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Entering the Circle

How can a product developer improve its systems perspective to facilitate a transition towards a circular economy?

Master's thesis in the master's program Industrial Ecology

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Abstract
Trucks are a cornerstone of the modern transportation system and society. The truck is increasingly subject to change and is becoming digitized, connected and automated with more electronic components in a truck. From an environmental perspective, the use of electronics in vehicles is not without problems. Valuable, scarce and non-renewable materials are increasingly used in these electronics and proper end-of-life treatment is lacking today. A large part of the unsustainable consumption and production can be attributed to the current “take-make-waste” models, which are linear in terms of resource use and material flows. Circular economy has been proposed as a more sustainable model where environmental degradation and economic growth is decoupled. In a circular economy, material and resources continue to stay within an industrial system and flow in circles. To transition towards a circle economy, there is a need for a systems perspective in order to avoid unwanted or unintended consequences. There are many aspects relevant in the product developing phase to consider concerning a transition towards circular economy. A system consists of several actors, and the system is affected by how they interact with one another. Product design has lacked a full environmental systems perspective, resulting in no or low requirements on design from a consumption of products point of view.

Moving from theory to practice is difficult; hence it is of interest to study how a systems perspective can be developed for a product developer. The purpose of this study was to examine how Volvo Group Trucks Technology, in the role of a product developer, can work more proactively towards a circular economy and improve current efforts by applying a systems perspective. Through a literature review, interviews and examining public sources the current work within Volvo Group Trucks Technology related to circular economy was investigated. Furthermore, a case study was conducted to study the material flow of electronic control units within the European Union to see if there was a problem with the production and consumption of them.

This study concludes that a systems perspective is essential when transitioning towards a circular economy. Based on the material flow analysis of electronic control units found in trucks in the European Union, it is stated that there is a problem with the production and consumption of electronic control units. The identified material flow is significantly more linear than circular, resulting in critical materials being lost every year. Lacking incentives to recycle and design features were found to partly cause the problem. From the results, it is further concluded that there is a good foundation at Volvo Group Trucks Technology for working proactively towards a transition to a circular economy. Many concepts and tools brought up by the industrial ecology methodology are to various extents already in place at Volvo Group Trucks Technology, e.g. eco-design and life cycle perspective.

A systems perspective can help an organization to see how different efforts and actors are connected.
A product developer needs to consider the perspectives of end-of-life actors in development projects to enhance the systems perspective. Furthermore, relevant knowledge needs to be shared within the organization and along the product life cycle to get better understanding for the system and for the product.

Keywords: circular economy, industrial ecology, systems perspective, sustainability, electronic control unit, eco-design, life cycle perspective

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Helena Lundström & Edvin Nordell

List of abbreviations

CE - Circular Economy
ACEA- European Automobile Manufacturers Association
CAST- Common Architecture and Shared Technology
ECU - Electronic Control Unit
EMF - Ellen MacArthur Foundation
EU - European Union
GTT - Volvo Group Trucks Technology
IP - Instrument Panel in a truck
MHCV - Medium and Heavy Commercial Vehicle
OEM - Original Equipment Manufacturers
PCB - Printed Circuit Board
PLC - Product Life Cycle

1. Introduction

1.1 Background

Trucks are a cornerstone of the modern transportation system as well as the modern economic system. Goods are transported through a global network of roads and infrastructure (Friedemann, 2016). While the truck has been around for over a century, it has lately become, along with the whole transportation system, subject to change with the rapid development of information and communication technologies (McKinsey, 2016b; Deloitte, 2016). The truck is becoming digitized, connected and automated. Common to all these trends is that the amount of electronics in a truck will increase. However, the use of electronics in vehicles is not without problems. Valuable, scarce and non-renewable materials are increasingly used in these electronics (Andersson et al., 2016; Ljunggren Söderman et al., 2014), but proper end-of-life treatment of electronics is lacking, with environmental issues and resource scarcity as a result (ProSUM, n.d.; Gabrys, 2014). United Nations has identified current production and consumption patterns as one of the more pressing global sustainability concerns as with resource scarcity, the needs of future generations is at risk (UN, 2015). The production and consumption of electronics in vehicles is characterized by low resource efficiency with materials becoming waste. Hence, it can be argued that due to material needed in electronics and for technical development are being used in a way that may eventually lead to resource scarcity, which could affect those dependent on the materials, among one the transportation system.

A large part of the unsustainable consumption and production can be attributed to the economic models behind consumption and production, which tend to be linear in terms of resource use and material flows (EMF, 2013; UN, 2015). Such linear models are what some call “take-make-dispose”-models where material flows in mainly a single direction, from extraction through production and usage, and finally towards disposal where a material loses much or all of its value. As virgin material is often less expensive than recycled, and negative externalities are unaccounted for, there have been few and low requirements on how goods are being designed and consumed (Fiksel, 2009). It is starting to become evident that current production and consumption cannot be considered sustainable.

Given the linear production and consumption patterns at fault, new models have been proposed where sustainability is at the focus while maintaining economic growth, i.e. decoupling environmental degradation from economic growth (EMF, 2013; Daly, 2005). One proposed model is *circular economy* (CE), which can be described as achieving economic growth while at the same time enforcing ecological sustainability by closing material flows and turning these flows into loops in the industrial system, keeping environmental impact to lowest possible level (EMF, 2013; Geissdoerfer, 2017). To transition to a circular economy, there is a need for systems perspective; else unwanted effects may take place (EMF, 2013). A product’s whole life cycle needs to be considered to ensure that the material is sent back as resources to the system again. Both the Ellen MacArthur Foundation (2013) and McKinsey (2016a) argue that there are new business opportunities by adapting to a circular economy.

In the business community, awareness is increasing; partly out of necessity as there is an operational risk due to resource depletion, and partly out of responsibility for contributing to the problem (O’Higgins & Zsolnai, 2018; Scherer & Palazzo, 2007). Adding to the increased awareness is the regulatory risk, where policy makers may force less proactive businesses to incorporate sustainability

(Gemmell & Scott, 2013). Thus, it can be argued that businesses should take sustainability aspects into account from several perspectives: from an operational perspective in order to remain relevant and competitive; from an ethical perspective as they are both part of the problem and the solution; from a business perspective where a proactive approach may yield new business opportunities; and from a regulatory perspective in order to foresee potential future scenarios where sustainability could be enforced by legislation.

Volvo Group Trucks Technology (GTT) is a truck developer who wishes to explore a transition towards a circular economy in practice. However, moving from theoretical and abstract concepts of circular economy to something tangible and practical is not an easy endeavor. As circular economy stipulates that materials stay in the system, there is a need for systems perspective. To apply a systems perspective puts further requirements on an organization (McKinsey, 2016a). Such requirements for a product developer could be to collect data needed to monitor material flows, new design knowledge and increased cooperation with actors along the product life-cycle. Hence, there are both product and organizational perspectives to consider when transitioning towards a circular economy. For a product developer, such as Volvo GTT, it is reasonable to assume that such a transition requires engagement on several fronts. Thus, it can be argued that it is of interest to study how a product developer may improve its systems perspective to begin a transition towards a circular economy.

1.2 Volvo Group

The Volvo Group is structured into several units based on their function as well as different product brands (Volvo Group, 2018). Some brands have a global presence, such as the Volvo Trucks brand. It is the objective and mandate of Volvo Group's top management, together with the brands, to develop business models and strategies. Volvo GTT, together with Group Trucks Operations (GTO) and Group Trucks Purchasing (GTP) are three cross-functional divisions which develop and produce Volvo's product portfolio. GTT is tasked with product and technology development, GTO with production of products and all its parts, and GTP is tasked with procurement of products, parts and services needed for the operations.

1.3 Purpose

The purpose of this study is to examine how Volvo GTT, in the role of a product developer, can work more proactively towards a circular economy and improve current efforts by applying a systems perspective. This is done by investigating current work related to circular economy within Volvo GTT, as well as conducting a case study for an electronic component and a literature review. The purpose of conducting a case study is to examine if there is a problem with production and consumption of the chosen component, and if so, why. To cover a broad spectrum of circular economy, the focus of this thesis is twofold; product focus and organizational focus, while showing the connection between the two. An intended outcome of this study is to provide a basis for further research as well as educate and inform the organization about circular economy. In the latter sense, this study bridges theory and practice.

1.4 Aim and Research questions

The aim of this thesis is to provide guidance for Volvo Group Trucks Technology on how to facilitate a transition towards a circular economy.

To address the purpose and fulfill the aim, the study was guided by the two research questions. The questions are both related to the product focus and organizational focus mentioned under section 1.3. The research questions are:

1. Is there a problem with the production and consumption of the studied component? If so, why?

To answer how systems perspective can facilitate a transition towards CE, it is here argued that it is of interest to examine how Volvo GTT is currently working on the firm level, inter-firm level and on the regional level when developing products.

2. How is Volvo GTT currently working with regards to CE and how can they develop their systems perspective?

1.5 Scope

To make the research more manageable in terms of time and resources, as well as enabling an in-depth case study, a specific type of electronic component was used. The chosen components for this study are the electronic control units (ECUs) in the instrument panel (IP). Additionally, the case study was limited to the European Union.

2. Literature review

The following chapter aims to explore and review literature relevant for the subject of this study, and in doing so prepare the reader for the following chapters in the thesis and create a foundation for understanding. Theoretical concepts will be presented, which act as basis for the analysis of the empirical findings.

2.1 Circular Economy

To better understand what circular economy is and how it applies to an organization which develops products or technology, a clear definition of the concept is required. However, the concept is contested. Therefore, critique against, and problematization of, circular economy is presented as it may provide a better understanding of the application of the concept.

2.1.1 About Circular Economy

The origin of the term *circular economy* is disputed, though the concept has evolved continuously over last decades as environmental and social concerns has grown (Winans et al., 2017). According to the Ellen MacArthur Foundation (EMF, 2013) the concept has evolved out of several other schools of thought, among them *industrial ecology*. Different definitions of the concept exist and what constitutes circular economy varies (Kirchherr et al., 2017). However, there are similarities among them. Common to many definitions of circular economy is a closed material flow through society based on the 4R framework: *reduce, reuse, recycle* and *recover*. When implemented, the turnover of resources throughout society will be to a large extent cyclic, i.e. resources are cycled back into the system, much like nutrients in ecosystems (EMF, 2013). As such, CE can be regarded as a kind of *industrial metabolism*, which refers to the turnover and processing of materials and resources through society (Lifset & Graedel, 2002).

The different options in the 4R framework can shortly be described as following. Reduce is generally interpreted as reducing the amount of material consumed, though many scholars and practitioners include rethinking, redesigning and refusing consumption (Kirchherr et al., 2017). Reuse is concerned with maintaining and prolonging the life of goods through e.g. repair, whereas recycling focuses on turning discarded goods and material into resources for production again. Recovery concerns retrieving energy in the materials, e.g. through incineration, and is a last resort when the other options are unsuitable. Recovery is disputed as a way to close material flows as material will inevitably be lost when e.g. incinerated. Following the 4R framework, a circular economic system will thus ideally have a largely closed material turnover with resources being used continuously and more efficiently compared to a linear system while simultaneously maintaining economic growth (Geissdoerfer et al., 2017; EMF, 2013).

Kirchherr et al. (2017) state that one of the CE definitions that has gained most traction is the one provided by the Ellen MacArthur Foundation. This definition refers to circular economy as "*an industrial economy that is restorative by intention; aims to rely on renewable energy, minimizes tracks, and eliminates the use of toxic chemicals; and eradicates waste through careful design*". EMF divides material flows in society into two distinct flows; biological nutrients and technical nutrients. The latter flow cannot be biologically processed, whereas the former can. In this thesis, the focus is on the flow encompassing technical nutrients and from the proposed definition, "*eradicates waste through careful design*" is the most relevant part. Figure 2.1 illustrates a circular industrial metabolism with the biological flows and the technical flows. In the illustration, reduce and recovery are left out, though both options are included in the EMF definition.

