Modular Design Approach as Enabler for Operational Efficiency of Closed Loop Manufacturing Systems

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To my grandparents, Giuseppe and Albina.

"All the effort in the world won’t matter if you’re not inspired" (Chuck Palahniuk)
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Abstract

The possibility of manufacturing like-new products by using only a fraction of the energy and raw materials that would actually be required to make the same new products is investigated. The field of recovering and adding value, besides restoring value, to already-used products could be environmental as well as economic opportunity for the manufacturing industry. By aiming at resources conservation in the supply chain, the manufacturing industry might, on one hand, significantly reduce the impact of their production practices on the environment, both by reducing the waste destined to the landfill and by decreasing the level of procurement of raw materials that inevitably leads to exhaust the non-renewable energy sources; on the other hand, it might close the loop on the raw materials, consistently reducing internal costs. The reactive response to the environmental legislations might not be the most successful solution. A proactive action that is intentionally restorative by design is desirable in the industry in order to be more environmentally conscious and profitable. Producing by re-producing is advised as the new adventure to embark on. This Master Thesis aims to present possible solutions to tackle the problem of resources’ scarcity on our earth, by starting from suggesting to avoid manufacturing what is not strictly needed, and to render this process as profitable as possible. Recovery activities, which include reuse, remanufacturing and recycling, are considered as a starting point to enable the revolutionary process of Resource Conservative Manufacturing (ResCoM). Since the majority of today’s products are not conceived for reuse and/or remanufacturing, the revolution should start from the design phase. The approach that the present thesis proposes is based on the concept of modularity exploited in the context of DfX (e.g. Design for Environment, Disassembly, and Remanufacturing). The modular design methodology, alongside ResCoM principles, might lead to the manufacturing of products with several lifecycles, whose number can be estimated at the design stage, and entails the planned recollection of the product at a defined time in order to remanufacture what is needed to get an upgraded and perfectly functional product that could be sold in the same or different markets.

This thesis concludes with a case study-based example of the methodology application that lies in the context of closed loop manufacturing systems. Closed loop dynamics are at the basis of the entire investigation. The design features of a fully modular semi-commercial washing machine, presented in the case study, show this methodology’s benefits achievable in the context of remanufactured products in a closed loop supply chain.
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Abbreviations

B2B: Business-to-business
B2C: Business-to-consumer
CLSC: Closed-loop supply chain
DfE: Design for the Environment
DfRemfg: design for Remanufacturing
DfX: Design for X (Design to support X activities)
EoL: End-of-life
EoU: End-of-Use
FP: Functional Product
ICT: Information and Communications Technology
LCA: Life-cycle Assessment
MFD: Modular Function Deployment
MLC: Multiple Lifecycle
OEM: Original Equipment Manufacturer
PSS: Product Service System
ResCoM: Resource Conservative Manufacturing
Re-mfa: Remanufacturability
SME: Small Medium Enterprise
1. Introduction

In this age, more than ever, manufacturing firms are exposed to the encumbrance of being competitive. Competitiveness can be measured by the ability of offering products that satisfy customers a way beyond their expectations, in terms of functionality, cost efficiency, trend and time efficiency. The manufacturing industry is therefore put under pressure to make the best use of resources, with regards to energy and materials, which are available on earth. If, on one hand, this incentive to fast production to the detriment of the few non-renewable resources left comes from the demanding party represented by consumers, on the other hand, it is exacerbated by the industry itself. Indeed, industrial operations, most often, do not take into account the safety of the environment owing to their desire of being successful on the market.

As stressed by the European Commission in plenty of the presented environmental directives, industrial production processes are accountable for a significant part of the total European pollution, particularly in terms of greenhouse gases and acidifying particles emissions, solid and water waste¹.

1.1 Background

U.N. warns that the world does not have much time left to tackle problems connected to proper use of water, energy, and resources in general, in a context of rapidly increasing global population. In fact, it is estimated that, by 2025, the world’s population will increase by one billion and it will get close to ten billion people by 2050². According to U.N. projections, by 2030 the world will require 30% more water, 45% more energy, and 50% more food ³ and if the consumption’s levels remain the same of what they are today, there will be no good consequences, but poverty. Today’s global behaviour is indeed testing the earth’s limits to supply. The U.N. report states that the modern development model is far from sustainable, therefore a radical change is needed and the starting point may be seen in the economic crisis that has afflicted the world for some years now.

In order to keep the levels of global warming below 2°C – the temperature increase from the levels of pre-industrial times - gas emissions from all major economies must be consistently reduced. Solutions to part of these global problems are offered by the United Nations with e.g. pre-fixed goals that lead to a low-carbon economy, with beneficial effects on several aspects, from the reduced level of pollution in the air that people breathe every day to less money spent on health care owing to reduced health problems connected to pollution⁴. The key is to be energy efficient and it is important that this goal is set in mind right from the conception of each product, being it a car or a household appliance. A solution to reduce gas emissions, the level of procurement of raw materials involved in the process of manufacturing of products, the non-efficient way of managing water and ecosystem would be reached through a policy of incentives and disincentives that should start from the governments. These might be the pioneers of sustainability among society, economy and environment.

“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. This is a pivotal statement in “Our common future”, also known with the name of the Brundtland Report as part of the UN Documents (1987). The achievement of the needs for the future generations might be hampered severely if actions are not taken to reduce the

¹ http://ec.europa.eu/environment/industry/stationary/ied/legislation.htm
³ http://www.reuters.com/article/2012/01/30/us-un-development-idUSTRE80T10520120130
⁴ http://ec.europa.eu/clima/policies/roadmap/index_en.htm
resources consumption, in terms of energy and virgin materials, waste of water, solid waste generation, and harmful carbon dioxide emissions. All these factors have caused serious damage to the environment, with a visible effect in climate change in the past decades. In addition, another issue might be similarly life changing as the risk driving factors mentioned above, and it consists of the drastically growing rate of the landfilling. The materials obtained by depletable resources employed in the manufacturing industry are no longer an option (Ferguson and Souza, 2010), especially in the times being when the consumers discard the products no-longer-needed extremely frequently. The technological advancements in business-to-customer products, such as cell-phones, outline a situation in which customers tend to dispose of their products even earlier than their useful lifetime, when they are actually still functioning properly. Today, more than ever before, industry produces more and more high-tech products, satisfying even the most demanding customers’ needs, with, however, a much faster obsolescence rate. It is, indeed, common to buy new products for the only reason that they are new and have a better aesthetic appearance, alongside with enhanced technology (Tchertchian et al., 2009). The land available for waste disposal will soon be depleted and the standards of living will inevitably become unbearable. The business practise that might lead to a long-lasting solution is to manufacture goods that are able to endure for extremely long time, thus reusing and/or recovering the non-renewable materials that constitute the products. In order to achieve this goal, recycling is no longer sufficient and not as sustainable as it is believed, therefore other procedures, such as remanufacturing, and components’ reuse, or reuse in different markets, must be investigated (Ferguson and Souza, 2010).

Alongside with the impelling WEEE regulations affecting the manufacturers and aiming to avoid improper recycling and/or recovery activities, or disposal of electric and electronic equipment waste, there is an urge for resources, such as virgin materials and energy, consumption reduction and waste production (United Nations University, 2008).

Indeed, according to a forecast related to the increases in the global population and consequently in the global GDP per capita, the total impact of resources consumed and waste generated is likely to be deleterious. It is, in fact, estimated that if the technology in fifty years is the same of today, the resources needed will be ten times more as well as the need for the capacity to deal with the waste being produced (Kumar et al., 2005).

It follows that an efficient methodology to allow for a sustainable development must be discovered because the current methods incur in some hindrances when it comes to remanufacture for multiple lifecycles.

