only as a suggestion on where to direct the focus, instead of a comprehensive decision-making tool. Future work is required to further develop this tool, and certain limitations to the usage of this tool must be understood before acting on its suggestions. These limitations are discussed in detail in the next chapter.

7 Conclusions

This thesis examined the recycling and reusage options of the materials used by Suunto in their products. This work was done in order to prepare for resource scarcity in the future. The preliminary goal of the thesis was to create a set of criteria, which can be used to evaluate the recyclability of exterior component materials used by Suunto in their products. The final goal was to develop a protocol, which can be used to approximate the recyclability of products. This protocol was based on the aforementioned criteria, and recyclability data of materials, which was acquired from the literature review.

Based on the literature review, a set of criteria to evaluate the recyclability of exterior materials was created. These criteria were developed into an evaluation protocol and tested on a wearable sports instrument product. The test was conducted by implementing the protocol into Microsoft Excel 2013 spreadsheet. Input for this spreadsheet was component data of the product, which was acquired from Suunto. As a result, a recyclability overview for this product was achieved. This product evaluation tool spreadsheet compiled data from all exterior materials present in a product, and calculated a recyclability overview for the tested product. This overview displayed the amount of materials in the product, separated for each EOL option as a percentage of total weight of the product. The selected EOL options were landfilling, energy recovery, downcycling, recycling, reuse after processing and reuse as such. Furthermore, a list of all exterior materials and their specific EOL options was created to act as a database for the spreadsheet.

The result indicated that most of the weight in the tested “Product A” was internal components, which were classified as miscellaneous electronic scrap. The exterior components’ materials comprised only recyclable or downcyclable materials. From this acquired result, it can be suggested that the usage of these downcyclable exterior materials can be re-evaluated, although the “Product A” already is a fairly sustainable product, as no landfillable materials or materials requiring incineration were used. However, certain limitations regarding this result must be understood. The limitations are presented next, and after that, more recommendations and possible future work is proposed.

7.1 Limitations

The evaluation protocol developed in this thesis is limited by factors which affect the recyclability of materials, but were out of the scope of this thesis. As presented in the literature review conducted in Chapter 3, such factors are: separation of materials from one another [9], thermodynamics of recycling processes [9], cost of logistics [9], [54], product disassembly costs [9], [44], [52], [53], [54], [55], refurbishing, repairing and remanufacturing of products [9], [54] and technologies of local recycling facilities [9].

This thesis proposed simple recyclability ratings for materials, based solely on their current end-of-life option. However, the reader, and the user of the evaluation tool, must be aware that a typical recycling chain includes multiple complex processes. Depending on the design of the product, a single component may not be easily disassembled, or a single material may be impossible to separate from the other materials in the product [9]. Therefore, it may not be feasible or even possible to recycle a single component or material, although the material in itself has received a rating which indicates possibility for recycling. Furthermore, as examined in Chapter 3.1, recycling is governed by complex thermodynamics [9], the presented recyclability rating may not be achieved for all components. Furthermore, location of recycling facilities, the available recycling technologies in them, and the cost of logistics were not included to the scope of this thesis. For example, PTFE is currently commercially recycled only in a single plant in Germany, which started operations in 2015 [99]. It may not be feasible to send the materials there, which causes other options, such as downcycling or incineration, to be more feasible in Finland.

Disassembling products may require excessive amounts of time and labor. If the value of disassembled products is low, the time and effort used for disassembling may negate the economic gains of reselling or reusing disassembled products and components. For example, a recyclability study by Remery et al. [54], which was examined in Chapter 3.3, suggested that manually disassembling a vehicle engine is about as feasible as landfilling it. In such cases, mechanical shredding of products may be used. Longer term solution for this is to design products for easier disassembly. Furthermore, refurbishment and repair of products were not included in the scope of this thesis. As presented in Chapter 3.1, such operations decrease the environmental impact of products more than recycling [9], and therefore could affect the assessment produced by the protocol hereby developed.

7.2 Recommendations

The material database and the evaluation tool in its current state can be used to assess the recyclability of exterior components, which have been disassembled from a product. The tool can be further utilized during the design phase of a new product, specifically when selecting materials for the designed product, as it gives an overview of product’s recyclability. However, as explained in the previous subchapter, the tool has limiting factors, and therefore, does not produce a comprehensive recyclability evaluation. This increases the possibility of risks and false assessments made by the evaluation protocol. Therefore, additional research mainly on the disassemblability of products and the feasibility of recycling is proposed before making decisions to change materials used in products.