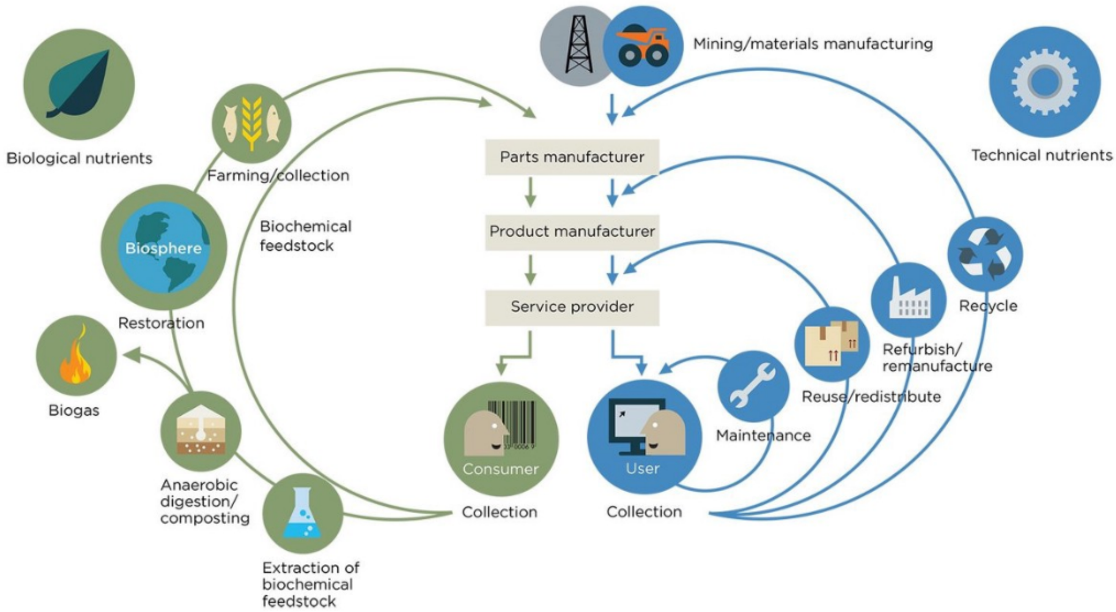

Figure 2.1. An overview of circular economy and circular material flows as perceived by EMF (2013). © Ellen MacArthur Foundation [2013]

According to Kirchherr et al. (2017), CE should not necessarily be seen as a sustainability concept. Based on their analysis of different definitions, CE is more concerned with economic growth while maintaining some level of environmental quality than contributing to sustainability, i.e. social, economic and ecological. Furthermore, there is currently no agreement or understanding of how to evaluate circularity of a system as there are no universally accepted metrics or indicators (Linder et al., 2017). Adding the many different definitions in circulation, how to assess the circularity of an economic system may be argued to be problematic and difficult.

2.1.2 The waste hierarchy

From an ecological point of view, the options provided in the 4R framework are different in terms of environmental impact (Hansen et al., 2002). The 4R framework can be categorized from better to worse in terms of environmental impact according to Hansen et al. However, this can be disputed as there may be cases where recovery may be more suitable than e.g. recycling or reuse. This categorization is called *waste hierarchy* and shows which options that should be prioritized in waste management to minimize environmental impact and close material loops. See Figure 2.2 for an illustration of the waste hierarchy.

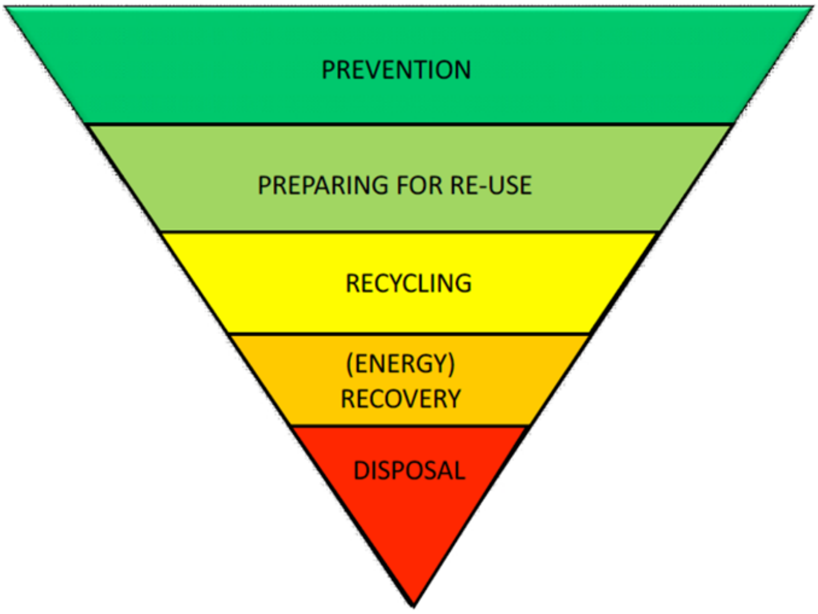

Figure 2.2. The waste hierarchy, the most desired cause of action, prevention of waste, is in the top of the upside down pyramid (European Commission).

Hansen et al. (2002) claim that for waste management to fit within the notion of sustainability it must encompass more than reactive end-of-pipe solutions and rather include proactive approaches (Hansen et al., 2002). In terms of saving resources and energy, preventing the generation of waste in the first place is the most efficient course of action (IVL, 2016). The prevention of waste eliminates the need for structures for collecting and treating the waste thus resulting in lower environmental and economic life cycle costs. Prevention refers to reduction in the 4R framework (Hansen et al., 2002). Prevention is often best handled as early as possible in design and development processes (Hansen et al., 2002).

An example is here provided to clarify what prevention may entail as prevention does not necessarily mean discontinuing production and consumption of products. Connecting to Kirchherr et al.'s (2017) examination of reduction, it can further encompass redesign and rethinking a product. Spotify and Netflix are here argued to be examples of actors who rethought products. Before these actors entered the entertainment market, music and movies were entertainment often consumed in a physical form, e.g. through VHS, DVDs and CDs. Spotify and Netflix thought of entertainment products differently compared to competitors, with the product being immaterial instead of material, e.g. the content of a movie is the product and not the DVD a movie is stored in (Antikainen & Valkokari, 2016). The media content could be provided to customers through a digital subscription service instead. Hence, consumption of entertainment could be done without the consumption of CDs, VHS and DVDs, thus reducing the need of these goods and the waste generated by them. Spotify and Netflix are two examples of product servitization, where the function of a product is sold as a service instead of the product itself. Ownership of products may be retained by the producer, and the functionality of the products is then sold to users instead. Relating to Volvo Group, this could mean selling the function of a truck, i.e. transportation, instead of the truck itself with Volvo Group retaining ownership of the truck.

Following prevention, *reuse* is the most favorable option in the waste hierarchy (Hansen et al., 2002). Reuse refers to using the product or material again without fundamentally modifying the structure or character of the product or material. This step in the hierarchy will require systems and structures for collection but not much in terms of processing. *Recycling*, albeit better than energy recovery, requires systems and structures for collecting and treatment. Finally, as a last resort is *disposal* which should only be an alternative once all other options have been exhausted (Hansen et al., 2002).

2.1.3 Connecting Circular Economy to Industrial Ecology

As CE can be described as a kind of industrial metabolism with cyclic material turnover, it is reasonable to look at how industrial metabolism is studied. Industrial ecology can be described as a scientific field which studies turnover of materials and energy throughout an industrial system (Lifset & Graedel, 2002). Industrial ecology is furthermore a concept which is aiming for transformation of industrial systems into closed-loop industrial ecosystems, where waste is cycled back as resources (Lifset & Graedel, 2002). Connections between actors within an industrial system are highlighted, dependencies pointed out, and resource flows are mapped. Problems and unwanted effects are to be avoided before implementation by forward-looking analysis. To achieve such a transformation, the business sector has a central role. Companies may affect technology innovation, which is deemed essential to lower environmental impact, and their involvement in alleviating environmental issues is therefore needed. Additionally, it can be argued that the inclusion of business is relevant as they have shared responsibility of the problems regarding current linear consumption and production patterns.

Given the shared traits between what CE is and what industrial ecology aims for, Saavedra et al. (2018) state that industrial ecology and its methodology is useful for studying and transitioning towards CE. Therefore, the theoretical framework for this study is based on the industrial ecology methodology.

2.2 Importance and Application of a Systems Perspective

To answer how a product developer can improve its systems perspective, what a systems perspective is and what it entails for a product developer needs to be defined. Furthermore, how can a systems perspective facilitate a transition towards a circular economy is of interest. This section therefore aims to clarify those questions, as well as show connections to CE.

To alleviate environmental issues and achieve system wide change, systems perspective is central in industrial ecology (Lifset & Graedel, 2002). Without systems perspective, it is difficult to foresee the outcome of a transition and there may be a higher risk for unwanted effects. Connecting to CE, EMF (2013) and Kirchherr et al. (2017) stress that systems perspective is essential and must be applied by all actors striving towards a transition. Ghisellini et al. (2016) and Linder et al. (2017) argue that there are several levels within an industrial system and CE must be implemented on all levels to achieve system wide change. In industrial ecology, systems perspective is not just about what can be done at each level, but rather about understanding and connecting different perspectives into a greater whole and seeing how the different levels interact and affect each other (Lifset & Graedel, 2002). As there are different ways to assess circularity depending on system level, circularity at one level may not mean circularity for the whole system and vice versa (Linder et al. (2017). This indicates that merely looking at a firm only may not be enough when transitioning towards CE.

Lifset and Graedel (2002) present three levels on which industrial ecology is applicable; the *firm level, inter-firm level*, and *regional level*. These levels correspond to the levels presented by Ghisellini et al. (2016) and Linder et al. (2017). At the firm level, tools such as ecodesign, pollution prevention and eco-efficiency are presented. For the inter-firm level, product life cycles and industrial sector initiatives are presented, and for the regional level, material flow analyses and dematerialization are presented. The different levels and related tools describe what each level may entail for an organization in terms of closing material loops. When dealing with systems perspective, multi- and interdisciplinary approaches can be taken to incorporate additional aspects (Lifset & Graedel, 2002).

The systems perspective and levels applied in industrial ecology are argued to omit some aspects which are of importance according to EMF when transitioning towards a circular economy. EMF (2013) state that business models, as well as inter-firm and stakeholder cooperation are essential aspects which need attention to achieve a change. These aspects are argued to fit well into the previously presented system levels; business models belong at firm level and inter-firm cooperation at inter-firm level. Furthermore, business model and cooperation are of relevance for a product or technology developer as these aspects may affect development processes and thus the outcome (Teece, 2010; EMF, 2013). Therefore, the systems perspective and systems level used in industrial ecology are used as a basis in this study and expanded to include aspects of importance to CE. Tools for each level are presented in the subsequent sections.

2.3 Firm level

2.3.1 Product design and development

Product design which takes environmental quality into consideration holds the potential of minimizing environmental impact from production, consumption and waste management of products (Hendrickson et al., 2002). Such product design is often seen as a proactive approach towards sustainability where harmful impacts are actively avoided during the design and development process. It may also remove the need of end-of-pipe solutions which are inherently reactive, e.g. treating emissions during use. Product and process design that take such consideration may be found under different monikers, e.g. eco-design, design for environment and green design among others (Lifset & Graedel, 2002; Hendrickson et al., 2002).

Eco-design incorporates the 4R framework by aiming for reduced use of materials, especially harmful, toxic and non-renewable material, and design for facilitation of reuse or recycling (Hendrickson et al., 2002; Lifset & Graedel, 2002). Sub-categories of eco-design have emerged, e.g. design for disassembly and design for recycling, which tend to focus on a specific part of a product life cycle. Energy recovery may be possible regardless of design to some extent. EMF (2013) expands on previous description of eco-design to include standardization and modularization, two aspects argued to lower complexity of products and facilitate a higher degree of reuse, remanufacturing and recycling. Thus, how a product is designed affects the production of it, the consumption of it and the end-of-life treatment of it. To avoid harmful and unintended impacts, knowledge of a product life cycle is therefore required (Lifset & Graedel, 2002). By applying eco-design with a life cycle perspective, the firm level is here argued to be connected to the inter-firm level. Hence, eco-design is of relevance for a product or technology developer transitioning towards a circular material flow.

Albeit eco-design has good potential, there are limits to its effect on lowering the environmental impact of a product (Gertsakis et al., 2002). An objection against merely relying on product design for remedying environmental problems is that it only promotes closed loop end-of-life treatment, e.g. recycling, but cannot assure it. Extended producer responsibility of products or partnerships with downstream actors may be needed to better assure proper end-of-life treatment. This further shows the necessity of applying a systems perspective, e.g. cooperation along a product life cycle, when closing material flows. Hence, further measures than eco-design are needed for a product developer when transitioning towards CE.

2.3.2 Business models

For companies, the business model can be either a barrier or driver of sustainability (Rauter et al., 2017). EMF (2013) proposes that business models are a key factor in achieving a circular system. The business models govern how a firm creates and captures value, which affects how a product is designed (Teece, 2010). Furthermore, the values stated in a business model determine whether or not sustainability aspects are relevant (Rauter el al., 2017). Therefore, a business model may in turn affect material turnover. Similar to Gertsakis et al. (2002), Teece argue that product development alone does not warrant success. Product development and business development should therefore be done in parallel to better achieve success.