1.2 Research Questions

The main points that will be addressed in this thesis are:

1. Demonstration of how modular design approach can be considered as an enabler for closing the loop of manufacturing systems.
2. Description of why modular product architecture can be considered more efficient than integral product architecture when activities to ensure resources conservation are performed.
3. Is the proposed approach efficient for closing the specific loop of firms manufacturing semi-commercial washing machines?
4. Does the current modular approach need a re-thinking to properly satisfy the global requirements on the environment?
1.3 Research Motivation and Aim

The central motivation for this specific research is driven by the impelling need of proposing a feasible solution to overcome the issue of overexploitation of earth’s resources.

This thesis project aims at showing that caring for the environment does not entail a negative impact on a country’s wealth. The increasing environmental consciousness sets the pace for a new trend that would allow manufacturing organizations to reduce the degrading impact on the environment and, at the same time, be profitable. It is a matter of restoring the economy through being ‘green’ and shaping the society’s mindset towards a more environmental education. The challenge of making profits while being sustainable is offered by showing how modular design approach would enable to close the manufacturing systems’ loop.

1.4 Delimitations

This thesis project aims at demonstrating the research questions formulated above. In details, the challenges associated with closing the loop for the manufacturing firms are investigated. However, the lack of examples of recovery activities to enhance resource conservation regards several different fields, yet not all of them are within the scope of this research.

Although the results of the study might be partly applicable to different product categories and might be of interest for various manufacturing firms, a specific highlight is on the firms producing semi-professional washing machines.

2. Research Framework

2.1 Definition of CLSCs, Resource Conservative manufacturing and Circular Economy philosophy

A forward supply chain is the complex of all the parties that, directly or indirectly, are committed in satisfying customers’ needs (Chopra and Meindl, 2010). Traditional forward supply chains are no longer adequate to fulfil the terms of the global requirements on sustainability since they entail a typical behaviour of buying, using, and discarding products without thinking of their environmental consequences. Moreover, the retention of this kind of system would presume unlimited and inexhaustible resources and energy (see fig. 1).

The traditional flow of materials, information, and funds from the manufacturer all the way to the customer is needed to return back, driving the used products back in the original chain (Ferguson and Souza, 2010). This is where a concept, new for some, comes into play: Closed-loop supply chains (CLSCs).

CLSCs encompass both the forward and the reverse supply chains, highlighting and dealing with the tactical aspects and the strategies that connect the two. Therefore, the reverse supply chain includes actions and relations among the parties involved in managing the flows of products taken back from the market for either early end-of-use (EoU) or end-of-life (EoL). Typical reverse supply chain activities include separation, reuse, remanufacturing, and recycling. Reverse supply chains are, indeed, feasible due to the existence of a strong reverse logistics network, where the reverse logistics accounts for the management of inventory and transportation of the returned products, namely the cores, and information associated with them from the consumer back to the Original Equipment Manufacturer (OEM), the firm in charge for recycling activities, or any third-party (Vachon and Klassen, 2010).
Ellen McArthur Foundation\(^5\) considers the linear “take, make, dispose” model, which is based on the procurement of great deals of resources and energy fast and easy to obtain, as an improper and unpromising model for the current cultural, environmental and economic framework. Indeed, given the limited nature of resources on earth, the effort of the manufacturing industry in reducing the fossil energy and resources consumption will solely postpone the disaster, but not avoid it. Therefore, structural and strategic changes in the operating system and modification in the consumers’ consciousness about wastefulness, thus modification of their behaviour must be achieved. Alongside with these, sustainable development will be enhanced if consistent changes are incorporated. These changes are of different origins, such as economical, based on cost, economic stability, market perception, strategic suppliers and rate of growth; societal, in terms of education, individual and community rights, governance interest and involvement; and ecological, with regards to environmental health, with reduction of hazards to humans, ecosystem vitality, environmental factors in production, leading to a successful industrial ecology (Chen et al., 2014).

It is, indeed, desirable and somewhat necessary to move towards Circular Economy. Ellen McArthur Foundation (2013) defines it as “the one that is restorative by design, and which aims to keep products, components and materials at their highest utility and value, at all times”.

In particular, moving towards Circular Economy entails a total elimination of waste and not only in the manufacturing processes, as Lean Manufacturing aims to do by tackling “Muda” (meaning waste in Japanese), but in all the processes involved in the creation of the product. Circular Economy can be defined

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as a form on industrial economy that has the specific objective of being restorative intentionally. The important step in achieving this goal lies in the product design that is required to be conceived to support the circulation of all resources used in the process of creating a product. Therefore, the foundation of this type of economy lies around the use and reuse of components throughout product lifecycles.

It is possible to have a better understanding of the concept of Circular Economy if it is put in comparison with the linear “take-make-dispose” economic model. The latter generates waste in all the processes and makes usage of non-renewable energy sources; the former aims at prolonging the product’s and/or component’s lifecycle by reusing or upgrading them, so that they can be useful for as many productive lifecycles as possible. The main strength point of this concept is based on the achievement of a smart strategy to manage resources in order to exploit reuse and reach service-life extension.

‘Design-to-fit’ is a pivotal driver in the fulfilment of optimized flows of materials, information and funds, and the delineation of an efficient framework that would be adequate and highly responsive to changes even in the long-term.

According to Ellen McArthur Foundation (2013), it is necessary that the OEMs have full control and responsibility over the goods from them manufactured, in order to improve serviceability and reduce to a minimum the sales of one-way consumption products.

The starting point for this industrial revolution in the context of resources’ conservation lies in the development of an efficient and effective network for the take-back of used products, business model design procedures that aim at manufacturing products that have more than one life, each of which is supposed to be long lasting, and that are designed in a way that it is easy to disassemble and refurbish them.

With the strong aim of developing sustainable strategies and after his first success in 1982 with his paper “The Product Life Factor”, the architect Walter Stahel actually encourages the ‘service-life extension of the goods’ by proposing activities, such as reuse, repair, remanufacture, and technologically upgrade.

Stahel coined the phrase “cradle to cradle” as a repulsive reaction to what someone defined as “cradle to grave”. He sees the grave for waste as a going-back solution that does not imply any form of progress. Graves are to be considered solely as last options, when nothing else is applicable.

The vision of “cradle to cradle” is now preferred to the “cradle to grave” one as also McDonough and Braungart (2010) argue in their book. They coin the phrase “waste is food”, meaning that all products should be designed in such a way that, after their useful life, they yield nutriment for something new that, in the manufacturing context, would be a product that flows in the circular pattern of the CLSC.

Thus, possibilities of remaking products starting from pre-made ones are to be exploited, alongside with the chances of assigning them new and different purposes and/or functions (re-purposing), then not just limiting to re-producing the same quality levels that the returned products had in their previous lifecycles. This ‘Design out waste’ is at the foundation of the circular economy philosophy.

Besides the valuable potential of using waste to re-create products, other pivotal principles on which the circular economy concept is founded are the smart exploitation of features that allow being readily reactive to the extremely fast-changing reality. Some of these features include modularity, versatility, and flexibility, which appear to be extremely relevant in this specific context. Efficiency is no longer the only requirement.

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6 http://www.mckinsey.com/insights/manufacturing/moving_toward_a_circular_economy
7 http://www.emg-csr.com/blog/circular-economy/
since it leads the product not to be extremely responsive to the changing market (Ellen McArthur
Foundation, 2013); on the other hand, it makes some systems weaker, as even pointed out by the trade-off
efficiency-responsiveness in the responsiveness spectrum in the effort of achieving a supply chain strategic
fit. Another pillar in succeeding in circular economy or ‘loop economy’ is the choice of using renewable
resources over the depletable ones.