The spreadsheet file can also be used to compile data from all products manufactured in a factory in to a single spreadsheet, in order to assess environmental impact of all used materials. Furthermore, such data may be multiplied by annual production volumes to assess yearly outcome of the production plant. These operations allow to assess the feasibility of recycling over a longer term. This feature can also be utilized during the design phase of a product, with an estimate of annual production volume. However, such operations are proposed only as a preliminary method in assessing feasibility, due to the limitations presented earlier. The proposed criteria for material assessment in this thesis are similar to what other research has suggested [46], and therefore, its reliability is arguably better than that of the developed evaluation protocol. However, the evaluation protocol can be further developed to include additional factors, which would improve its reliability. Such methods for improvement are proposed next.

7.3 Future work

This thesis focused on evaluating the recyclability of exterior materials used by Suunto in their product manufacturing. However, since Suunto products contain electronics as internal parts among other components, a more comprehensive approach is required to thoroughly assess the recyclability of products. The evaluation protocol can be further developed to include the aspects presented earlier as its current limitations. Therefore, the possible directions for future work are:

- Assessing the possibilities of separation of materials from one another creates increased reliability, because all materials in a product may affect the recyclability of other materials to which they are connected [9]. Such an assessment could also be incorporated into the product design phase [9], [54].
- Cost of logistics may be the determining factor as to whether the recycling of a certain material is feasible [9], [54]. Therefore, these costs should be taken into account.
- Product disassembly costs create a significant impact on the feasibility of recycling, and were included in similar studies [9], [44], [52], [53], [54]. Therefore, these costs should be examined more closely before deciding on disassembling. Furthermore, the disassembly sequence could be optimized with an evaluation tool [55].
- Effect of refurbishing, repairing and remanufacturing of products [9], [54]. All these are more environmentally friendly options than recycling, therefore potentially affecting the results produced in this thesis.
- As new recycling technologies are constantly under research, the material database presented in this thesis may become outdated if new recycling methods are introduced to the markets. Regular updates are therefore recommended.
- Including a more comprehensive assessment of coatings and additives, which may affect recycling options of materials and products [9], [77].
- Evaluating the internal components recyclability [9].

Incorporation of any or all these aspects increases the reliability of the evaluation protocol, since it would then comprise a more comprehensive view of total life cycle impacts of materials and products. Furthermore, life cycle assessments may be conducted for products to acquire relevant data [5]. Suunto could benefit from continuing this kind of research, because comprehensively assessing the life cycles of products with these type of tools allows benchmark manufacturing, labor, and logistical costs, which generally leads to decreases in their expenses [5]. Furthermore, in its current simple form, the database acts as a list of materials which can be re-evaluated regularly in the case of new recycling methods being developed or updated with new materials that are considered for the manufacturing of sports instruments at Suunto.

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Appendices

A. Chemical compositions of metal grades

Table 8. The chemical composition of aluminum 6061-T6 [57]

Element	Weight
Aluminum, Al	95.8 - 98.6 %
Chromium, Cr	0.04 - 0.35 %
Copper, Cu	0.15 - 0.40 %
Iron, Fe	≤ 0.70 %
Magnesium, Mg	0.80 - 1.2 %
Manganese, Mn	≤ 0.15 %
Other, each	≤ 0.05 %
Other, total	≤ 0.15 %
Silicon, Si	0.40 - 0.80 %
Titanium, Ti	≤ 0.15 %
Zinc, Zn	≤ 0.25 %

Table 9. The chemical composition of aluminum 6063-T6 [57]

Element	Weight
Aluminum, Al	≤ 97.5 %
Chromium, Cr	≤ 0.10 %
Copper, Cu	≤ 0.10 %
Iron, Fe	≤ 0.35 %
Magnesium, Mg	0.45 - 0.90 %
Manganese, Mn	≤ 0.10 %
Other, each	≤ 0.05 %
Other, total	≤ 0.15 %
Silicon, Si	0.20 - 0.60 %
Titanium, Ti	≤ 0.10 %
Zinc, Zn	≤ 0.10 %

Table 10. The chemical composition of low carbon stainless steel grade 304L [138]