In the strive for a more sustainable society, companies must be recognized for their distinctive position as global actors and change agents with the possibility to give rise to considerable changes within their sphere of influence (Rauter et al., 2017). It is argued that corporations and their contribution towards sustainable development is highly needed and essential to bring about a change (Moon, 2007).

2.4 Inter-firm level

2.4.1 Product Life Cycle Management

In industrial ecology, life cycle perspective tends to focus on studying environmental impact of a product or service over its whole life (Lifset and Graedel, 2002). This study is not intended to examine any environmental impacts, however, it is here argued that the life cycle perspective is still of relevance. By looking into the life cycle of a product and examining what happens to a product during its life, why there is a problem may partly be answered. Furthermore, actors which affect the material flow can be identified. These actors can be of interest for cooperation to enhance circularity as well as gain a better understanding of the system.

Product life cycle management, PLM, is a term with many interpretations and overall it can be summed up as a *"products centric- life cycle-oriented business model in which data are shared among actors, processes and organizations in the different phases of the product life cycle for achieving desired performances and sustainability for the product and related services*" (Terzi et al., 2010).

To further elaborate on what PLM is, the following section will investigate the concept using an example provided by Terzi et al. (2010). Development of a car includes many actors, designers and engineers, taking part of the design chain. The manufacturing process is both very fine tuned and complex, also involving its own set of actors. Moving on to the next phase of the product life cycle, the car will be sold and enter its use phase involving a large variety of different actors in its service chain such as salesmen, customers, workshops, dealers, resellers, garages. Lastly, the End-of-life for a vehicle is another complex phase regulated by legal requirements and involving dismantlers, waste management and recyclers. During the life of a car vast amounts of information is yielded and used by actors within and outside of the company. The actors having their own perspective on the product yield information niched toward their specific area of competence. The common goal using a PLM perspective is to collect all this knowledge and making it available for relevant actors in order to achieve better products and services. The example object is here argued to be changeable from a car to a truck to better suit the subject of this study.

To adopt a PLM perspective and utilize the information in the system in an efficient way, the issue of data storage and availability must be considered as information does not reach its full potential if it is not accessed by the right persons or groups in the right time. Terzi et al. (2010) further argues that clear structures for collecting data (notes, data sheets, drawings etc.) is essential for avoiding information silos and information getting lost.

Cooperation between companies and departments within the firm is argued to support management in finding and assessing alternatives when working with new product development in order to identify the best possible solution (Klassen and Vachon, 2003). Thus, collaborative activities are vital for successful product development and improvement (Johnson et al., 2010). Unfortunately, many firms do not succeed in gaining profit from collaboration, possibly due to lacking communication and harmonization of the process (Barratt, 2004). Furthermore, the overall success of the venture is also influenced by the access to technology and organized processes (Cooper et al., 1997). Participants must thus be familiar with their roles and the expectations on them to enable collaboration and avoid barriers (Zhang, 2011). Silo thinking is one barrier in particular that can be regarded as troublesome as it hinders new product development. This is something that must be recognized early on and participants in the collaboration process must work towards overcoming these thinking silos and adopt a product centered mindset (Lambert et al., 1998; Childerhouse and Towill, 2011).

PLM has emerged as a new important focus area and key aspect for the future as companies strive to continuously improve customer value and identify new ways of achieving competitive advantage (Terzi et al. 2010). Previously, many companies concentrated on improving product, quality, cost and time to market whereas companies today are starting to become aware of the importance of innovation to maintain customer satisfaction. Customer satisfaction has moved beyond simply being content with the product to include a more holistic view encompassing environment, risk, lifecycle cost etc. Products have transitioned from being merely an item to a complex system including both a physical product and intangible assets, e.g. various services. For industries to be able to provide products characterized by holism they need to gain extensive information about the products life cycles (Terzi et al. 2010).

Many companies today lose contact with their products relatively shortly after the product is sold or when the warranty expires thus interrupting the product information flow (Terzi et al. 2010). The diminished or non-existent flow of information hinders feedback loops and complicates the work of designers and engineers, tasked with product development, as they are strongly reliant on product feedback to develop/make/ improved and more sustainable products. As argued by Terzi et al. (2010), through a PLM perspective, i.e. collecting and utilizing knowledge from the product life cycle, the use of resources, production and services connected to the product can be optimized.

2.4.2 Stakeholder involvement

EMF (2013) state that cooperation between stakeholders along a product life cycle is important in order to ensure cyclic material flows and joint value creation. Such cooperation could have an effect on the product life cycle as well as creating incentives to work with CE. Stakeholders relevant for this study refer to actors along the product life cycle chain, both up- and downstream.

In the article *Stakeholder participation for environmental management* (Reed, 2008) it is argued that the nature of environmental and sustainability issues requires an approach characterized by flexibility, openness to changing circumstances and encompassing a diversity of different values and knowledges. With the ambition to successfully deal with those kinds of issues stakeholder involvement is increasingly important particularly with regards to including diversity in terms of values and knowledge (Stringer et al., 2007). Environmental and sustainability problems are claimed to require a systems perspective which is better applied by involving various stakeholders (Richards et al., 2004).

Estrella and Gaventa (2000) argue that stakeholders are often not invited to participate in the early stages and thus miss out on the early stages of a development process. It is more common for stakeholders to be invited to phases concerning implementation, monitoring and evaluating the outcome (Estrella & Gaventa, 2000) even though extensive stakeholder participation is argued to yield better basis for decision making (Reed, 2008). It is further argued that involvement should be done as early as possible in the process to help ensure a systems perspective. Another key aspect relevant for the overall success of the involvement is the need for clear objectives and facilitation of the process by skilled and knowledgeable people (Reed, 2008).

2.5 Regional level

2.5.1 Material Flow Analysis

Material flow analysis (MFA) is an analytical methodology for investigating and quantifying flows and stocks of a specific material or substance within a predefined system (Shi & Yang, 2013). The methodology is frequently applied to gain understanding for anthropogenic systems and activities but also to diagnose and investigate the state of industrial systems (Brunner & Rechberger, 2017). Hence, MFA can be used for investigating systems when transitioning towards a circular economy.

A material's turnover through a system is quantitatively examined by connecting sources, sinks and stocks, and pathways (Brunner & Rechberger, 2017). A system is defined in space and time, called system boundaries, and within the system there are various processes which affect a material in some way, e.g. transform or transport. The boundaries enable an examination of material flows throughout the system, and depending on the geographical space chosen; an MFA can be applied on different scales. In defined and closed systems, the law of conservation of matter applies; within this system matter cannot be either created or destroyed (*Encyclopædia Britannica,* 2018*)*. Due to this law of physics, the result of an MFA can be verified and controlled by mass balance calculations, comparing all connected stocks, flows, sinks, intermediates, inputs and outputs for the investigated process or system. This characteristic has made MFA a highly favorable tool for analysis and means for decision-support in several disciplines e.g. waste management, resource management, policy assessment and environmental management (Brunner & Rechberger, 2017). When a flow has been mapped through a system, it can be illustrated to present an overview of the studied system. See Figure 2.3 for a conceptual MFA illustration.

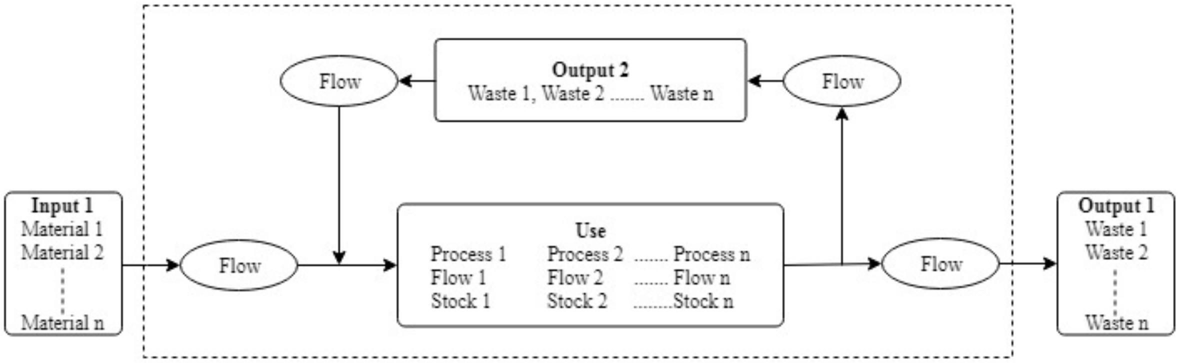

Figure 2.3. A schematic picture showing a MFA flowchart (illustration based on Brunner & Rechberger, p. 71, but reworked by the authors).

Consequently, MFA is a useful and multifaceted tool for analyzing industrial systems, often connected to and performed in combination with analysis of economy, energy, urban planning etc. (Brunner & Rechberger, 2017). Benefits of MFA include the possibility to analyze and assess a system and deduce where in that particular system materials or substances end up. It contributes to the identification of sinks and losses in the system which is useful when implementing suitable countermeasures to influence and change the system towards desired goals. MFA is hereby argued to be a valuable tool when transitioning towards CE as it may disclose if there is a problem with the current industrial metabolism, and where the losses are.

2.6 Change Management

Time and again, companies and organizations are faced with challenges forcing them to change and adapt to the new situation if they desire to remain relevant and competitive on a changing market (Kotter & Schlesinger, 2008). Senge (1999) reflected upon why change initiatives fail and presented four guidelines or recommendations for managing change. *Start small, grow steadily, do not plan everything, expect challenges - it will not go smoothly.* These guidelines are argued to be good to keep in mind when dealing with change management in order to increase the chances of succeeding with implementing the change. Furthermore, Senge (1999) investigates challenges connected to change management when initiating a change process. A transition towards CE can be regarded as a change, which stipulates the need of change management to better ensure a successful outcome.

Working with change initiatives is time consuming and to avoid resistance from the people tasked with the assignment they must be given the time and resources needed (Senge, 1999). People will need help to manage the change; hence it can be a good idea to early on evaluate and understand what kind of support that will be needed to develop relevant new skills and mindsets. Values that are aligned with and support the change initiative are important for getting the employees aligned. Without conviction, commitment will not follow and nor will the desired change. The importance of management leading by example is argued to be a key factor for gaining acceptance from employees as the latter will look towards management for reinforcement of the values.

The nature of change and implementation of it is nuanced and require many people and groups to contribute (Cameron & Green, 2006). To succeed with a change process within an organization, a combination of individuals, teams, informal groups, leaders and management must be aligned and work towards the same goal. According to Cameron and Green (2006) leaders and management have an important role to play in change processes; enabling it to happen.

Buchanan and Huczynski (1985) argue that knowledge and how it is managed is a key factor to managing change. Knowledge management is a collective term for creating, collecting, sharing, using and managing information to improve a company's business performance (Wang, 2002). In a rapidly changing world, more and more people argue that knowledge and the management of knowledge is one of the most critical resources for maintaining high performance (Von Krogh et al, 1996). It is argued that a key factor behind companies who keep their competitive edge on the market is due to their ability to successfully develop, improve, protect and renew knowledge (Badaracco, 1991).

2.7 Critical raw materials

According to the European Commission (2010), a raw material is labeled as *critical* after evaluating factors such as the political and economic situation of the country or region where the material is produced, the supply concentration and stock, the potential of finding and using substitutes and finally the current recycling rate (Graedel & Nuss, 2014). These materials have a significant impact on the European economy hence their status as *critical* raw materials. Access to raw materials is crucial for maintaining production in existing industries but also for developing future technologies (EC, 2017).

Economic growth and technological innovation has resulted in increased global demand for many valuable materials and securing access and supply to these materials and minerals has become an important issue for many economies with no or limited domestic raw material extraction (EC, 2017). The economy of the European Union is today reliant on import of minerals and metals to meet the market demand. This creates a need to address the issue of resource availability in a structured way. Consequently, with the purpose of taking a proactive approach and early identify critical materials with a supply risk and high economic importance for the region and its industries, the European Commission put forward the “Raw Materials Initiative” in 2008 and created a list of critical raw materials. Since the list was first published it has been changed and updated several times, adding and removing materials. The latest list encompasses 27 critical raw materials, see Table 2.1.

Table 2.1. Raw materials classified as critical by EU.