In addition to this, it is important to “Think in ‘systems’”, meaning to be able to totally understand the
interconnections and relationships among the parts constituting a whole system. These factors are taken into
account in the frame of society and environment, where the thinking of a real world system does not follow
the linear logic.

As the word economy in ‘circular economy’ suggests, economic aspects are considered, in the sense that
the smallest loops, which Walter Stahel defines as a set of the processes of reuse, repair, remanufacturing
and remarket of the products, are the greatest drivers of monetary advantage, measurable in higher income
for the manufacturer and lower price for the customer, alongside, obviously, with the ecological and social
benefits observable.

“You don’t have to do any of this, survival is not mandatory” (Stahel, 2013). This is the sentence with
which Walter Stahel usually makes his conclusions to open people’s eyes to new horizons that encompass
the adoption of circular economy as a real and feasible way of making business. He stresses the fact that if a
competitor manages to be successful thanks to circular economy, then the other companies are automatically
no longer competitive.

2.2 Resource Conservative Manufacturing (ResCoM) Landscape

Resource Conservative Manufacturing (ResCoM) recalls the principles of Circular Economy. It might be
defined as an upgrading step of the conventional forms of resource conservation, e.g. traditional
remanufacturing and recycling, and it does distance itself from it. However, recycling and remanufacturing,
alongside with other kinds of recovery activities, are considered as the basic procedures in order to enhance
this novel type of resource conservation.

The main hypothesis on which ResCoM bases its thinking is that a product does not have a single life, on
the contrary several of them. Thus, assuming that the product is at its \( n^{th} \) life (with \( n=1,2,\ldots,n \)), ResCoM’s
duty is mainly the one of proceeding at a careful analysis of it and its components, based on cost, resources
consumed, the possible value that could be recovered and recaptured, and impact on the environment. This
product’s examination is done in order to assess the length of the following lifecycle, based on an evaluation
of the effectiveness, reliability, and trends of the item, and possibly estimate how many lifecycles the
product would have.

Only subsequently to the determination of the optimal number of lifecycles, a product is designed
correspondingly. Right at the design stage, it is decided also when to collect the products from the market for
testing before proceeding at the recovery. This whole process would not be easy and not feasible in some
situations, without an IT supporting system that keeps track of all the useful information regarding the
product throughout its multiple lifecycles (Farazee, 2011).

Additional supportive methods would regard the possibility of adding features to the product destined to
the market and to extended lifetime. For instance some electronic devices, e.g. chips, might be implanted in
the product with the aim of keeping record of the data related to its life, so that the evaluation of its condition
at the \( n^{th} \) EoL would be done in a faster and easier way. The activities to execute on the returned product
would be assessed even without the need of disassembling it first (Fleischmann, 2010).
The following figure (see fig. 2) shows the new consideration of multiple-lifecycle-products in ResCoM thinking when these are compared with regular one-way consumption products. The blue descendent curve represents the common behaviour of product during its lifetime. In fact, generally a product’s performance and value tend to decrease with the passing of time. The products having multiple lifecycles, as proposed by ResCoM, will be characterized by lifecycles whose value and societal prestige increase with time (Rashid et al., 2013).

The effort of planning the recollection of products would ensure a better control on the typical uncertainties of the reverse supply chains, being uncertainties in quality, quantity and timing in which the cores are returned to the OEM. Indeed, when the manufacturers acquire the cores from the market, they have to take into account different tactical aspects that require management. Therefore, they need to actively accept the returned products, by checking their conditions (quality), and foreseeing their amount (quantity) in order to exploit the economies of scale in the reverse flow, and approximately know when the cores will be returned (timing) (Fleischmann, 2010).

ResCoM does not constitute a final practical tool to solve the issue of overproduction of waste, yet provides a holistic approach that defines optimum solutions based on the goals of reducing to zero both environmental impact and damage, and maximizing the conservation of resources. In order to allow for a successful application of ResCoM, a solid reverse logistics network, well balanced within the closed-loop supply chain, is necessary (Farazee, 2011).

The practice of resource conservation is meant to be part of an existing manufacturing system; therefore it constitutes the foundation for a closed-loop manufacturing system that includes Re-activities. Despite of the effort of integration between the novel and the traditional manufacturing systems, it is clear that the same business models cannot be followed. In fact, the business model supporting the ‘make-use-dispose’ approach is neither defined nor designed for the purpose of closed-loop supply chains.
It follows that the activities concerning product design, supply chain, business models, and manufacturing strategies need to be conceived as integral parts of the same system. All these activities must be governed by the same specific rules that are expressed by resource conservation and economic benefits. It can be deduced that the business paradigm is the result of a unique set of criteria, well balanced with each other, and that contributes to the achievement of the environmental and economic goals through closed-loop manufacturing systems (Rashid et al., 2013).

As pointed out by Nasr and Thurston (2006), it is necessary to propose guiding rules in order to achieve a sustainable development, since the traditional industrial systems follow different laws from the ones of industrial ecology. Indeed, the former aim at producing products and services with the main purpose of satisfying customers’ demands, with the environment sake not representing the principal concern. The latter aims instead at satisfying customers’ needs by choosing the most environmental friendly flows of both energy and materials.

Therefore, Graedel and Allenby (1994) propose a self-explanatory visualization of the model that traditional manufacturing systems should aspire to (see fig. 3).

The closed-loop or circular flow model (Type III) suggests a 100% reuse of resources at the raw materials level and use of exclusively renewable energy sources (Nasr and Thurston, 2006).

![Figure 3 Flow models (Graedel and Allenby, 1994)](image)

The laws proposed by Nasr and Thurston (2006) directly connect to the holistic picture that sets the achievement of the circular flow model as a goal. These can be summarized as:

1. Minimization of material and energy resources consumption in the process of fulfilling customers’ needs and product functional requirements.
2. Maximized use of employed resources.
3. Elimination (ideal) or minimization (more realistic) of damage on the environment through gas emissions and waste.

Therefore, by following these rules, it would be possible to close the loop on the material flow, allowing for the recirculation of resources with damage and waste reduced to a minimum. The tools considered appropriate to achieve this kind of model are reuse, remanufacturing and/or recycling at the product or even at the component level (Nasr and Thurston, 2006).

A more realistic model that might have principles aligned with the ones discussed above is presented in figure 4. It is closer to the Type II flow model visualized in figure 3.

![Figure 4 Closing the loop on the material flows (Nasr and Thurston, 2006)](image)

What is represented in figure 4, however, describes the current concept of closed loop manufacturing or what has been defined in the academic literature as ‘conventional forms of resource conservation’ (Farazee, 2011). In comparison with this conventional form, the novel ResCoM presents some new characteristics, being that the products are not designed for a single lifecycle, but for multiple; customers become an active part of the business venture; forward and reverse supply chains are strongly connected elements of the same enterprise.

ResCoM, indeed, does distance itself from ‘conventional forms of resource conservation’ mainly because it does not adopt recovery alternatives only when the product physically fails to perform its functions and a solution that succeeds in modernizing the product is more difficult to find. The strategy of the traditional resource conservation appears indeed to be reactive rather than proactive, since it is based on remanufacturing and recycling only at the EoL of the products. ResCoM, instead, proposes to decide the length, in terms of performance or time, of each lifecycle right at the design phase, considering, thus, the possibility of designing a product with multiple lifecycles. The main novelty is, however, that the products...
have not only a predefined life length, but are designed in such a way that they can react and adapt rapidly and satisfactorily to eventual changes or shifts during each lifetime due to generational variance (Rashid et al., 2013).