Element	Weight
Carbon, C	≤ 0.030 %
Chromium, Cr	18 - 20 %
Iron, Fe	65.045 - 74 %
Manganese, Mn	≤ 2.0 %
Nickel, Ni	8.0 - 12 %
Nitrogen, N	≤ 0.10 %
Phosphorous, P	≤ 0.045 %
Silicon, Si	≤ 0.75 %
Sulfur, S	≤ 0.030 %

Table 11. The chemical composition of stainless steel grade 316 [138]

Element	Weight
Carbon, C	≤ 0.080 %
Chromium, Cr	16 - 18 %
Iron, Fe	61.995 - 72 %
Manganese, Mn	≤ 2.0 %
Molybdenum, Mo	2.0 - 3.0 %
Nickel, Ni	10 - 14 %
Nitrogen, N	≤ 0.010 %
Phosphorous, P	≤ 0.045 %
Silicon, Si	≤ 0.75 %
Sulfur, S	≤ 0.030 %

Table 12. The chemical composition of low carbon stainless steel grade 316L [138]

Element	Weight
Carbon, C	≤ 0.030 %
Chromium, Cr	16 - 18 %
Iron, Fe	61.9 - 72 %
Manganese, Mn	≤ 2.0 %
Molybdenum, Mo	2.0 - 3.0 %
Nickel, Ni	10 - 14 %
Phosphorous, P	≤ 0.045 %
Silicon, Si	≤ 1.0 %
Sulfur, S	≤ 0.030 %

Table 13. The chemical composition of steel grade 420 [138]

Element	Weight
Carbon, C	0.38 %
Chromium, Cr	13.60 %
Iron, Fe	84.30 %
Manganese, Mn	0.50 %
Silicon, Si	0.90 %
Vanadium, V	0.30 %

Table 14. The chemical composition of titanium grade 2 [139]

Element	Weight
Carbon, C	≤ 0.10 %
Hydrogen, H	≤ 0.015 %
Iron, Fe	≤ 0.30 %
Nitrogen, N	≤ 0.030 %
Other, total	≤ 0.30 %
Oxygen, O	≤ 0.25 %
Titanium, Ti	≥ 98.885 %

Table 15. The chemical composition of titanium grade 5 [139]

Element	Weight
Aluminum, Al	5.5 - 6.75 %
Carbon, C	≤ 0.080 %
Hydrogen, H	≤ 0.015 %
Iron, Fe	≤ 0.40 %
Nitrogen, N	≤ 0.030 %
Other, each	≤ 0.050 %
Other, total	≤ 0.30 %
Oxygen, O	≤ 0.20 %
Titanium, Ti	87.725 - 91 %
Vanadium, V	3.5 - 4.5 %