EU’s list of Critical Raw Materials 2017			
Antimony	Fluorspar	LREEs	Phosphorous
Baryte	Gallium	Magnesium	Scandium
Beryllium	Germanium	Natural graphite	Silicon metal
Bismuth	Hafnium	Natural rubber	Tantalum
Borate	Helium	Niobium	Tungsten
Cobalt	HREEs	PGMs	Vanadium
Coking coal	Indium	Phosphate rock	

HREEs stands for heavy rare earth elements, and include dysprosium, erbium, europium, gadolinium, holmium, lutetium, terbium, thulium, ytterbium, yttrium (EC, 2017). LREEs stands for light rare earth elements and include cerium, lanthanum, neodymium, praseodymium, samarium. PGMs stands for platinum group metals and include iridium, osmium, platinum, palladium, rhodium, ruthenium.

2.8 Electronic control units

The case study follows ECUs in the instrument panel in trucks. An explanation of what an ECU is, its purpose, what it contains in terms of raw materials and substances is deemed relevant.

Electronic control unit is an embedded system for controlling and integrating actions in vehicles (Wang & Chen, 2010). ECUs manage the electrical systems or subsystems in the vehicles, and thus control basic operations and functions in the vehicle, such as powertrain control and safety assistance (ProSUM, n.d). Electronics and software are becoming increasingly more important in the automotive industry and following the trend of electric and self-driving vehicles it can only be expected that the amount of electronics in the vehicles will continue to increase (ProSUM, n.d).

ECUs consists of plastic covers and printed circuit boards (PCBs), with the latter being composed of several materials including metals e.g. Au, Pt, Pb, Ag, Cu. The ECU is connected to other components in a vehicle through wires. See Figure 2.2 for an illustration of an ECU and its parts. The material composition can vary between different types of PCBs and producers but an example of material composition is shown in Table 2.2 (Wang & Chen, 2010).

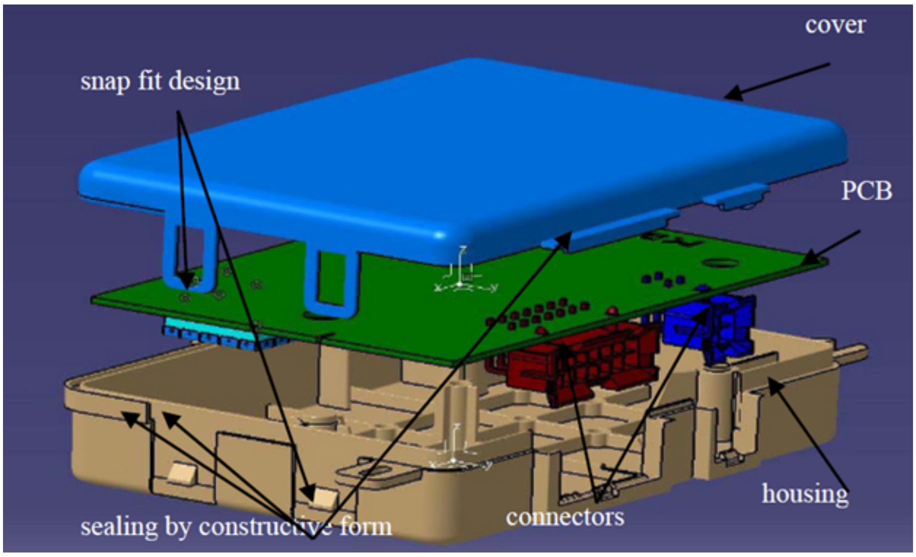

Figure 2.4. A schematic picture of a general electronic control unit (Cazacu et al., 2017).

According to Wang and Chen (2010), discarded PCBs can contribute to heavy metal contamination unless properly taken care of. Considering the necessity of the metals in ECUs, it is of economic and environmental interest to retrieve those materials from the waste treatment process and thus keep the substances within the economic system (Wang & Chen, 2010).

Table 2.2. Material composition of a PCB in an ECU shown in percentage of total weight of the PCB.

No.	1	2	3	4	5	6	7	8	9	10
Material	Resin board	Cu	Solder	Fe	Ni	Ag	Au	Pd	Bi, Sb, Ta	Others
Ratio (%)	70	16	4	3	2	0.05	0.03	0.01	0.02	4.91

2.8.1 Critical materials in an Electronic Control Unit

Critical materials in an ECU can be obtained by comparing EU's list of critical raw materials with the materials in a PCB. Four materials classified as critical by EU can be found in an ECU, namely antimony, bismuth, tantalum and palladium, see Table 2.3. Antimony, bismuth and tantalum are treated as one group, and not separately.

Table 2.3. Critical materials in an ECU and their weight percentage of a PCB.

Material	**Percentage of PCB weight**
Antimony (Sb)	0.02 (for all three combined)
Bismuth (Bi)	
Tantalum (Ta)	
Palladium (Pd)	0.01

Material availability is dependent on several factors; stocks in the lithosphere, extraction of virgin material, recycling, and geopolitical distribution (Andersson & Råde, 2001). Stocks consist of reserves and resources, and the distinction between the two is that the former is stocks that can be economically extracted, whereas the latter can be extracted but not economically. Based on current reserves, recycling rate and consumption of a material, availability can be forecasted (Andersson & Råde, 2002). These factors are dynamic, hence, the material availability forecasts are less reliable as the availability changes.

Antimony is currently expected to be available for 11 years to come (USGS, 2018). For bismuth, there is no current estimation of reserves, which hinders a forecast of material availability. Tantalum will be available for another 84 years based on current extraction and reserves. Palladium is part of platinum group metals, and current reserves are for the whole group of metals and not specifically for palladium. Hence, there is no forecast for palladium. These forecasts can come to change as reserves and extraction varies with fluctuations in market demand, advances in extraction or recycling technology and discovery of new mineral deposits. Hence, these forecasts should not constitute sole basis for material analysis, but to be analyzed together with material criticality.

All four of the identified critical materials are scarce (USGS, 2018). Furthermore, the extraction and production of these metals are concentrated to a few regions, with China being a prominent producer of all of them (USGS, 2018) and the EU is dependent on imports of these materials (EC, 2017). These metals are used in various applications, among one electronics, and are deemed important for European industry. Hence, they are classified as critical.

3. Methodology

The following chapter will introduce the methodology of the study. Explanations to what has been done and why are presented in order to give understanding of the research direction and strategy.

3.1 Working process

The working process of this study was based on the direction of search and strategy, which in turn were decided by the literature review and together with the collaborating organization, Volvo GTT. The process was divided into four main parts; *literature review*, *data collection*, *case study* and *analysis*. In the following sections, each part is explained. The case study was conducted in parallel with the other parts and will be explained accordingly. This study is characterized by a qualitative research approach, i.e. collected data is textual and retrieved through interviews. The qualitative approach, as described by Bryman and Bell (2015), was chosen since it is suitable for the interpretive nature of this study as the authors seek to interpret, identify and explain the interviewees' responses.

From the literature review and discussions with Volvo GTT, initial purpose and research questions of explanatory and normative nature took form. Björklund and Paulsson (2014) argue that when the desired outcome is to gain a deeper knowledge and both describe and explain, an explanatory approach is recommended. Continuing, normative studies are suitable when the existing knowledge and understanding of the chosen area of research is relatively profound and part of the objective is to provide guidance and possibly suggest measures. The work process was characterized by iterations, where purpose and research questions were revisited and revised continuously together with the collaborating organization.

3.2 Literature review

The initial phase of the project was dominated by finding and reviewing literature on topics related to circular economy, e.g. circular economy, circular product design, sustainable business. From the iterations and revisions of the purpose and research questions, the direction of search changed to focus more on circular economy, systems perspective and product development. From the initial data collection, literature review was expanded to include stakeholder involvement and change management. A literature review for the case study was done in parallel and focused on what an ECU is and what it contains, as well as critical materials. Sources included scientific reports, articles, journals and books. The literature was mainly obtained and gathered from Chalmers University Library database, Google scholar and Web of Science. Findings and results from the literature study were vital for understanding and specifying research objectives, placing the study in a wider context and thus contribute to increase the overall quality.

3.3 Choice of component

The electronic control units found in the instrumental panel were chosen as component of interest in this study for several reasons. Firstly, research on this type of component was found rather limited and would thus make a contribution in terms of adding knowledge to a relatively unexplored field. Secondly, based on current trends and the expected development in the industry the importance of ECUs can be presumed to increase in the future thus creating a need for investigations. Finally, ECUs contain printed circuit boards which in turn hold many critical materials featured on the European Commission's list of critical raw materials.

3.4 Data collection and interviews

As data collected, used and analyzed by firms are often considered confidential, data concerning Volvo Group presented in this report was either obtained from publicly available sources, or after review has been considered as open data. The critical materials in an ECU presented in this thesis are based on material content of an average ECU and may thus differ from the ECUs in use. Industry as well as company specific data have been collected from publicly published reports.

Based on Bryman and Bell's (2015) interview guide for qualitative research, the design of the interviews was semi-structured to encourage open answers, but still connected to the subject of study. Open-ended questions were used to promote and encourage responses from the interviewee without influencing the responses. Subjects for the interviews were people within Volvo Group, the automotive industry or with relevant knowledge connected to the aim of the study and the research objectives. Due to the time limit, suppliers were excluded from the sampling. The purpose of conducting the interviews was to gather important insights from persons active in the investigated field and get an understanding of how Volvo GTT is currently working towards a circular economy. Interviews were all but one conducted in person; the remaining one was conducted over the phone. Both approaches have its benefits, but personal interviews were preferred. The reason for preferring personal interviews was based on Bryman and Bell (2015), who explains that personal interviews may be more flexible and are more likely to last longer.

To attain a high level of ethical consideration in this study, the interviewees were all granted anonymity to ensure their privacy and they gave their consent to be included in the study. To ensure the anonymity of interviewees, only the organization they represent is provided. Interviewees have been given an individual reference that is used in the thesis to denote the interviewee. In the table below are all interviewees accounted for based on their role and organization, Table 3.1. Three interviews have been conducted outside of Volvo Group.

Table 3.1. List of interview references based on represented organizations.

Organization	Reference
Swedish dismantler	I1
Group Trucks Technology	I2
Volvo Trucks (brand)	I3
Group Trucks Technology	I4
Reference company	I5
Group Trucks Operations	I6
Swedish recycling company	I7
Group Trucks Technology	I8

3.5 Field visits and research meeting

In the initial stages of the projects a field visit was made to the Tuve factory in Gothenburg, which assembles trucks. A representative held a guided tour of the factory and explained and showed the different stations along the production line. During the visit the authors had the opportunity to ask questions and get insights to the early stages of the product life cycle thus creating a good foundation for the continued study.

Towards the end of the data collection, the authors were invited to attend a project meeting for Explore, a project within Mistra *Closing the loop*, focusing on commercialization of vehicle recycling. The authors attended as observers with the purpose of listening and learning. The meeting was attended by the automobile industry, dismantlers, recycling business, manufacturers and academia.

3.6 Treatment of data

The information collected through the interviews was treated by the use of principles originating from the field of design thinking and the Stanford d.school. Information, quotes, stories, numbers etc. were written down on post-its which were put on walls and then rearranged and categorized into themes. The themes that emerged during this stage lay the foundation for the structure for chapter 5, “Empirical findings”.

3.7 Mass Flow Analysis

With purpose of further examining and investigating the flows of the chosen component and the critical materials it contain, an MFA was conducted. The first step of the MFA was to set the boundaries of the studied system with respect to time, geographical area, and processes and activities of relevance. The system boundaries were decided iteratively by the availability of data, through interviews with actors along the component lifecycle and by discussions between the authors. The subsequent step was quantifying the flows to, within and from the system. The first and second steps were to some extent conducted in parallel. The third and final step of the MFA was analyzing and interpreting the system in terms of circular economy. In the final step, the critical materials in an ECU were taken into consideration.

The system boundaries were set to the European Union’s 28 member countries and the course of one year. Included processes were selected through interviews and data collection. See Figure 3.1 for a conceptual flowchart of the system. The main reason for choosing EU28 were homogenous efforts targeted towards production and consumption patterns, as well as a shared and open internal market between the member states. The process of producing ECUs is excluded as production occurs globally. Hence, the inflow to the system consists of both imports and domestic production.