A scheme that would significantly clarify ResCoM’s novel approach to resource conservation is presented in figure 5. In figure 4, it is clear that traditionally the approach is based on having three main loops, consisting of the activities of recycling, reuse and remanufacturing, that take place after the retirement of the product from the market. The novel approach advocates, on the other hand, that there would be two loops at two different levels, in which one consists of reuse as an integral part of remanufacturing before the retirement phase, and the other consists of recycling covering the reverse flow when disposal can still be avoided. Thus, when ResCoM encourages that resource conservation should be part of an existing manufacturing system, it actually entails that it becomes part of the forward supply chain.

In any way, in order to be in line with the ResCoM challenges, a unique business model must be shaped, since none of the existing ones would be able to support such an extensive system. Yet, the assumptions required on the business model will be discussed below (Rashid et al., 2013).

Figure 5 Novel ResCom approach to CLSC (Rashid et al., 2013)

### 2.2.1 Definition or Re-X activities in the context of CLSCs

Remanufacturing, as well as recycling and reuse have been mentioned as the desired recovery activities to perform, however they have not been defined in details. The definition of these processes with the meaning that will be used in the current thesis work will follow.
Recycling is the process of recovering raw materials for the same purpose the material had in its origins or eventually for different ones. This alternative is desirable when the core has limited or no function left, and whose materials are not hazardous or difficult to recycle. Recycling involves composting and it is one of the most practical methods of decreasing the deal of waste. Energy recovery from incineration is not part of the recycling process. In the case in which waste cannot be recycled, incineration, that can decrease the volume of solid waste by up to 95%, will be performed as the last possible treatment method, since it does not close the loop (Ferguson and Souza, 2010).

Recycling is considered slightly better than product disposal in the landfill in the context of both economic and environmental efficiency; therefore it should be performed solely when there is no other feasible recovery option (Rashid et al., 2013). Indeed, in order to proceed in the direction of waste reduction, one promising path is not recycling, but the effort to avoid generating such waste, by gradually reducing it with the adoption of policies of reusing, and remanufacturing.

Reuse, if internal, encompasses light or no refurbishment at all (Ferguson and Souza, 2010). Reuse or redistribution can be defined as the process of executing minimal maintenance and no aesthetic modifications, followed by cleaning of the product and re-entering it in the market with the same functions and form it had before collection.

Refurbishing and Remanufacturing are sometimes used with an interchangeable meaning, but not in this context. These are value-added operations since they assure that the product has a certain quality level that would allow for economic profitability (Ferguson and Souza, 2010).

Refurbishing is based on the effort of bringing the product back to acceptable working conditions and it is done with the repair and replacement of the main product components that are usually faulty or close to the breakdown. Generally, there is no technical upgrading involved in this process, but only a few aesthetic changes, e.g. painting, change of fabric, in order to update the product’s appearance.

Remanufacturing involves the operations of disassembling and recovery at the subassembly or component level. Not exclusively faulty parts are removed from the product, but especially functioning and reusable parts, which are consequently refurbished before being reintroduced in a new product. It is indeed a thorough process aiming at restoring cores to “as-new” conditions, and it involves meticulous procedures, such as disassembly, cleaning, inspection, repair, replacement of parts and final reassembly (Hauser and Lund, 2003). When remanufacturing, testing is always performed in order to assure quality of the product and, in the context of closed-loop manufacturing systems, the constituent components are usually upgraded technically, not only aesthetically in order to have an enhanced product after its reintroduction on the market. It is the case concerning the “next generation” products, which are remanufactured products with new features incorporated. It connects to the difference between the traditional concept of closed-loop manufacturing systems and the novel ResCoM concept. In the former context, in fact, remanufactured items are brought back to a functional level either by substituting faulty components with new ones or by collecting still functional components from a failed product. On the contrary, in the ResCoM framework, the products are collected, after each designed lifecycle, to be remanufactured to the original performance.

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9 http://www.ellenmacarthurfoundation.org/circular-economy/circular-economy/interactive-system-diagram
requirements or upgraded to new specifications. It is basically possible solely when the product is designed for multiple lifecycles (Rashid et al., 2013).

Therefore, if, on one side, refurbishing might be seen as a light remanufacturing, on the other side, remanufacturing is considered the most promising non-disposition option that properly closes the loop, with enhanced materials recirculation, less energy and material input required, and less waste generated. Indeed, compared to recycling, remanufacturing keeps more of the energy expended in transforming input (raw materials) into outputs (finished goods).

Obviously, reuse has even lower general consumption of resources, with regard to material and energy, in comparison with remanufacturing, but its feasibility is restricted to the condition of the components. Indeed, these should keep at least part of the original value and be conform to the quality standards in order to be reused without affecting negatively the life span and reliability of the final product (Nasr and Thurston, 2006).

Rashid et al. (2013) believe that remanufacturing, in particular, drives recovery of products, resources savings, and product life extension. However, figure 6 shows how each of the presented recovery activities and other enabling EoL strategies are associated to specific stages, such as ‘raw material production’ through recycling, ‘product manufacture’ through remanufacturing, upgrading, downgrading, and reuse of components, ‘distribution’ through reuse of products.

![Figure 6 Most important EoL scenarios and associated processes (Duflou et al., 2008)](image-url)
2.3 Modular Function Deployment (MFD)

The modular design approach that has been addressed to is based on the MFD methodology. MFD was presented by Erixon in 1998 (Börjesson, 2014) as a matrix-based method that aims at creating product architectures with the parallel consideration of specific company’s strategies, which can be translated in the so-called Module Drivers. This is the methodology currently used at Modular Management10.

2.4 Why is modularity an enabler for closed loop manufacturing systems?

Gershenson et al. (1997) see modularization as “the goal of good design” since it is able to generate functional differentiation and independence between distinct modules and to “maintain the independence of functional requirements”.

In the past decades, industry has shown high interest in manufacturing modularity as an opportunity to be more flexible to the market and customers’ changes, thus more competitive. With manufacturing modularity it is meant a characterization in which the modularity potential is integrated into the manufacturing processes to simplify them; therefore modularity is not only driven by the end purpose of the product, but also by the manufacturing line effectiveness.

After the creation of product families and understanding the implications of modularity on product design, modular design has stopped being a design by chance, making it possible to repeat the manufacturing processes generating highly functional goods. Unstructured modularizations are indeed the reason driving uneconomical products and are often the cause for redesign since the existing design cannot always be adjusted to new customers’ expectations. Unstructured modularizations, moreover, represent a cumbersome bottleneck when the manufacturing process turns out to be unproductive because, when the design lacks of a somewhat standard structural platform, it is difficult to avoid the failing process. In the same way, it would require much effort to replicate a prosperous process that is not based on standard interfaces characteristic of modularity. Therefore, modular design is seen as an opportunity for reducing manufacturing costs, lead times, enhancing product families, and increasing customers’ satisfaction (Eager et al., 2010).

The strength point of modularity can be summarized in the exploitation of standardization of interfaces (Gu and Sosale, 1999) that favours the possibility of generating several distinct product configurations only by replacing some modules with others or adding extra ones to the standard modular platform.

The main interest in the current section of the thesis work is to show that modularity is not only an empowerment for the manufacturing processes, but it can also be an enabler for designing products with multiple lifecycles, with an interest in all the stages of each product’s lifecycle. Past related studies show that modularity with regards to life cycle characteristics, such as reuse, recycling, maintenance, upgradeability, and remanufacturing, has been called “Life cycle modularity”. With this purpose, both reading and evaluation of existing academic papers concerning with the same subject have been done.

The authors Xing et al. (2006) state that “A modular product serves a common interest of upgrade and remanufacture by facilitating the separation, swap and insertion of interested components”.

The interested components just mentioned are the so-called modules. Although the industry and the academic field are familiar with the terminology of module, and modularization, it is reasonable to accurately define these terms.