B. Categories of the EU RoHS and WEEE directives

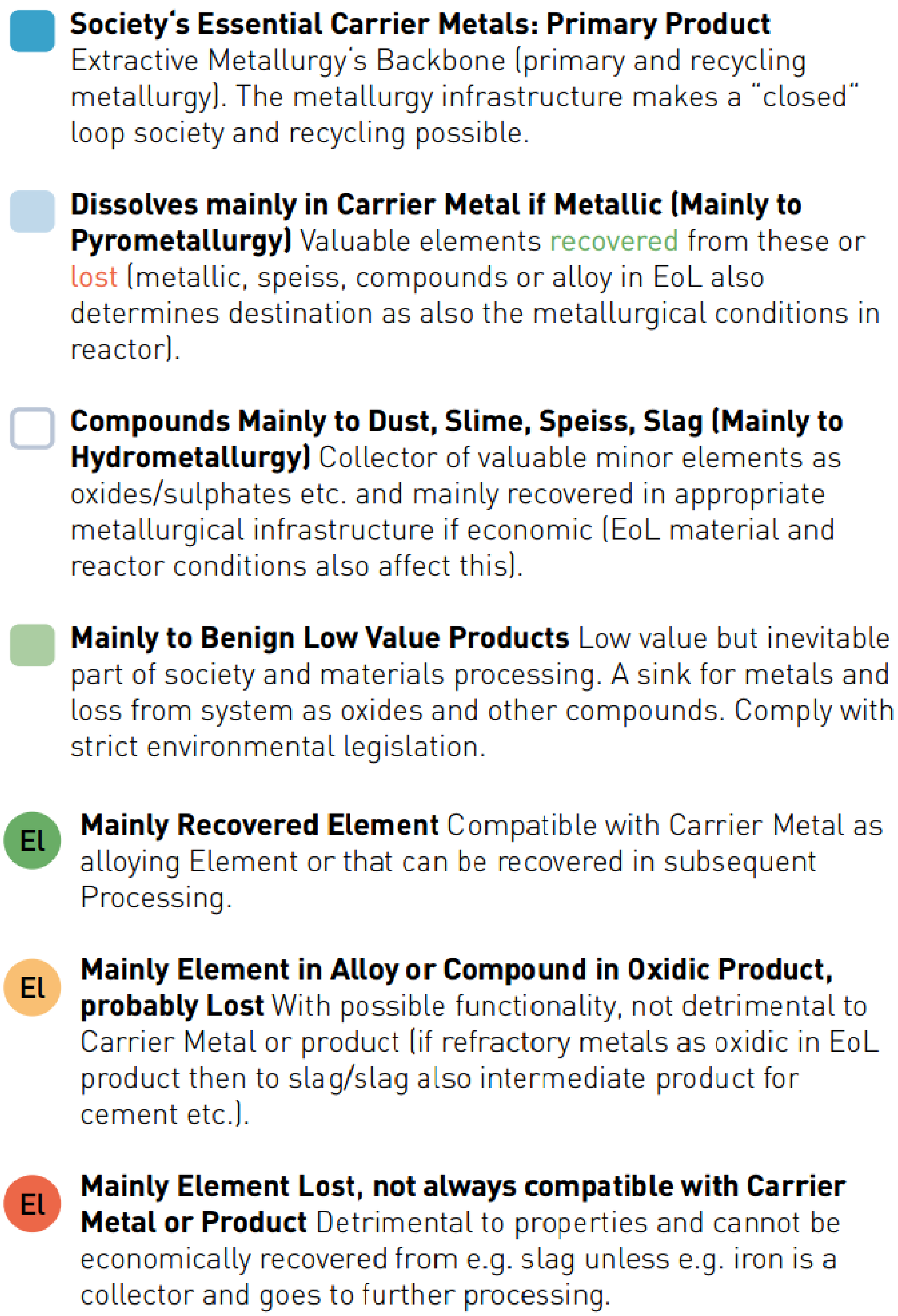
The European Union's Restriction of Hazardous Substances 2011/65/EU, also known as RoHS 2, and Waste Electrical and Electronic Equipment (WEEE) 2012/19/EU directives apply to:

1. Large household appliances
2. Small household appliances
3. IT and telecommunications equipment
4. Consumer electronics
5. Lighting equipment
6. Electrical and electronic tools
7. Toys, leisure and sports equipment
8. Medical equipment
9. Monitoring and control instruments, including those used in industrial installations
10. Automatic dispensers
11. Other electrical and electronic equipment not belonging to the aforementioned categories [29]

The directives do not apply to:

1. Equipment designed for the protection of security interests and military purposes
2. Equipment designed to be sent into space
3. Large-scale stationary industrial tools
4. Large-scale fixed installations
5. Means of transport for persons or goods, excluding electric two-wheel vehicles which are not type-approved
6. Non-road mobile machinery made available exclusively for professional use
7. Active implantable medical devices
8. Photovoltaic panels designed, assembled and installed by professionals
9. Equipment designed for research and development purposes, only made available on a business-to-business basis
10. Equipment specifically designed for installation as part of the aforementioned equipment [29]

C. The Metal Wheel



🟦 **Society's Essential Carrier Metals: Primary Product** Extractive Metallurgy's Backbone (primary and recycling metallurgy). The metallurgy infrastructure makes a "closed" loop society and recycling possible.

◽ **Dissolves mainly in Carrier Metal if Metallic (Mainly to Pyrometallurgy)** Valuable elements recovered from these or lost (metallic, speiss, compounds or alloy in EoL also determines destination as also the metallurgical conditions in reactor).

☐ **Compounds Mainly to Dust, Slime, Speiss, Slag (Mainly to Hydrometallurgy)** Collector of valuable minor elements as oxides/sulphates etc. and mainly recovered in appropriate metallurgical infrastructure if economic (EoL material and reactor conditions also affect this).

🟩 **Mainly to Benign Low Value Products** Low value but inevitable part of society and materials processing. A sink for metals and loss from system as oxides and other compounds. Comply with strict environmental legislation.