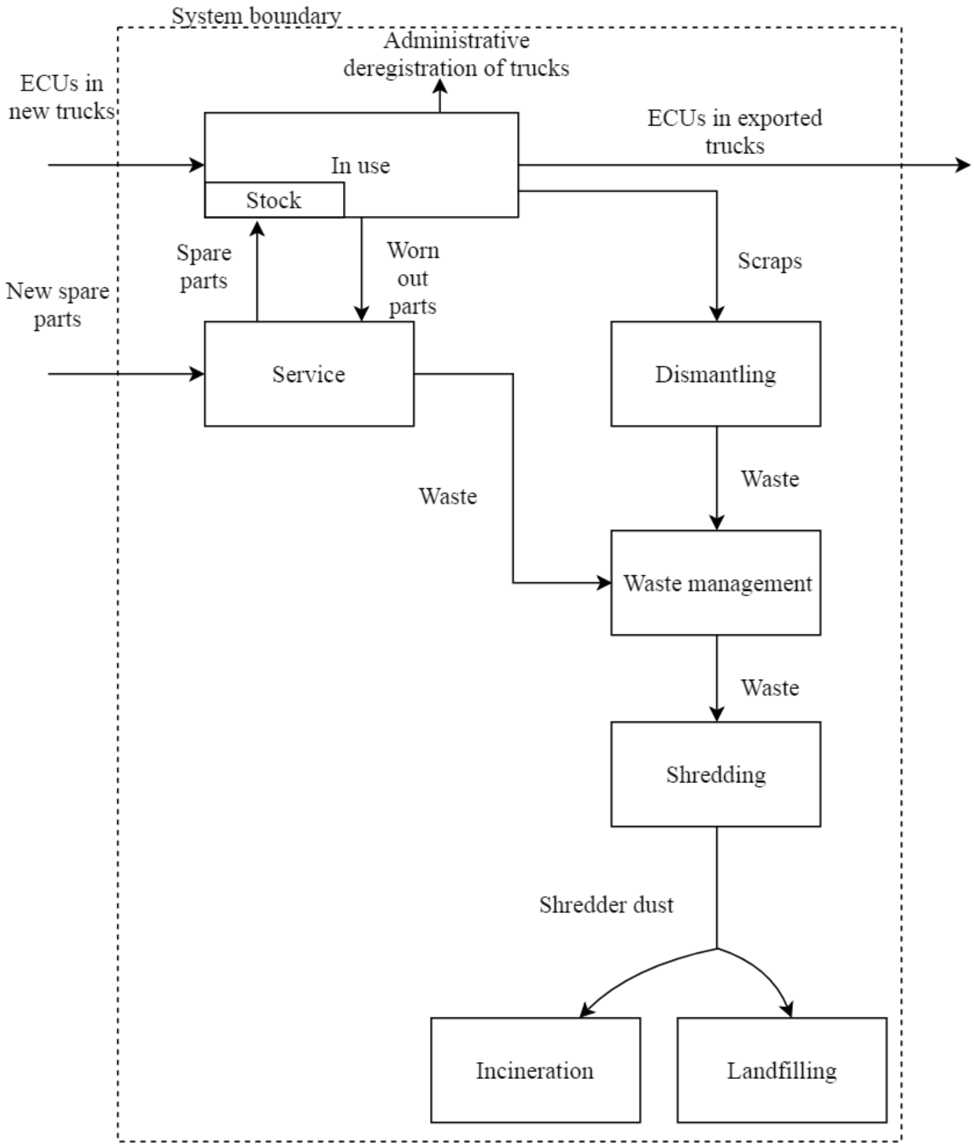

Figure 3.1.An illustrative flowchart of the studied system.

To estimate the flow of ECUs found in instrument panels of trucks in EU, following data was needed:

- The number of ECUs in an instrument panel of a truck.
- The number ECUs consumed during the life of a truck.
- Inflow of trucks to the EU.
- The number of trucks in use in EU.
- Outflow of trucks from the EU, including export and end-of-life vehicles.

To further estimate the part of the flow originating from Volvo, same variables but with data specific for Volvo was needed. Additionally, the material content of ECUs was needed to estimate substance stocks and flows in the system. Thus, by following the flow of trucks in total, and from Volvo, a material flow of ECUs could be estimated and analyzed. Two significant digits were used for data estimations and calculations. Sources of data regarding flow of trucks and ECUs: Swedish Transport Agency and European Automobile Manufacturers' Association (ACEA).

4. Results

In this chapter, the collected data is presented and analyzed based on the research questions of this study. Analysis is based on the theoretical framework provided in the literature review.

4.1 Examination of the studied component and its industrial metabolism

The following section will address the first research question. RQ1*: Is there a problem with the production and consumption of the studied component? If so, why?*

First, a description of how ECUs are developed from Volvo GTT's perspective is presented. This is followed by an examination of the product life cycle of an ECU. Then, a material flow analysis of ECUs is presented to examine whether or not there is a problem with the production and consumption of ECUs. The development and product life cycle both describe why the system looks like it does, and can further explain why there is a problem, if there is one. When referring to ECUs in this report, only the ECUs in the instrument panel were studied.

4.1.1 Development of Electronic Control Units

The ECUs are not manufactured or developed by Volvo Group (I2). Instead, Volvo procures ECUs from global suppliers, so called Original Equipment Manufacturers (OEM). In the procurement process, Volvo GTT set certain requirements on the ECUs. These requirements can be sorted into three categories: legal, technical and functional requirements. Partly what defines the requirements is where they originate from. Functional requirements often stem from the market and focus on user experience, whereas technical requirements originate mainly from Volvo and focus upon the operations of the vehicle. Legal requirements, often material and safety aspects are enforced by legislation. Regarding material requirements, critical and toxic materials should be avoided (I2; Environmental policy, 2016).

There are only around a dozen suppliers of ECUs globally, and it is therefore likely that different truck manufacturers do business with the same OEMs (I2). This means that in terms of hardware, trucks from different manufacturers may be equipped with similar ECUs. There are currently no industry standards as for types of ECU (I2).

Generally, ECUs are adapted to the truck models they are developed for and have a life expectancy of five to ten years. When the ECUs are installed in the truck by Volvo GTO, the ECUs have already reached maximum capacity regarding computational power (I2). This leaves little room for future upgrades or additional features. Thus, regarding the hardware there is no intergenerational compatibility between different generations of ECUs (I2; I1). The technical development of ECUs is rapid due to being influenced by the technical development of consumer electronics. Hence, an older truck cannot use a newer ECU, and a new truck cannot use an older ECU. Volvo Trucks has a policy that each component is to be maintained as a spare part for 20 years (I8).

During the development of ECUs currently in the system, which were developed several years ago, CE had less focus compared to today (I4; I8). Given that many manufacturers work with the same OEMs, it was believed that this was the case for the whole truck industry as well. Downstream actors such as dismantlers and recyclers were rarely consulted when examining which requirements are deemed important for ECUs. OEM's view on CE was not investigated in this study.

4.1.2 Product Life Cycle of an Electronic Control Unit

The product life cycle of an ECU describe what happens to it during its lifetime, and its flow through the industrial metabolism. To some extent, the life of an ECU is coupled with that of a truck since the ECU is a vehicle component.

The life of an ECU begins before that of a truck, as it is a component produced by OEMs and the truck is produced by Volvo. The product life cycle is presented from the truck assembly and onwards. From the interviews rough estimates for the life cycle of an ECU in EU and the life cycle of a Volvo produced truck in EU could be made. These estimates are assumed to be applicable to all ECUs and trucks in EU. For the end-of-life treatment of ECUs, collected data were specific for Sweden, but is assumed to be applicable to EU.

The life of a Volvo produced truck in EU starts at one of Volvo's assembly plants, where it is assembled into a functional product. Components are either sourced from suppliers, such as the ECUs, or manufactured by Volvo (I6, I2). The first customer often has the truck for a couple of years or up to a certain distance driven, depending on what comes first (I3). The average lifespan of a truck is difficult to estimate as it depends on how the truck is used and maintained (I3). Continuing, the truck can then be sold a second time, either within EU or exported. For a used truck that is sold again within EU, it is used for several years to come, after which it is scrapped or sold in EU, or exported (I3; I1).

The lifespan of an ECU, five to ten years, is shorter than the life of a truck (I2, I1). Given their shorter lifespan and necessary function for a truck, ECUs are often exchanged one or two times during the life of a truck (I2, I1). Attempts to repair ECUs have been made, but they have not been successful due to difficult troubleshooting (I1). Therefore, ECUs are not repaired but exchanged for new ones. The broken ECUs that are replaced are sent as waste from the service shops to waste handlers (I1).

When the life of a truck is over, it is sent to dismantlers for scrapping and waste treatment, along with the ECUs in it (I1). For each truck, Volvo provides a dismantling manual with the vehicle documentation to facilitate dismantling and proper end-of-life treatment. ECUs are dismantled into plastics and electronics, with the latter primarily consisting of printed circuit boards (PCB) and wires. The plastics in ECUs can be sent for recycling, but PCBs, where the critical material is found (Wang & Chen, 2011), are sent to waste treatment (I1, I7). There are many materials, including the critical materials, fused closely together on a PCB which are difficult to separate (I1). In these cases it is difficult for a dismantler to get paid enough by a recycler as costs for material separation increases (I1, Jensen et al., 2012). According to the Recycler, there are currently no economic benefits in retrieving the materials used in the PCBs in ECUs, even for passenger vehicles, as the cost of doing so today exceeds the value of retrieved materials. Many critical materials found in electronics in passenger vehicles are not recycled, but rather treated as waste and exit the industrial metabolism (Berglund, 2015). There is a high risk that many electronic components in a passenger vehicle are sent to shredding, and finally incineration or landfilling (Jensen et al., 2012). Hence, the waste treatment of PCBs from ECUs in Sweden will likely consist of shredding them into shredder dust, which is then sent either to incineration for energy recovery or landfilling. In rare cases, some ECUs are kept by the dismantler and sold as spare parts, around ten per year. Thus, the second least and the least favorable options in the waste hierarchy are the ones used today.

4.1.3 Knowledge of product life cycles

In the case of ECUs, interviewed organizations had different knowledge of the life cycle depending on the function of the unit. Volvo GTT had good knowledge from upstream processes to usage as these are of high importance for the development of ECUs (I2) and less knowledge of the downstream and end-of-life processes. The dismantler had knowledge from usage and downstream to end-of-life treatment. According to Terzi et al. (2010), to gain a full product life cycle perspective and enhance product development, i.e. apply Product Life cycle Management, it is important to collect the information and create a knowledge network for easy access of information.

For a truck, it was concluded from the interviews that Volvo GTT and Volvo Group have good knowledge of the life cycle from upstream processes to the usage of the first owner. An average truck changes ownership from one to several times during its life. Open borders within EU and export out of EU further contribute to the complexity of monitoring the life cycle as the truck will likely move between countries during its life. Hence, there is no clear picture of the whole life cycle of the trucks, especially not for the end-of-life processes, which may differ depending on the region the truck end the life is in. Gertsakis et al. (2002), Stringer et al. (2007) and Reed (2008) state that partnerships with various actors along a product life cycle, among them downstream actors, are needed to close material loops and minimize environmental impact.

4.1.4 Material Flow Analysis of Electronic Control Units in the European Union

The collected data and assumptions made are presented in this section. A compilation of collected data and all the calculations of the material flows are found in Appendix A.

Since the product life cycle of an ECU is largely coupled with the product life cycle of a truck, the flows of ECUs are largely coupled with the flow of trucks. Hence, investigating the truck flow is necessary in order to estimate the material flows for ECUs. What defines a truck varies between regions and the European Automobile Manufacturers Association (ACEA, 2017) has several vehicle categories that include trucks. These categories are defined by intended use and weight of the vehicles. The category of interest for this study is Medium and Heavy Commercial Vehicles (MHCV), which are vehicles intended for commercial transport activities and with a weight of 3.5 tonnes or more. All of Volvo Group's trucks produced for the European market can be categorized as MHCVs. Hereinafter; MHCVs will be referred to as trucks.

The average number of ECUs in the instrument panel in an average truck is estimated to five, though the figure varies depending on customer specification (I6, I2). It is here assumed that all trucks in use in EU have five ECUs in their instrument panels. Furthermore, the average lifespan of an ECU is between five to ten years, see section 4.1.1, but is here assumed to be 7.5 years. The turnover of a truck in the system is estimated to 17 years; hence three sets of ECUs will be consumed during the lifetime of a truck in the EU. It is rare with reused ECUs in Sweden, and reused ECUs are therefore considered negligible when calculating flows. The same is assumed to apply to EU.

In 2015 there was an inflow of 360 000 trucks to the EU, with a total of 6.2 million trucks in use (ACEA, 2017). The inflow is assumed to be accounted for in the total number of trucks in use. No data regarding outflows from the system could be obtained. The variations in total stock of trucks in EU have been around +/- 2% per year, with an average annual inflow of 330 000 trucks for the last ten years (ACEA, 2017). It is therefore assumed that the system is static with outflow equal to inflow, i.e.

outflow of trucks and outflow of ECUs equal their inflows. In Sweden when vehicles are no longer in traffic they are deregistered from the national vehicle registry (Swedish Transport Agency, 2018). Deregistration is done for all vehicles permanently leaving the usage phase. Hence, it is here argued that deregistration data can be used to map and partition the outflow from the use phase. This deregistration data is assumed to be applicable to the EU. Of the trucks leaving the usage phase in Sweden, 64% were deregistered as exports, 26% as scrapped and the remaining 10% were deregistered for administrative and other purposes (I9). In the first and last cases, it is unknown where the trucks end up. What happens to the ECUs in the exported trucks was not studied and is therefore unknown. The whole material flow is illustrated in Figure 4.1.