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10 https://modularmanagement.com
A module is defined as “a standardized unit; a combinable, changeable part or component; any in a series of standardized units for use together” (Ericsson and Erixon, 1999).

Erixon et al. (1996) define a module as a “product in the product” since it represents a subpart of the same product system. Modular Management\(^\text{11}\) describes a module as “a functional building block, with specified and standardized interfaces, chosen for a company-specific strategic reason”.

Therefore, modularization is described as the process of “decomposition of a product into building blocks, with standard interfaces”, following the principles dictated by the company strategies (Ericsson and Erixon, 1999).

Börjesson (2014) describes a Product Architecture as an arranged combination of physical elements, in which functional characteristics are attributed to physical components, through the use of specified interfaces between the physical components.

Product families have been mentioned also, thus it is appropriate to explain their meaning. In platform design, which is an extension of modular design, when different products share a number of components, these are clustered together to form a platform that is shared by these products. A family of products is defined as a complex of items that share the same platform (Gu et al., 2009).

Therefore, a modular architecture is the result from the combination of different modules, each with a specific functionality. It presents an almost uncoupled design, in which the so-called functional building blocks are considered as single units that share standard interfaces through which they transfer information and energy. On the contrary, in an integral architecture, all the interfaces between components are highly dependent on each other, namely coupled. This feature of the integrated design might lead to high complexity when trying to assign specific functions to specific components (Börjesson, 2014), with even increased difficulty when trying to assess the reuse potential of a product.

Generally, the advantages of a modular architecture over an integrated one can be seen in the fact that the former is able to obtain higher volumes and numbers of product variants inside the same product families by using a smaller number of basic product’s components. The picture below (see fig. 7), which has been produced by the expertise of Modular Management, shows these benefits clearly.

\(^{11}\) https://modularmanagement.com
Modular products are structured in a way that they present detachable modules that can be manufactured and assembled independently. During their lifecycles, these modules can be detached and exchanged with others for an efficient maintenance and targeted serviceability.

After the modular product is collected, it can be disassembled and tested for assessing which modules can be reused, which need recovery and which are destined to recycling or, in an extreme case, to disposal. Thus, modularity can render the product more competitive in terms of marketing, serviceability, and remanufacturing for extended life time, having beneficial effects on several aspects of the product’s life (Gu and Sosale, 1999). This is due to the fact that product’s modularity impacts, among various properties, the ease of service, thus disassembly and reassembly, hence, it is fundamental to find the optimum sequence of organizing components into modules (Newcomb et al., 1998).

Seliger and Zettl (2008) propose in their study the vision of presenting and manufacturing modular products in sustainable value production networks.

Modularity is seen as an opportunity for companies to be more agile and responsive to extremely fast-changing market conditions, and, at the same time, a means to internally cost savings through e.g. process reuse. Modular design approach permits to interchange modules throughout product lines, allowing for a wider variety of final products, so that the most diverse customers’ needs might be satisfied. In addition to this, manufacturing based on modular design would benefit from the exploitations of economies of scale, becoming consequently more cost and time efficient and optimizing assembly lines (Eager et al., 2010).

An adequate proposal of green design of reusable modules might be successfully suggested through the aid of environmental and economic evaluation for multiple lifecycles (MLCs). In order to outline a design methodology, factors, such as number of reusable modules, number and duration of each cycle, must be analysed. According to the analyses and tests done by Tchertchian et al. (2009) on a precise product
category, the concept of having products with modules decomposition and multiple lifecycles for reusable modules is highly favourable both environmentally and economically.

The study conducted by Tchertchian et al. (2009) is one of the few proposing an alternative method that would fill the technology gap present when firms aim to remanufacture with the goal of closing the loop and create products useful for several lifecycles. Therefore, in order to adapt to the new requirements on resources consumption and waste generation, by still assuring high quality standards on the products, a new production (design and manufacturing) model that fits in the new concept of circular economy is likely to be the turning point. This model is based on modular design architecture that would enhance the product in its entire lifetime and permit a better and easier treatment of the modules when it is time to interchange them.

On one hand, much effort has been put in the past decades in the possibility of rendering the disassembly operations more efficient, faster and easier to perform than they were in the past. The same Tchertchian et al. (2009) recall how Gungor proposed an excellent sequence of disassembling through an algorithmic method in 1997. On the other hand, the optimum disassembly sequence does not take fundamental factors, such as environment and economy, into account. Therefore, the speed of disassembling is not the main factor to consider, since the effort of completely disassembling a product might not justify the cost and the practical use of doing that (Kara et al., 2006).

In the viewpoint of Tchertchian et al. (2009), “Design for Modularity” must represent an integral part of the life cycle of products in order for both designers and managers to investigate and analyse the products they are dealing with through several lives and not only a single one. Moreover, the conception of the product will be new as well. It would be conceived not anymore as the mere result of a sequence of manufacturing processes, but as a more complex entity characterized by several internal connections. As Gehin (2008) suggests, there must be a turning point in the approach to manufacturing of products and the focus should switch to the recapture of value and consequent valorisation of components to be used in several life applications.

“Design for X” (DfX) encompasses the reusability concept on the whole and has a highlight on the types of advancements to apply at the design phase in order to better deal with the decisions to take at the EoL of the product. As a response to WEEE Directive, Industry should react by strategically using DfX that, besides being a potential for remanufacturing, has different goals, namely: decrement of disassembly costs; homogeneous material fraction, so that the consequent separation, eventually for recycling, is facilitated; modular design and exploitation of component commonality and standardization when possible (Zuidwijk, 2007).

High potential is seen in product modularity as an integrated element of DfX and as a means to favour sustainable development, since modularization is based on having several “sub-systems”, namely modules, acting independently, and contributing to constitute a more complex system functionality (Seliger and Zettl, 2008). Indeed, each module has at least one predefined function for which it is designed and built into the product system, and the modules are designed to be as uncoupled as possible (Suh, 1997).

By having strong intra-module (among components) connections and weak inter-module relations, modularization is an enabler for economic changes and maintenance, remanufacturing and realignment. It is made easier by removing and exchanging the modules that present some defects or those which are obsolescent. This, in turn, might most likely lead to better product suitability in the context of circular economy (Seliger and Zettl, 2008).

On the same path, Xing and his colleagues (2006), who cooperated in the discovery of the PURE model for evaluating the capability of the product to be upgraded in the context of remanufacturing, remark the
importance of understanding and capturing the connections and relations between components and modules as well. Firstly, they state that the so-called indicator “Lifecycle Oriented Modularity” (LOM) is, alongside with fitness for extended utilization and compatibility to generational variety, a key parameter to assess the potential of the product to be upgraded, so that it becomes more prone to increase its useful life span. Thus, modularity is considered one of the main pillars that allow perceiving information regarding any eventual future improvements in the product and/or any suggestions concerning changes in the design or redesign stage before the product is ready for being dismissed. More in details, the degree to which a product’s intra-module relations and inter-module dependence defines what is known as modularity of a product.

According to Xing et al. (2006) the just cited characteristics are defined correspondingly as “Correspondence ratio” (CR) and “Cluster independence index” (CI), where the former measures how strong the connections between components in the module are, and the latter gives an indication of the amount and intensity of physically dependent relations between modules. As already mentioned above, extended and upgraded product’s life is enabled by having weak connections between modules in a structural platform, since the relations between components mainly represent how well the product responds to the functional specifications, and the inter-module independence is responsible for enhanced modules interchange-ability. They claim that the lower the number of modules and the connections between them, the better the chances of product upgradeability. Therefore, it can be deduced that in the specific remanufacturing context of their investigation, CI is a valuable factor to constantly consider since it indicates how well the modular structural architecture matches the requirements of remanufacturing. On the other hand, CR is not a relevant parameter in the present circumstances. In their study, a theoretical mathematical calculation is made to assess the value of LOM and in the consideration of remanufacturing as the main final goal, the number of modules in a product architecture must be kept as low as possible (Xing et al., 2007).