El **Mainly Recovered Element** Compatible with Carrier Metal as alloying Element or that can be recovered in subsequent Processing.

El **Mainly Element in Alloy or Compound in Oxidic Product, probably Lost** With possible functionality, not detrimental to Carrier Metal or product (if refractory metals as oxidic in EoL product then to slag/slag also intermediate product for cement etc.).

El **Mainly Element Lost, not always compatible with Carrier Metal or Product** Detrimental to properties and cannot be economically recovered from e.g. slag unless e.g. iron is a collector and goes to further processing.

Figure 27. Explanation on how to read the metal wheel. [2]

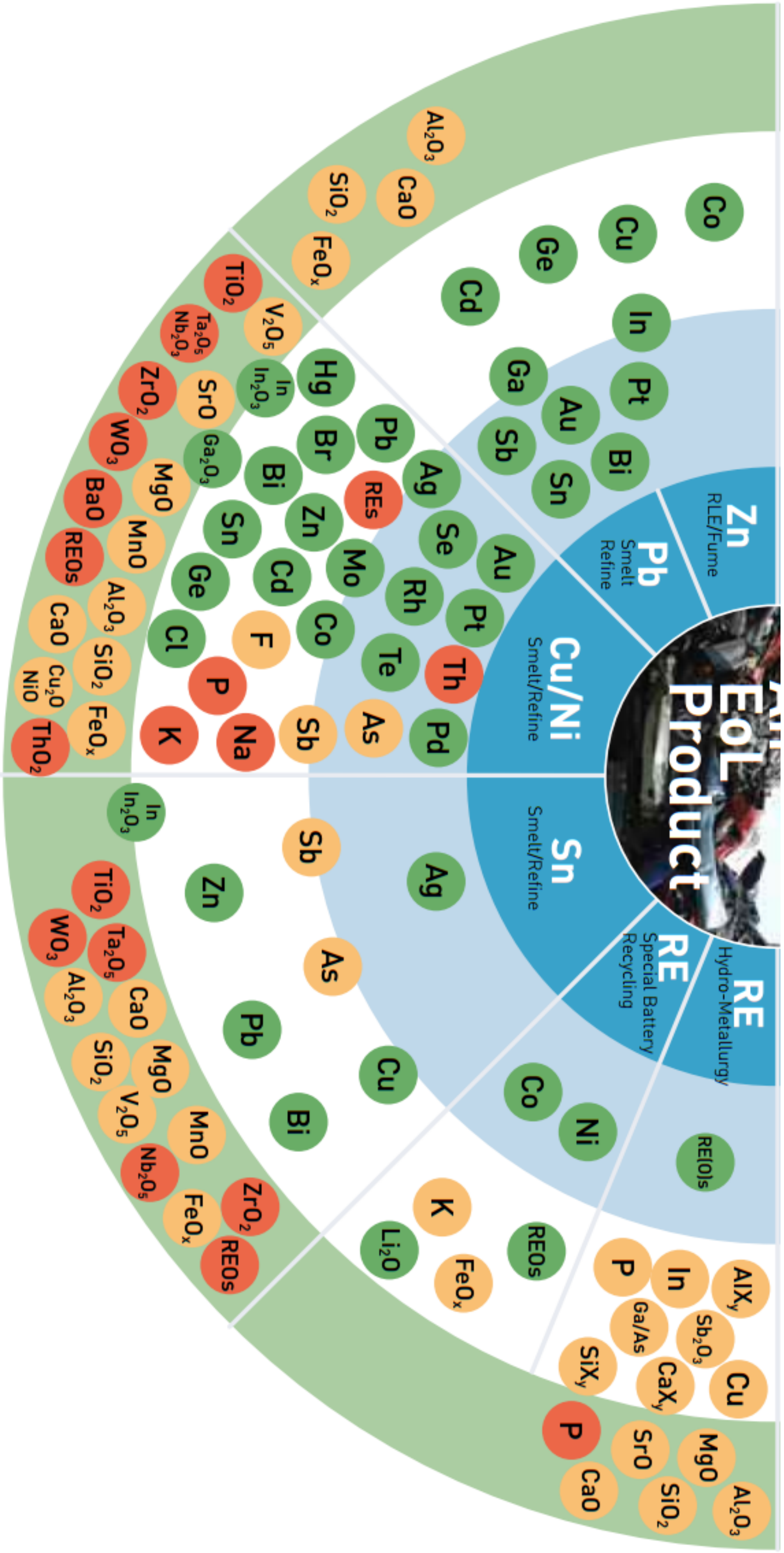


Figure 28. The metal wheel, part 1 of 2. [2]