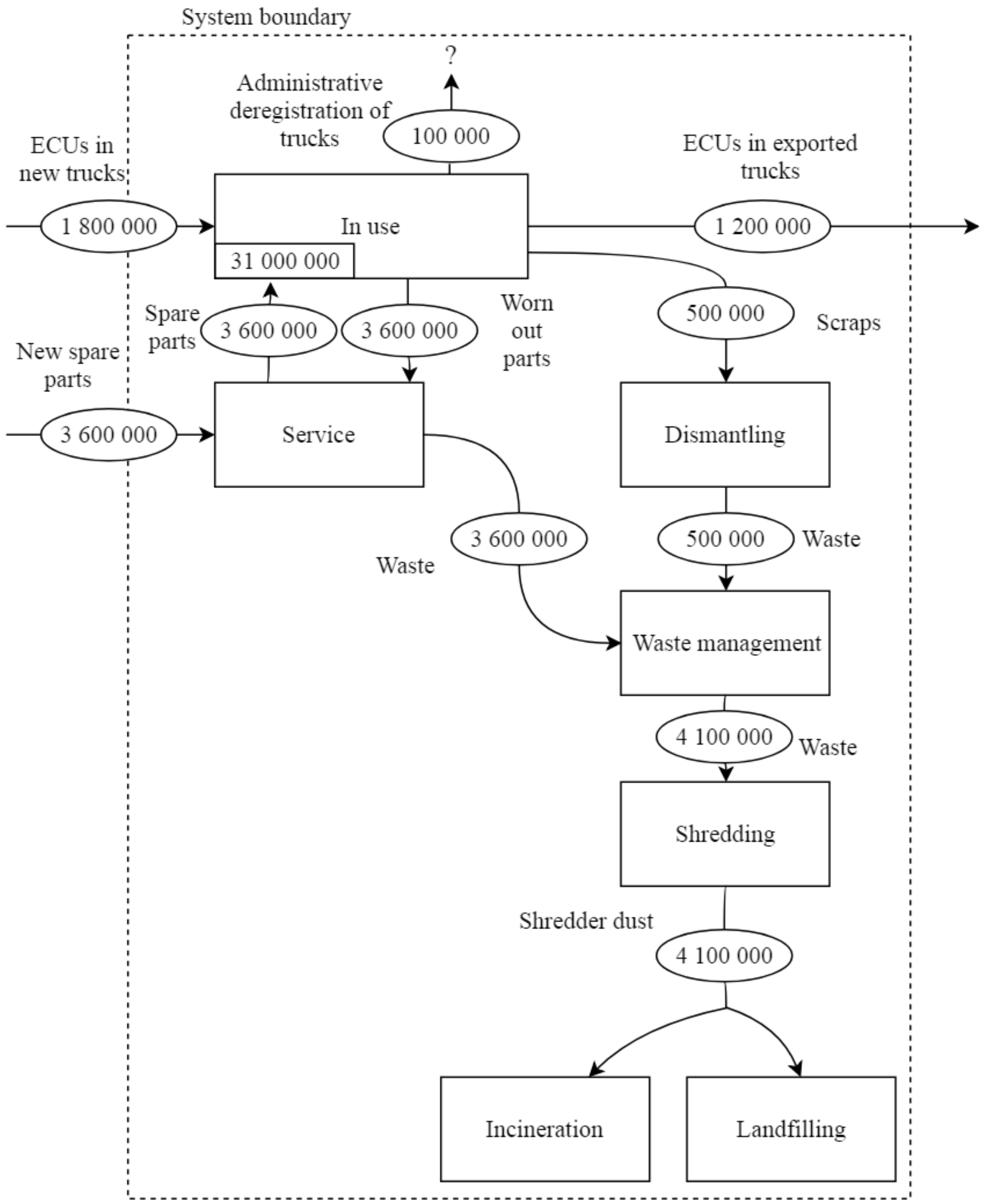

Figure 4.1. Illustration of material flow of ECUs in EU.

Based on Wang & Chen (2011), it is assumed that there is only one printed circuit board (PCB) per ECU and that all PCBs are homogenous in terms of size and content. It was assumed that an average ECU has a weight of 220 grams (I8). All ECUs are assumed to have the same material content. In

Table 4.1, the waste flow for the critical material in ECUs is shown. The outflows of critical material are further illustrated in a Sankey diagram, see Figure 4.2.

Table 4.1 Critical material in ECUs leaving the system as waste.

Critical material	Amount leaving the system as waste
Antimony (Sb)	180 kg per year (for all three metals)
Bismuth (Bi)	
Tantalum (Ta)	
Palladium (Pd)	90 kg per year

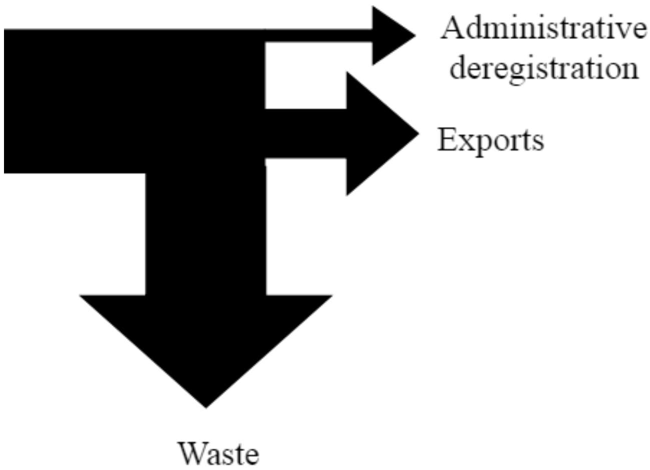

Figure 4.2. Sankey diagram of outflows for critical materials in ECUs.

Material prices indicate market value of a material and the United States Geological Survey (2018) present material prices for all of the identified critical materials. With the weight of a PCB in an ECU, the material content of a PCB and material prices, the value of the PCB could be estimated. The value of critical materials in a PCB was estimated to be low compared to the total material value of a PCB; see Table A7 in Appendix A. The total material value is estimated to 4.3 USD per PCB. Since there is one PCB per ECU, and the waste flow consists of 4.1 million ECUs, the total material value of the waste flow is roughly 18 million USD per year.

There are no recognized metrics for evaluating circularity of a system (Linder et al. 2017) however, the studied system is categorized as linear. Many of the identified factors reinforcing the linearity of the system are not within control of any single actor and not caused singularly by any actor. Given the low resource efficiency in the system, it is argued that there is a problem with the production and consumption of ECUs, showing distinct traits of “take-make-waste”. Even in a circular economy, some waste is likely generated, but these outflows should be substantially smaller compared to the ones in a linear system. Small flows of reused ECUs exist, but they are considered negligible. The interviewed dismantler sold very few ECUs per year, and for other dismantlers in Sweden the situation was believed to be similar. No further circular flows were found, hence the studied system showed no traits of circularity unless ECUs that are exported go back into the system.

Assuming that the system will stay the same, 76% of all the ECUs entering the system will eventually exit as waste. This means that 76% of all the critical materials entering the system with ECUs will end up as waste in EU. If the transport system relies on these critical materials, the production and consumption of ECUs is part of the "take-make-waste" problem. It can be assumed that lower availability of these materials would not only affect the transport industry, but everyone relying on the transportation system or need of ECUs.

23% of the outflow is exported. As no data could be found regarding destination of exported trucks, following the export flow is difficult. s. How waste is treated is here argued to depend to a large extent on market forces and legislation, e.g. value of waste compared to value of virgin resources or enforcing recycling. It is reasonable to assume that there are regional difference in waste treatment and treatment option. Therefore, there could be instances outside the studied system where reuse, remanufacturing, or recycling is conducted for ECUs.

The system is mass balanced, though there is a flow which cannot be tracked; the flow following deregistration of trucks for administrative purposes. Given the uncertainty surrounding this flow, stock could be increasing or leakage could be occurring for critical materials somewhere in the system, processes which have not been identified in this study. This flow is the smallest of the identified outflows from the use phase, but is still considered important if closed material loops are to be achieved.

Additional functionalities require more computational processing power, which is often achieved through either more or larger circuit boards. Following more electronics in trucks, the number of circuit boards in a truck is likely to increase. That could mean that the amount of critical material in ECUs, and in the truck, will increase. Though, the amount of critical materials needed for a circuit board to function has gone down due to technology improvements (I7).

The focus of the study is on the ECUs in the instrument panel, though trucks contain additional control units. Since it has not been suggested these other control units are treated differently, it is likely that they face a similar fate as the studied ECUs.

4.2 Current Situation and Improvement Possibilities

This section addresses the following research question. RQ2: *How is Volvo GTT currently working with regards to CE and how can they develop their systems perspective?*

To answer how a systems perspective can facilitate a transition towards CE, it is here argued that it is of interest to examine how Volvo GTT is currently working with regards to CE at the firm level, inter-firm level and at the regional level when developing products. This section will encompass findings from the interviews, the annual and sustainability report, and the environmental policy of Volvo Group.

4.2.1 Product Design and Development

Volvo Group is currently adopting a standardized modular system for technology, called Common Architecture and Shared Technology (CAST). Electronics are part of the CAST (Volvo Group, 2018). The system aims to reduce the number of assembly alternatives by enabling a shared component platform between the truck brands, as well as facilitate easier assembly and disassembly. When developing a new product, CAST can thus be used and the increased commonality brings benefits to both customers and the company, while lowering the complexity of the products at the same time. EMF (2013) state that standardization and modularization are two important design aspects which should be incorporated when designing for a circular economy as it may facilitate disassembly and lower complexity. The relatively low degree of standardization and modularization as well as high complexity in vehicles were specifically given as examples of barriers to efficient dismantling of ECUs (I1). Thus, it can be argued that Volvo GTT actively aims to lower those barriers with the CAST system.

When Volvo GTT are designing or developing new products, specific attention is to be given to avoidance of critical and toxic materials, resource efficiency and recycling potential (Volvo Group 2018; Volvo Group, 2016b). To facilitate implementation of such design factors in development projects, a specific eco-design tool has newly been developed and is currently being implemented (I4). This design and development approach used by GTT is similar to what both EMF (2013) and Hendrickson et al. (2002) define as eco-design. Use of the eco-design tool in product development projects is evaluated and decided in the beginning of each project. To be able to judge the need of the tool, some criteria are set and it is also recommended to advice environmental expertise (I8). When the ECUs currently in the system were developed, CE had not been in focus and this eco-design tool did not yet exist.

It was brought up during two interviews that due to the eco-design tool being newly implemented, support for using the eco-design tool could be improved to ensure better use of it. Furthermore, it was claimed during one interview that resource efficiency and securing proper end-of-life treatment are sometimes balanced against other environmental efforts. A systems perspective implies that important aspects and factors should be considered, otherwise the risk of unwanted effects increase (Lifset & Graedel, 2002). To change a system, change must be implemented on all levels in the system (Ghisellini et al., 2016; Linder et al., 2017). For Volvo GTT, this could imply better support when using the eco-design tool.

4.2.2 Internal and External Cooperation

A theme brought up by several of the interviewees was a need for better structures and support to find information regarding product life cycles (I4; I2; I8). Furthermore, a need for improved communication and knowledge exchange between divisions and functions to enhance life cycle thinking was expressed. As shown previously in the product life cycle of ECUs, different actors along the life cycle had knowledge of different parts of the life cycle, but they were not necessarily sharing their knowledge with each other efficiently. It is here argued that this is an example of silo thinking (Lambert et al., 1998; Childerhouse & Towill, 2011). Clear structures and support for finding and storing information is important from the aspect that it facilitates for others to find and use it (Terzi et al., 2010; Childerhouse & Towill, 2011).

The complete life cycle is to be taken into account when Volvo GTT is developing products (Volvo Group, 2016b; Volvo Group, 2018). There are efforts being made at Volvo GTT where they are working alongside suppliers and customers to make products and components better adapted to circular material flows (I4). For example, when developing engines and gearboxes the whole life cycle is considered from the beginning of the development process and relevant actors along the product life cycles, both upstream and downstream, are also involved. Many engines and gearboxes are remanufactured and used again (Volvo Group, 2018). Thus, both engines and gearboxes fit within CE. Both engines and gearboxes are developed and produced by Volvo Group, giving better possibilities for control over the life cycle, whereas ECUs are manufactured by external suppliers.