With regards to recycling, modular products have once again an advantage over the non-modular ones. In fact, these can enhance material recovery through recycling by module configurations, carefully separating recyclable from non-recyclable materials (Seliger and Zettl, 2008).

The effort that is put in turning a company’s goal into a pattern to follow in the product design results in the definition of the Module Drivers, which can be described as piloting units for modularization. Among the module drivers considered in the MIM (Module Indication Matrix) in the MFD (Modular Function Deployment) methodology, there is one concerning recycling. When it is taken into account, the number of different materials within the same module should be limited to the minimum, and hazardous and highly recyclable components are divided, thus the eventual disassembly for recycling is facilitated (Ericsson and Erixon, 1999).

However, Kimura et al. (2001) argue that one of the key factors to make manufacturing more environmentally conscious would be reusing the product’s parts rather than recycling them. This can be done through the understating of the design boundaries during usage and their detailed evaluation to achieve better designs that could be appropriate for the future use modalities. What is more, they investigate the employment of modularity in design and consider it as a possibility and eventually an opportunity to obtain products with a higher reuse potential. When dealing with modularization in the context of reuse possibilities, “each module is considered as a unit of reuse” (Kimura et al., 2001).

A module is not necessarily a single part and a sub-assembly is not necessarily a module, but a module is often a sub-assembly (Ericsson and Erixon, 1999). It is “a physical or conceptual grouping of component” (Newcomb et al., 1998). Therefore, the module being reused might consist of different parts joint together and having common functions, but it would still be treated as a single logical unit.

Gu and Sosale (1999) state that the most crucial decisions must be made at the design stage and highlight that when an item at its EoL is collected from the market, some of its components might be reusable as well as recyclable and/or remanufacturable. This is the point at which modularity comes into play with all its
benefits: the implementation of modular design permits a partitioning of these components into separate detachable modules, which in turn might be more easily removed and remanufactured or reused in different applications.

Modular products, for their characteristic of being configurable, are prone to accommodate specific customized requests of particular functions in the product, by performing little changes in the choice of modules, hence without revolutionizing the entire design structure. The re-arrangement of some optional modules enhances proper upgrading and customization of product variants even in the case of products composed of reused/remanufactured parts.

When a product is designed to be produced, designers have to deal with issues of different nature, such as design breaking down, ease of manufacturing, parallel assembly, testing, maintenance, reuse, remanufacture, recycle, and so forth. As discussed above, modular products might satisfy concurrently all the presented requirements on product life cycle objectives. These requirements can be listed as the division of design into sub-tasks to allow for:

- Parallel development
- Production processes improvements and parallel assembly
- Standardization
- Services, in terms of both preventive maintenance and fault repairs
- Upgrading
- Enhanced reconfiguration possibilities
- High product variety and customization
- Recycling, reuse, and disposal

However, a pondered choice of modules must be made based on both the specific life cycle goals to achieve and the most relevant product features that the specific firm aims at. It is pivotal in order to avoid inconvenient conflicts that might verify in a realistic scenario (Gu and Sosale, 1999).

It can be deduced, from the research literature, that modularity offers the vital link to EoL strategies, e.g. remanufacturing, between the current product design to the future one (Tchertchian et al., 2009), thus favouring the need of redesign and upgradability to react to the inevitable need for technical and aesthetical modifications.

The possibility of reusing modules, however, must be investigated from an industrial perspective. If, on one side, the beneficial environmental effects of reusing are well ascertained, on the other side, it does not prevent firms from facing limitations of different nature, e.g. technical, functional, and economic (Tchertchian et al., 2009).

As discussed above, some product’s components might be good candidates for reuse when manufacturing new products. This is where remanufacturing comes into play, with its novel meaning of an opportunity for advancements in the product being recovered. However, remanufacturing is not always the perfect solution. It is, indeed, considered propitious in both the environmental and financial contexts only if the product is designed with the aim of recovery after its life cycle (Tchertchian et al., 2009).

Eco Design, or Design for Environment (DfE), has proved to be successful in changing technical solutions in order, for instance, to reduce the amount of pollution produced. This approach, despite of being somewhat effective, is not sufficient for closing the loop, since products need more than technical
modifications (Rose, 2000) in order to last longer time and be reused when manufacturing the “next generation” products.

Indeed, some recent studies show that, in the context of Life-cycle Engineering, which represents the strategy of including in the early design phase all the elements valuing the life cycle of the product (Gershenson et al., 1997), modular design appears to be beneficial for the majority of these aspects, with a focus on assembly, service, recycling, and reuse (Gu and Sosale, 1999). Obviously, time and ease of disassembly are highly useful parameters to the planning of EoL scenarios, thus a specific design for disassembly must be considered. The possibility of making trade-off decisions must be taken into account as well, since the rate of disassembly depends on the rate of valorisation of the components. Some products are worth being entirely disassembled for reuse, some others are not (Tchertchian et al., 2009).

The environmental factors considered of great importance to reduce the damage to the earth are hardly considered in the architectures developed by using modularity.

In sum, the functional building blocks, which constitute the result of the modular decomposition of an assortment of products, have characteristics that show to be optimum in the context of ResCoM.

Modularity, due to the minimal interactions between physical components it creates, favours a situation in which modules are easily removed, exchanged, maintained, repaired, and reinserted when needed. Since the detachable modules can be manufactured and assembled independently, they can also be reused, remanufactured, and recycled separately from the rest of the product to which they belong.

By replacing some of the faulty or obsolete modules with new others, the life of the product is likely to be extended. If the modules, instead of being recycled, are reused with the possibility of upgrading enhanced by a design easily adjustable to generational - both technological and aesthetic - changes, the product will not only have an extended life, but several of them. These conditions would lead to reduce the consumption of both depletable and renewable resources and clearly decrease the amount of waste produced in the manufacturing processes and with the disposal in the landfill. The scenario that manufacturing modularity and lifecycle modularity enhance would lead to products with multiple lifecycles, with an increasing prestige with the number of lifecycles.

2.4.1 Suggested theoretical ways of applying modular design methodology in the context of product life cycle objectives

The discussion about the reason why modularity is an enabler for closing the loop of manufacturing systems does not embody any practical ways concerning the design methodology applications. Furthermore, the presentation of modular advantages on its own does not justify the effort of investing in modularization to guarantee that the chosen product life cycle objectives are fulfilled.

Following, the modular design methodology, resulted from the study of the researchers Gu and Sosale (1999), is presented as an example of empirical application.

In connection with what has been covered in the above section, ideally a modular architecture can accomplish all the various product life cycle objectives, yet this would not be possible in reality without incurring in discord issues. It follows that the designers, at the design stage, must decide among specific trade-offs.

When a firm chooses to apply modular design to the assortment of products it manufactures, the design approach can be of two types. In fact, according to Gu and Sosale (1999), it is possible (i) to first constitute
the modules in relation to the product life objectives and consider making trade-off decisions in the second instance once different modular configurations are available to choose from; or (ii) to first assess a weighted average objective and then, taking it as a guiding factor, modularize the whole product. However, the first approach shows to be more practical in a realistic scenario; moreover, it permits to create modules based on precise requirements, without considering an average of them, so that the firm can be closer to the customers’ expectations as well. The methodology developed by the scholars Gu and Sosale (1999) aims at fulfilling the requirements of both the modularization approaches.