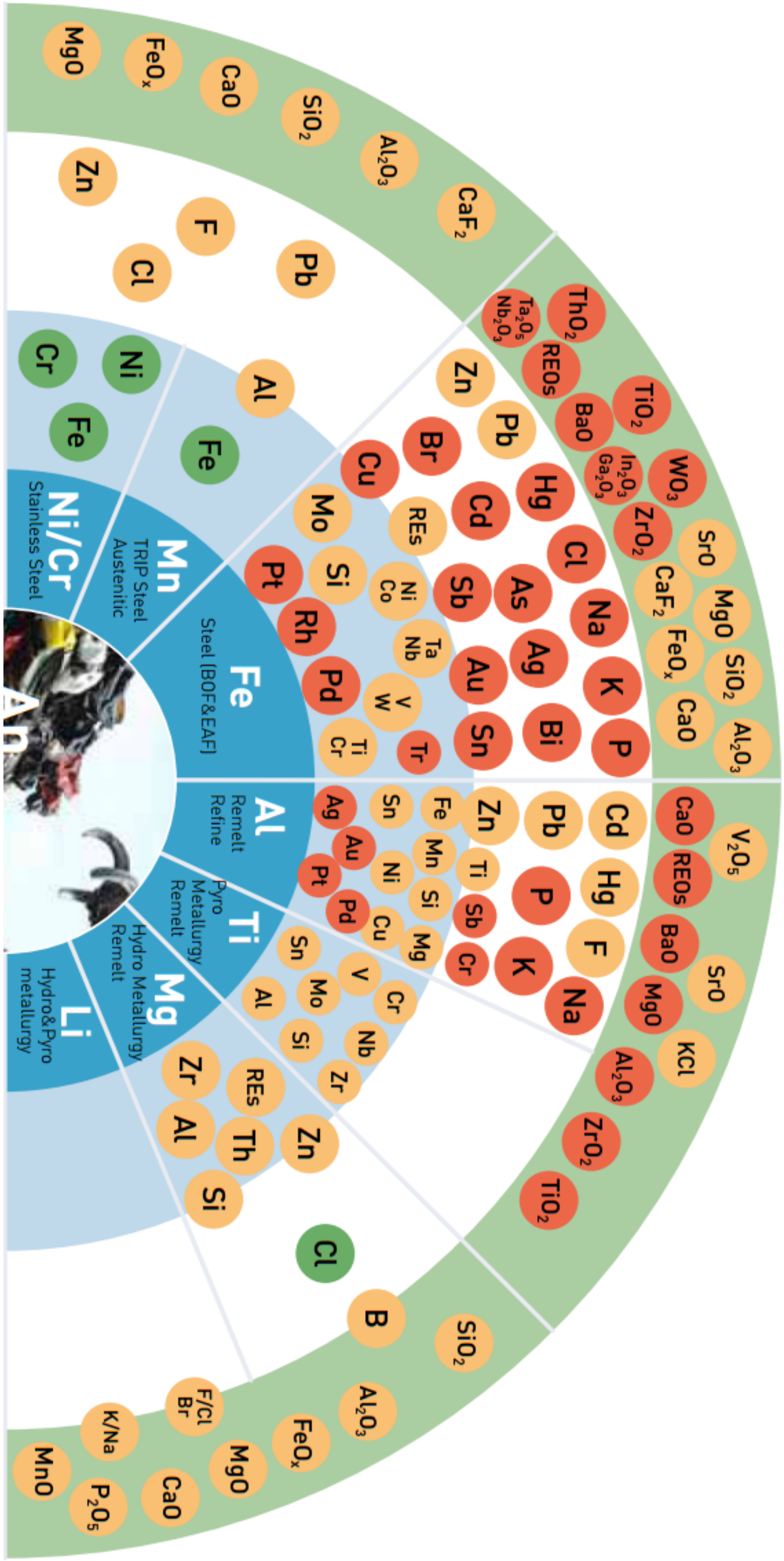


Figure 29. The metal wheel, part 2 of 2. [2]