As illustrated in the product life cycle and development of ECUs, the end-of-life processes and actors were at the time of development not fully considered. Thus, it cannot be said that a life cycle approach, or systems perspective, had been in focus at GTT during the development of ECUs currently in the system. A life cycle approach stipulates cooperation with other actors along the life cycle (Terzi et al. 2010). By further including downstream actors, such as dismantlers and recyclers, and their perspectives in the development process, it is here argued that a better systems and product life cycle perspective can be achieved. Inclusion of downstream actors was also an expressed desire from one interviewee.

From an interview with another company, also a product developer, an example of when eco-design without life cycle perspective was given (I5). Albeit every component in a product had been designed according to eco-design principles, specifically designing for recycling, not all components could be recycled. Due to the placement of the components in the product, dismantling of it was affected. When certain components containing fluids were dismantled, the fluid leaked onto other nearby components causing material contamination and thus diminishing their value. Consequently, this led to the recycler being less willing to accept the damaged components as the material could not be recycled. Eco-design had only been applied on the components, but not on the end product which thus affected the dismantling of the end product and its components. By starting to include the perspectives of end-of-life treatment actors, the company began to apply more of a systems perspective on their own products as to ensure recyclability in practice of their products.

The example above indicates what Gertsakis et al (2002) stated, that eco-design only promotes end-of-life treatment, e.g. recycling, but does not ensure it. Furthermore, eco-design which fails to look at the system a product exists in is, by Hendrickson et al.'s definition, not eco-design. This scenario given in the example could exist for many vehicle manufacturers given the complexity of their products. End-of-life actors may be considered "*gate keepers*" of the later stages of a material flow because they control whether or not material is sent back to the system. Hence, consideration of the inter-firm level, e.g. downstream actors and their perspectives, is argued to be important when transitioning towards CE as through cooperation, systems perspective is better applied.

Over half of the interviewees stated that the business models used by most companies today do not support a circular economy. By having a business model which supports CE, it was argued to be easier to work proactively towards a circular economy. Eco-design itself is not enough when closing material loops (Gertsakis et al., 2002), and as Teece (2010) point out, development of products and business models should therefore be carried out in conjunction. EMF (2013) state that in order to transition towards a circular economy business models need to support circularity. Therefore, cooperation between product and business development is essential, and cooperation improves the systems perspective.

Volvo GTT participates in and partly finances several research projects connected to circular economy, e.g. Mistra's Closing the Loop projects. The focus of these research projects have been on the regional level. From these research projects, valuable knowledge regarding resource efficiency and how to close material loops has been created. One interviewee stated that it is not only the knowledge created that is of importance, but also the network of actors participating in the research. It can be argued that it is of importance that the knowledge and network from the research projects are shared to make use of them to their fullest potential. Viewing a transition towards CE as change, continuity is important (Senge, 1999). By ensuring continuity in the research projects, Volvo GTT can take advantage of the knowledge and networks created through the projects as well as gain valuable experience, all of which are important aspects of learning and thus changing according to Buchanan and Huczynski (1985).

5. Discussion

The study, with main focus on results and methodology, is discussed in this chapter. Furthermore, assumptions, data and applicability are reviewed.

The purpose of the study is how Volvo Group Trucks Technology, in the role of a product developer, can work more proactively towards a circular economy and improve current efforts by applying a systems perspective. The subject was investigated through a case study, interviews with actors along the product life cycle, site visits on a production plant and dismantling facilities, participation in a research project meeting, and an extensive literature review. The case study was conducted to examine any potential problems connected to production and consumption of the case component, electronic control units in the instrument panel.

5.1 Is there a problem?

Based on the material flow analysis of ECUs found in trucks in EU, it is here stated that there is a problem with the production and consumption of ECUs from a critical material point of view. The identified material flow of ECUs is significantly more linear than circular, resulting in critical materials are lost every year. It is also likely that the material flow will increase as connectivity and automation of vehicles increase. If the system stays the same, the material losses will thus increase. What causes the problem is more difficult to say as systems of this kind are governed by several factors, many of which have not been studied in this case. Examples of such factors could be business models, regulative frameworks, culture and norms. With connectivity and automation, business models may come to change, which could affect the industrial metabolism of truck components, such as ECUs. Though, this study has shown that part of the problem can be attributed to lack of incentives and possibilities for end-of-life actors, e.g. dismantlers and recyclers, to send material back as resources to the system again. As the ECUs are manufactured by external suppliers, which were left out of the study for time reasons, this study has not been able to prove if eco-design has been applied or not on the ECUs. The interviewed dismantler stated as well that there was a problem to recycle the material due to the design of printed circuit boards in ECUs. It is therefore the belief that eco-design has not been applied by the suppliers.

5.2 Developing the Systems Perspective at Volvo GTT

From the results, it is here concluded that there is a good foundation at Volvo GTT for working proactively towards a transition to a circular economy. Many concepts and tools brought up by the industrial ecology methodology are to various extents already in place at Volvo GTT. Furthermore, Volvo Group owns a dismantling business. However, the systems perspective needs to be developed in order to make better use of these tools and concepts. Design and collaborative efforts could be improved, both internal and external, as to include more perspectives found within the system.

When developing products, all system levels must be considered if production and consumption problems are to be avoided. Product design is needless to say of great importance when transitioning towards CE, especially since part of the identified problem is argued to be caused by design and development processes of ECUs. Use of the eco-design tool is required by Volvo GTT when necessary. However, the ones deciding if the eco-design tool is to be used may need more support to

make an informed decision. Product development with a systems perspective must consider the complete life cycle perspective; else potential problems may be unavoidable.
Identifying and investigating production and consumption problems of this kind, especially on a component basis, may be too grand of an endeavor for any one actor in terms of cost and time. A truck alone consists of well over a thousand components, making problem identification both costly and time consuming. Therefore, participation in industry wide research projects which focus on problem identification and solving is a useful and beneficial approach, and is here argued to be a good way of gaining systems perspective. Volvo GTT is participating in and partly funding research projects focusing on circular economy, which is good in terms of acquiring new knowledge and networking. However, a problem with Volvo GTT's research participation lies in the structure for bringing the knowledge from the projects back to the company, making it available for use in coming development projects. Hence, better knowledge management is needed. Without proper knowledge management, valuable insights regarding CE may be missed during design and development.

Generally, for product developers to enhance their systems perspective, it is here argued for the need of including stakeholders and their perspectives more. To bring those perspectives in to the development process the authors of this report argues that it is important to have someone tasked with representing those groups. Terzi et al. (2010) argue that non-existent feedback loops hinders the work of developers, but a supporting function which bridges several perspectives can facilitate functioning feedback loops. Further, to overcome the difficulties of working proactively with CE and to develop a systems perspective, a supporting function is argued to be beneficial. Such a function could provide the needed knowledge to make informed decisions, or guide where to find it. An additional role of a supporting function could be to ensure the inclusion of different perspectives, especially end-of-life, from the whole product life cycle in development projects. Von Krogh et al. (1996) and Badaracco (1991) argue that efficient knowledge management is a key factor for high performance as well as continuous improvements. A supporting function could contribute to bridge the problem with knowledge retention from research projects, and making use of the knowledge within different departments of the organization. A supporting function could in that sense increase awareness of and need for eco-design and life cycle perspective. Volvo GTT is a central actor in the life cycle of some Volvo products, connecting upstream and downstream actors. Furthermore, Volvo GTT develops products and technology, with the possibility to affect upcoming products and technology. Hence, Volvo GTT should pose the question of whether such a supporting function could be beneficial for developing their systems perspective. In alignment with Senge's (1999) as well as Cameron and Green's (2006) reasoning on change management, for an efficient supporting function, itself needs support from leaders and management to succeed.

As to which strategy Volvo GTT should use for the ECUs, the following can be said. The 4R framework was presented as different means to close material flows through an industrial system. Based on what was seen with the ECUs, e.g. low intergenerational compatibility, and how rapid the development of them seem to be, reuse is argued to be less suitable. Therefore, in order to close material flows while relying on the current business model, Volvo GTT should either focus on *reduce* or *recycle*. By selecting e.g. recycling, Volvo GTT can set additional requirements on the ECUs towards the suppliers to facilitate proper end-of-life treatment of ECUs. Recovery and disposal cannot be recommended as the critical materials would be lost.

A better life cycle perspective can be gained through enhanced collaboration with the various actors along, e.g. dismantlers and recyclers. Though, eco-design alone, albeit with a life cycle perspective, cannot close material flows. Hence development needs to be done in conjunction with e.g. business development.

5.3 Methodology, data and assumptions

A prominent focus of this study has been the perspective and role of a product developer, with the latter being confined to what can be considered and handled in the product developing phase. This has affected the direction of search for this study, i.e. what has been investigated in the literature review and interviews.

Regarding the case study, to make the project more manageable the research was limited to the ECUs in the instrument panel. However, it is reasonable to assume that there are many more electronic devices in a truck and including them will thus provide a larger material flow more coherent with the actual flows in the system. Furthermore, the material flow for ECUs is probably several times larger than what is presented in this case. When estimating the material content of the PCBs in the control units it was assumed that there is no difference between manufacturers and that there is only one PCB per ECU. These assumptions do not necessarily correlate with reality, and material content, in terms of amounts and which materials, can thus be assumed to vary, consequently affecting the amount of critical materials in circulation in the system. The assumption that two sets of ECUs are exchanged during the life of a truck is furthermore subject to criticism. Trucks produced today have yet to reach both service and end-of-life, thus how many sets of ECUs that on average are exchanged is yet to be known. Furthermore, some trucks being scrapped today are of high age and yet have the original set of ECUs installed, which affect the material flow of ECUs.

Suppliers and upstream actors were excluded in the study, their perspectives are absent. The importance of a complete life cycle perspective has been stipulated in this study, but could not be fully achieved in this here.

It was a desire from the authors’ part to learn more about repairs and exchanges of ECU in operating vehicles and the intention in the beginning of the project was to include additional perspectives such as repairers to cover a more holistic view of the investigated component and the system in which it fits. However, all attempts to do so were without success and due to the limitations of the project time it was unfortunately not possible. Working towards including more perspectives is something that can be used to improve the study and should be considered for the future.

There are many aspects relevant in the product developing phase to consider concerning a transition towards circular economy. A system consists of several actors, and the system is affected by how they interact with one another. This study has focused on a few of them and is thus a clear limitation to the study and something to consider when conducting further research on the subject.

Since the available information in this field was limited, the explorative approach was deemed most suitable. The explorative nature of this study can be considered as both an advantage and a limiting factor. The research was qualitative and as such under the risk of interpreter bias which is important to recognize when reviewing the result and analysis.

5.4 Applicability of Results and Methodology

The results of this study are argued to be useful for a product developer in understanding how the system levels are connected and what these connections entail. Furthermore, the results can contribute to prepare an organization such as Volvo GTT for upcoming changes in requirements, either through legislation or customer demands. CE theory has been linked to more practical aspects, and this study has in that sense bridged the gap between the two.

The overall methodology used in this study is here argued to be useful for both academic and practical endeavors. The methodology used in this study is argued to be applicable elsewhere, especially for product developers, and in other industries that wish to work more proactively with circular economy. Furthermore, the approach could be useful in research in terms of problem identification and investigating causes behind the problem.

Research regarding recycling of electronics in passenger vehicles have shown similar results to the ECU case study provided here, i.e. critical materials in electronics in vehicles are to a large extent lost. The issues of future resource availability and resource efficiency are relevant to address for both passenger cars as well as for trucks.

It is reasonable to assume that there are regional differences with regards to dismantling and recycling rate of electronics in vehicles. Hence, the applicability if this study is here argued to be valid only for the studied system, i.e. the European Union. The regional differences could stem from varying economic incentives and also how the dismantling and recycling process is carried out. Furthermore, this study only considers products currently in the system. There could be efforts made elsewhere which aim to close the material flows of ECUs, but have not been studied.

5.5 Proposals for future research

This study has focused on ECUs only, but there are a lot more electronic components in a truck than ECUs. Therefore, for future studies, a focus could be on all electronics in a truck as many of them will likely contain critical materials as well. The recycler stated that there are currently no economic incentives to recycle the critical material in ECUs, but PCBs in consumer electronics are recycled. Thus future research should be connected to wider research on the field of waste electrical and electronic equipment to see how the vehicle industry differs from e.g. home electronics and why.