The standard stages that are characteristic of the method are: Problem Definition, Interaction Analysis, and Module Formation. Although these stages are clearly helpful in the modularization of assortments of products, the realistic scenario above mentioned is characterized by stages that are highly connected to each other in the fulfilment of customers’ satisfaction.

For instance, Modular Management can suggest an example of typical phases of the modularization method used by the company. When adopting the MFD modularization methodology, the approach consists of customer segments’ analysis, customer’s requirement definition, functional analysis, product properties’ definition, identification of product properties targets and their extent in order to define the product assortment variety, technical solutions’ evaluation, clustering of technical solutions in order to form modules candidates, definition of interaction through interfaces, and identification of product’s configuration.

When defining the problem, it is necessary to evaluate different product’s features, such as the variety and durability of components, their value, the technological shift, production rate, the focus on functionality or on style, and whether the products are part of a B2B or a B2C (Rashid et al., 2013).

In the context of re-design possibility, which is the main interest of this Degree project, it is important to evaluate the chance of generating a design that can adapt to future needs and changes in both functions and structure. Moreover, sub-systems in the existing physical structure of the product must be identified as the future changeable units (Gu and Sosale, 1999). Indeed, when a planned development is forecasted, it is wise to isolate the technical solutions that will be subject to future technological changes in a way that it would be easier to exchange only the interested modules.

In the “Interaction analysis” phase, a clustering of components is done, so that they constitute a module, with the aim of keeping strong the relations intra-module and to the minimum the ones between different modules. Each objective of modular design leads to the definition of factors that can, in turn, be divided in sub-factors, creating, in this way, a hierarchy of interactions. What results from this stage is a set of information useful for the grouping of components into modules, which can be visualized by an interacting matrix, in which the type of modules’ interaction is described (Gu and Sosale, 1999).

The corresponding interacting matrix under question is e.g. the “Interface Matrix” in the MFD methodology. This matrix permits to visualize the interaction of the modules, after they are entered in the cells in the expected order of assembly. The interaction can be in the form of Attachment, Transfer (energy, material, signal, etc.), Control and Communication (Ericsson and Erixon, 1999). The following table shows what is the logic of interaction behind the different strategically functional building blocks (modules) that are connected to form products.

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12 [https://modularmanagement.com](https://modularmanagement.com)
When forming modules, it must be considered whether or not the components clustered together can be separated. A clustering algorithm is employed to group the components with the highest correlation rate in the same module entity. The arrangement of modules is controlled by the maximum number of modules allowed and by a normalizing factor that ensures that the risk of generating only one single module is avoided (Gu and Sosale, 1999).

Being guided by “Module drivers”, which are the powerful drivers for modularization (Erixon et al. 1996), Tchertchian et al. (2009) suggest a modules characterization in function of the EoL strategies (see Table 2). Moreover, they propose modularity also to reduce the costs associated with the reverse logistics of cores by choosing the module driver “Strategic supplier”, so that both aggregation and shorter distances are exploited.

<table>
<thead>
<tr>
<th>EoL Strategies</th>
<th>Module Properties (Erixon et al., 1996)</th>
<th>Modules Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>RECYCLING</td>
<td>Pollutive Materials</td>
<td></td>
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<tr>
<td></td>
<td>Easy Recyclable</td>
<td></td>
</tr>
<tr>
<td>MAINTENANCE</td>
<td>Quality: Separate Testing</td>
<td>Ease of Quality Insurance</td>
</tr>
<tr>
<td></td>
<td>Maintenance: Service and Repair</td>
<td>Ease of cleaning- to repair- testing</td>
</tr>
<tr>
<td>REUSE</td>
<td>Carry Over</td>
<td>Long life</td>
</tr>
<tr>
<td></td>
<td>Technology Evolution</td>
<td>Technology Stability</td>
</tr>
<tr>
<td>UPGRADING</td>
<td>Upgrading Planned</td>
<td>Functional Upgradability</td>
</tr>
</tbody>
</table>

Table 2 Modules Characterization
When the main intent at the EoL of a product is to remanufacture, it is difficult to do so with the entire complex since its life span is equal to the one of the weakest component or components’ assembly. These parts are those that usually deteriorate faster and become technologically obsolescent earlier than others, thus they might not be reusable. However, the turning point is to collect the product and remanufacture those parts that have more reliability, last longer, are less subject to any types of changes, so that they can be implemented as remanufactured modules in new identical or more developed products.

Indeed, a component or an assembly might be reused as it is in newer products if it lasts longer than the product itself. A practical example would be to have a product that is durable for five years, yet one of its components’ lifespan is twenty years. In this case, the component could be used, after the first lifecycle, other three times in similar products (Tchertchian et al., 2009).

Yet, although some components might be extracted by the mother product, a modular approach would be much preferred since each module is technically and functionally independent from the others, thus it is conceived as a “product in the product” (Erixon et al., 1996), and hence the possibility of reuse is facilitated.

However, as pointed out by Tchertchian et al. (2009), the EoL operations constrain the design of the modular product; therefore the components that are prone to have a similar life should constitute the same module.

The upgrading of modular products concerns the reuse of modules whose technology changed, to some extent, from the previous to the present generation, hence the value of the product might be recaptured, or even made higher, simply by removing and substituting one obsolete or faulty module. In addition, it is shown how remanufacturing would be optimized by modular approach, if some fundamental factors, such as ease of identification, checking, handling, access, inspection, separation, and so forth, are assured.

The researchers Tchertchian et al. (2009) provide a satisfactory visualization of the practical procedures to perform in order to close the manufacturing system loop (see Fig. 8). When this assessment is done, the life length and the number of lifecycles of each module must be estimated to foresee how many times the modules can be reused in the manufacturing process, and, in this way, guarantee that the products do not last for only one lifecycle, but for several of them.

Tchertchian et al. (2009) develop a model, with the aid of Simapro LCA software, for assessing the possibility of having multiple lifecycles products. In a simplistic decision process about how many products must be analysed, they argue that if Z corresponds to the amount of possibilities a module can be reused in the product life cycle, then Z products must be evaluated in order to have a clear view of the impacts that remanufacturing would have over the specific module. The products at issue are different types of the same category. Among these, the $Z^{th}$ will be completely new, not constituted by recycled or reused components, whereas the remaining $Z-1$ will be the so-called “Empty boxes”, namely products with several slots in which remanufactured modules are to be added.

Functional parameters regarding information, material, and transportation as well as costs assessment involved in the reverse supply chain network, and refurbishment possibilities are also considered to have a more realistic perception of the product lifecycle. It is, in the end, deduced whether recovered modules can be used in new products and for how many lifecycles, according to design specifications and performance evaluation, in terms of costs and environment.
In conclusion, the theoretical methodologies, presented in the above section, developed by some researchers regarding the possibility of integrating modular design in the manufacturing of products that are meant to have several lifecycles, in order to close the manufacturing loop, reflect the practical requirements that their design should have. In the specific context of resource conservation, modules configurations must be formulated in the perspective of product’s lifecycle objectives and they must have reasons to justify the specific modular design and the resulting manufacturing processes.

In order to derive a successful modularization that would enable circular economy, it is necessary to consider several features of the product’s components, such as their reliability, efficiency, cost, proactive maintenance need, possibility of upgrading in prospect of future aesthetic and technical changes, and so forth. In addition, the choice of technical solutions that are going to constitute a module must be done carefully, trying to prioritize the clustering of those components that have similar lifespans. This approach allows for an easier estimate of the length of product’s life based on the evaluation of components’ lifecycles and the duration of each cycle.