Another interesting research aspect is business models and their effect on product design and material flows. Product servitization is often heard in the context of circular economy, i.e. selling function of a product instead of the product. Such a change requires new business models and structures which do not rely on number of sold units. Even with a circular business model, product design must change and the ensurement of proper end-of-life treatment. Product design, business development and life cycle perspective must go hand in hand to transition to a circular economy, one without the other is not enough. For further research, inclusion of business development could therefore be of interest to see how it affects the material flow in detail.

Passenger vehicles in EU are governed by an end-of-life directive, which does not apply for trucks, which stipulate that a certain amount of each vehicle should be possible to recycle. Despite this regulation, electronics in passenger vehicles are not yet functionally recycled. Hence, it could be of interest to study design of legislation, intended outcome and its actual outcome.

Regarding the proposed supporting function, it is highly relevant to consider its design to ensure it fit its purpose. Hence, it can thus be argued to be of interest to find out how future studies on this subject can be of interest for Volvo GTT.

Finally, for future research, a recommendation is to include all actors along a product life cycle, from upstream suppliers to users to downstream end-of-life actors and system factors found outside a product life cycle, e.g. regulations and norms. Such a focus is likely to better study cause and effect of production and consumption.

6. Conclusion

This study has investigated how a product developer can improve its systems perspective to facilitate a transition towards a circular economy. From the results, it was shown that even though efforts targeted towards a transition to a circular economy, the systems perspective may be lacking which hinders the efforts to reach their full potential. The need for a systems perspective is essential when changing a system, else the risk of unwanted consequences exist. Furthermore, a systems perspective can help an organization to see how different efforts and actors are connected. Adapting methodologies and tools such as eco-design can be an important contributor to achieve the greater goal but is deemed insufficient as the only means. Eco-design alone does not warrant a circular material flow, thus product life cycle perspective and business development done in parallel are needed.

From the MFA, it was shown that the material flow of ECUs in trucks is linear, i.e. a “take-make-waste” pattern with critical materials being lost. This is also the case for ECUs in passenger vehicles. Hence, there is a problem in terms of resource use of ECUs in the EU. By examining the product life cycle of an ECU and the development of it, the problem could partly be attributed to the design, lack of efficient separation and recovery techniques and absence of incentives for dismantlers and recyclers to send the material back into the system. Volvo GTT who is in charge of developing all of Volvo Group Truck’s products has a possibility to contribute to changing the system to a more sustainable one, especially in terms of resource efficiency. Furthermore, Volvo GTT is a central actor in the product life cycle of Volvo products, connecting upstream processes and actors with downstream. In terms of transitioning towards a circular economy, there is a good foundation to build on at Volvo GTT. It was found that their systems perspective could be developed further to improve their current CE efforts and a transition towards CE.

Based on the results, following recommendations are given to develop systems perspective:

- Involve end-of-life processes and actors more in the development process.
- When participating in research projects utilize them better and ensure knowledge retention from them is well spread. Take full advantage of the networks and knowledge within research projects and ensure that the knowledge and ideas developed are being brought back.
- Connect related product life cycle knowledge existing along a product life cycle.
- Provide enhanced support for those who need it regarding use and implementation of eco-design and similar tools.

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Appendix A

As no specific data for the flows of ECUs have been found, data regarding the flow of trucks have been collected and used as a basis for estimating the material flows of ECUs found in instrument panels in EU. Throughout the data collection, derivation and calculations, two significant digits have been used. A more detailed explanation of the flow is given in subchapter 4.1.2, though the flow is briefly explained here for illustrative purposes. All figures are for EU unless otherwise stated. The material flows of ECUs are *only* for ECUs found in the instrument panel specifically.

The material flows of ECUs in EU.

The data that has been collected is compiled in Table A1. The collected data is not sufficient for estimating material flows in the system. Thus, certain data was assumed to make estimations possible. Major assumptions are presented in subchapter 4.1.1, with some minor assumptions for calculations are presented here. Furthermore, certain data was derived from the collected data. Following the compiled data, calculations for the MFA are presented. Assumed and derived data is presented in Table A2, with the derivations presented previous to the table. Then an illustration of the material flow is presented, see Figure 4.1.

Table A1. Collected data regarding the flow of ECUs in instrument panels in EU.

Data	Amount
Number of ECUs in IP of a long haulage truck	5 ECUs
Lifespan of an ECU	7.5 years
Trucks in use in EU	6 200 000 trucks
Inflow of trucks to EU 2015	360 000 trucks
Percentage of trucks exiting usage phase that is exported	64%
Percentage of trucks exiting usage phase that is sent to scrapping	26%
Percentage of trucks exiting usage phase due to administrative purpose	10%

The outflow of trucks from the usage phase is assumed to be equal to the inflow, i.e. 360 000 trucks per year.

The lifetime of an average truck could not be found, however, the turnover time for a truck in the system can be derived by dividing the total trucks in use divided by the yearly outflow of trucks:

$$6\ 200\ 000 \text{ trucks in use} \ / \ 360\ 000 \text{ trucks exiting the usage phase per year} \ = \ 17 \text{ years}$$

By taking the turnover time of a truck and dividing it with the lifetime of an ECU, the number of sets of ECUs consumed per truck can be obtained: $17/7.5\ =\ 2.3\ sets\ of\ ECU$

Since the number of sets can only be an integer, the figure is rounded upwards to 3 sets of ECUs per truck. Thus, a truck will need to replace all ECUs in the instrument panel twice during its lifetime. There will therefore be an inflow of ECUs to EU for service matters. Assuming a normal distribution of the age of trucks in use, the inflow of ECUs for service matters is twice the size of the inflow of ECUs following new trucks. See Table A2 for the derived data.

Table A2. Assumed and derived data needed for estimating ECU flows.

Data	Amount
Outflow of trucks from EU	360 000 trucks per year
Turnover time for a truck	17 years
Number of ECU sets consumed during the turnover time of a truck	3

Continuing with the inflow of ECUs to the system, it is here argued to consist of mainly two flows, namely inflow of new trucks to the system as well as the ECUs for service matters. The inflows of ECUs following new trucks is obtained by taking the number of trucks flowing in and multiply it with the number of ECUs in an instrument panel:

$$360\,000\ trucks\ *\ 5ECUs\ per\ truck = 1\,800\,000\ ECUs\ per\ year$$

Given the assumed normal age distribution of trucks, the inflow of ECUs for service matters is:

$$360\,000\ \text{trucks} * 2\ \text{generations in need of service} * 5\ \text{ECUs per truck} = 3\,600\,000\ \text{ECUs per year}$$

The total inflow of ECUs to the system is thus 5 400 000 ECUs per year.
The total amount of ECUs in use is given by taking the number of trucks in use and multiplying it with the number of ECUs per truck:

$$6\,200\,000\ trucks *\ 5ECUs\ per\ truck = 31\,000\,000\ ECUs$$

Given the assumed static system with outflows equaling inflows, this must apply to ECUs as well. Important to note though is that the outflow from the usage phase is partitioned into different flows. The outflow of trucks that is due to exports amounts to 64% of 360 000, whereas trucks sent for scrapping amount to 26% of 360 000. Scrapping is performed during dismantling of the truck. Furthermore, an equal flow to the ECUs flowing in for service matters must be exiting the usage phase, i.e. 3 600 000 ECUs.
Outflow of ECUs following exports:

$$0.64 * 360\,000\ trucks * 5ECUs = 1\,200\,000 ECUs\ exported$$

ECUs leaving the usage phase sent for dismantling:

$$0.26 * 360\,000\ \text{trucks} * 5\ \text{ECUs} = 470\,000\ \text{ECUs sent for scrapping}$$

ECUs leaving the usage phase due to administrative reasons follow the outflow of trucks due to administrative reasons which is the remaining part:

$$360\,000 * 5 - (1\,200\,000 + 470\,000) = 100\,000\ ECUs$$

ECUs leaving the usage phase due to replaced in service matters: *3 600 000 ECUs as waste*

At the dismantlers, ECUs become waste and is sent for waste management. ECUs that are replaced during service is also treated as waste and sent for waste management. From waste management, both flows are thereon treated as a single flow. Hence, the flow from waste management and onwards amount to:

$$470\,000\ \text{ECUs} + 3\,600\,000\ \text{ECUs} = 4\,100\,000\ \text{ECUs sent as waste per year}$$

In Table A3, all the flows of ECUs in EU are listed together with the sizes of the flows.

Table A3. The flows of ECUs in EU.

Data	Amount
Inflow of ECUs following new trucks	1 800 000 ECUs per year
Inflow of ECUs for service matters	3 600 000 ECUs per year
ECUs in use in EU	31 000 000 ECUs
Outflow of ECUs due to export	1 200 000 ECUs per year
ECUs exiting the usage phase and sent for scrapping	470 000 ECUs per year
ECUs exiting the usage phase due to service	3 600 000 ECUs per year
Outflow of ECUs as waste	4 100 000 ECUs per year
ECUs exiting due to administrative reasons	100 000 ECUs per year

With all the flows to, from and within the system estimated, the MFA for ECUs can be illustrated together with sizes. See Figure 4.1 for an illustration of this MFA.

Validating the results is done by mass balancing the system:

$$(1\,800\,000 + 3\,600\,000) - (1\,200\,000 + 4\,100\,000 + 100\,000) = 0$$

Regarding the critical material content of printed circuit boards in ECUs, the data seen in Table A4 applies.

Table A4. Critical material content of PCBs in ECUs.

Material	**Percentage of PCB weight**
Antimony (Sb)	0.02
Bismuth (Bi)	
Tantalum (Ta)	
Palladium (Pd)	0.01

With the assumptions that there is one PCB per ECU and that all PCBs are homogenous with a weight of 220 grams, critical material flows can be estimated.

Total annual inflow of Sb, Bi and Ta:

$$5\,400\,000\ ECUs * 0.22\ kg\ per\ PCB * 0.0002\ fraction\ of\ Sb, Bi\ \&\ Ta = 240\ kg\ of\ Sb, Bi\ \&\ Ta$$

Annual outflow of Sb, Bi and Ta due to export:

$$470\,000\ ECUs\ exported * 0.22\ kg\ per\ PCB * 0.0002\ fraction\ of\ Sb, Bi\ \&\ Ta$$
$$= 21\ kg\ of\ Sb, Bi\ \&\ Ta$$

Annual outflow of Sb, Bi and Ta as waste:

$$4\,100\,000\ ECUs\ as\ waste * 0.22\ kg\ per\ PCB * 0.0002\ fraction\ of\ Sb, Bi\ \&\ Ta = 180\ kg\ of\ Sb, Bi\ \&\ Ta$$

Annual outflow of Sb, Bi and Ta due to administrative purposes:

$$100\,000\ ECUs\ as\ waste * 0.22\ kg\ per\ PCB * 0.0002\ fraction\ of\ Sb, Bi\ \&\ Ta = 4\ kg\ of\ Sb, Bi\ \&\ Ta$$

Total annual inflow of Pd:

$$5\,400\,000\ ECUs * 0.22\ kg\ per\ PCB * 0.0001\ fraction\ of\ Pd = 120\ kg\ of\ Pd$$

Annual outflow of Sb, Bi and Ta due to export:

$$470\,000\ ECUs\ exported * 0.22\ kg\ per\ PCB * 0.0001\ fraction\ of\ Pd = 10\ kg\ of\ Pd$$

Annual outflow of Sb, Bi and Ta as waste:

$$4\,100\,000\ ECUs\ as\ waste * 0.22\ kg\ per\ PCB * 0.0001\ fraction\ of\ Pd = 90\ kg\ of\ Pd$$

Annual outflow of Sb, Bi and Ta due to administrative purposes:

$$100\,000\ ECUs\ as\ waste * 0.22\ kg\ per\ PCB * 0.0001\ fraction\ of\ Pd = 2\ kg\ of\ Pd$$

Value of materials in an ECU

By taking the amount of each material in a PCB in an ECU and multiplying it with current market value and then summarizing it for all materials, the total material value of a PCB can be obtained. The material composition of a PCB can be seen in Table 2.3 under section 2.8. The weight of a PCB is 220 grams. Resin board and solder are left out as it is argued to have a low value. The material "others" is also left out due to non-disclosed material. Content will be rounded to two digits. Material prices indicate the market value of a material and are retrieved from United States Geological Survey (2018). For antimony, bismuth and tantalum, an equal distribution is assumed.

Table A5. Material content and value of a PCB in an ECU.

Material	Content, grams	Content Value, USD
Copper (Cu)	35	0.22
Iron (Fe)	6.6	0.47
Nickel (Ni)	4.4	0.064
Silver (Ag)	0.11	0.058
Gold (Au)	0.066	2.8
Palladium (Pd)	0.022	0.7
Antimony (Sb), Bismuth (Bi), Tantalum (Ta)	0.044	0.0031
Total Value:		**4.3**