Moreover, an assessment of the costs involved and of the environmental impact that these processes would have must be done in order to foresee their feasibility and success.
2.5 Analysis of existing case-based studies: Modular designed products as enablers for multiple life cycles

2.5.1 Vacuum Cleaner Case Study (Gu and Sosale (1999))

Gu and Sosale (1999) propose the evaluation of a vacuum cleaner as a case study of modular design as helper for the proper achievement of specific planned product life cycle objectives. The choice made for these objectives consists of preferring goals such as service/maintenance, reuse, recycling, and adequate disposal. The vacuum cleaner is analysed through three phases that are characteristic of the methodology used by them.

In the first stage of problem definition, they present the life objectives desired, mentioned above, to modularize the product category in a way that it can attain the related benefits. The decisive information that is needed for the service/maintenance objective regards the failure rate of each component, level of skilled personnel required, type of equipment that performs the service, repair time, and estimate of downtime.

Factors crucial to the reuse potential are components’ value and estimation of their life span. In order to recycle properly, it is necessary to know which are the potential of remanufacturing and the level of recyclability of the parts. Indeed, if the remanufacturing potential is high the modules destined to recycling should be grouped more carefully, so that they are extracted easily and disassembly time is highly reduced. For an adequate disposal, it must be considered how homogeneous the used material is.

Then, once both the functional and physical connections between the different components of the vacuum cleaner are established, the interfaces matrix is built, and the evaluation criteria are expressed.

In the specific case study analysed, some evaluation criteria have been chosen as closer to the thesis’ field of interest.

For instance, re-manufacturability is assessed by making an evaluation in terms of (i) which components can be easily reused by reassembling in a new product (high re-mfa), (ii) whether the work to do before reusing is demanding (medium re-mfa), and (iii) whether some machining is needed prior to reuse (low re-mfa).

With regards to recyclability, on the other hand, a component is considered highly recyclable if the process is not too laborious to perform and there is high incentive involved; it has a medium recyclability if the incentive is significant, despite of the difficulty of the process; and the recyclability is low when neither the incentive nor the ease are consistent.

In the methodology with which the researchers analyse the vacuum cleaner, a weighted average interaction for two components $i$ and $j$ is calculated by the aid of a mathematical formula, therefore all the weights are assigned to the different objectives, based on their relative influence.

In the modules’ formation, the chosen candidates are constituted by the components that necessitate physical juncture and require the fulfilment of similar goals. The final number of modules generated for the combined goals of maintenance, reuse, recycle, and disposal is ten.

In conclusion, it has been pointed out by the researchers that when forming modules for different objectives, namely for different scenarios, some of the modules were in conflict with others, and this contradiction led to having a higher modules’ number. An increase in the amount of modules implies inevitably an increase in inter-module interactions. They argue that, although the modular architecture and choice of modules proposed by them is a mere suggestion, the increase in number of modules and its consequent increase in the interactions between them might be contained if the components subject to future change, namely to redesign, are identified. In conclusion, as all the theories, also this one must be verified by
a practical application consisting of the performance of product redesign based on the presented modules’ formation. In this way, the benefits of modularization are tangible.

2.5.2 Espresso Maker Machine Case Study (Tchertchian et al. (2009))

The model for the assessment of MLC products described in the previous section is substantiated through the application to an industrial case study: Espresso maker.

For the experiment, three coffee machines have been chosen: a manual machine without doses (PA), a manual with coffee doses (PB), and an automatic one with doses (PC). The configuration of the case study is based on making a LCA in terms of machine’s usage options, so that the MLC possibilities are determined as well as the environmental impacts due to the coffee doses and energy consumption.

The choice of this specific consumer good has been made since the coffee machine has basically three modules, namely pump, boiler, and infuser that, according to the evaluation done, can be eventually reused.

With interest in the three modules considered, the pumps and boilers do not vary consistently among the different espresso machines, whereas the infuser, which is more subject to technological changes, renders a machine different from another.

In details, the vibrating pumps have a longer lifespan because they are characterized by rather short cycles, and somewhat technologically stability, since their technology has not changed considerably over the past twenty years. The disassembly operation is somewhat difficult, yet worth the effort due to the long lifespan of the part. Oiling is necessary for remanufacturing the pumps.

The boiler is a valuable and crucial component in the coffee maker system; its breakage usually leads to the disposal of the whole machine. However, to avoid discarding, descaling before remanufacturing might be an alternative worth trying both environmentally and money wise. In this case disassembly is not easy either, but it is worth the endeavour given the part’s high value.

With regards to the infuser, it can be easily disassembled and regularly washed/cleaned prior to remanufacture.

As mentioned above, only the three modules that are going to be analysed are actually good candidates for reuse through remanufacturing. Therefore, the researchers’ effort lies in finding the proper modular clustering that is environmentally and economically beneficial.

The scenarios considered in the study are the following: 1) WEEE scenario according to WEEE Directive; 2) Reuse of the infuser only; 3) Reuse of the infuser and the boiler; 4) Reuse of all the three modules.

An economic assessment (ECrMLC) has been conducted for each of the considered scenarios. In particular, the cost of each module at the end of every life cycle has been determined in relation to the costs of transportation, Ctps, to and from the OEM, storage, Cw, and final treatment, Ct, (reuse, remanufacturing, and/or recycling). Therefore, the total cost is calculated as: Cglobal = Ctps + Cw + Ct.

Based on the evaluation obtained from ProdTect®, the treatment cost is assumed to include disassembly, recycling, and materials’ resale. The number of modules to be remanufactured does not affect the transportation and warehousing costs, yet they are influenced by the treatment costs, which vary according to the scenarios.

Simultaneously, an environmental assessment (ENrMLC) has been done in accordance with the reused module n (Mn), the number of life cycles of the module (Zn), and the value time in years (N).

A life cycle assessment of the products is performed for the four different scenarios at issue. The assumptions made are that Z is up to three because beyond this number the technological gap would be too

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wide; N varies from 1 to 5, and it is kept constant for one life cycle. Possibilities of upgrades are to be considered after assessing the compatibility of the recovered modules with the architecture of the new product.

After the LCA evaluation, simulation is performed and a graphical representation of the different possible configurations is shown on a Cartesian chart with regards to environmental impact and economic costs. By identifying the products at each lifetime in the chart, it is possible to get several configurations from which the designers can select the modular combination that best suits their case.

It has been shown that the use phase of the espresso machine impacts the environment by approximately 90%, due to the doses and energy consumption even when the machine is in the sleep mode, therefore the impact of the products is not only related to the effect of remanufacturing on the manufacture and EoL stages. The final analysis of the results obtained by the researchers Tchertchian et al. (2009) shows that, for product P_C (automatic coffee maker with doses), the environmental and economic repercussions of the manufacturing phase are 5% less if the three modules are remanufactured compared to the treatment (recycling) that WEEE envisages.

Tchertchian et al. (2009) advise the designers to make decisions regarding the multiple-lifecycle products early in the design process because it is the only possible way of designing sustainable products. By making the environmental and economic performance assessments an integral part of the design stage, it is possible to isolate the technical solutions.

Moreover, it is feasible, at the same time, to determine the limitations of EoL treatments, such as the definition of the optimal dismantling time, the type of recovery, and the selection of recovered modules to use in the new products, and the logistic boundaries, in terms of costs, and legislations. Based on the results of the LCA on modularised products, it can be argued that the decomposition in modules while taking into account possibilities of multiple lifecycles has a better impact, in terms of environmental and economic performance.

### 2.6 Examples of industrial practices that have succeeded in closing the loop through Remanufacturing

The Ellen McArthur Foundation, founded in 2010, has galvanized a rethinking and consequent redesign of products that would accelerate the practical process towards the circular economy. The Foundation has global partners, such as Cisco, Kingfisher, Philips, Renault, and Unilever that have consistently supported the Foundation with its goals. Besides these global partners, there are about 90 other leading companies contributing into the development of the circular network; these constitute an active involvement in “The circular economy 100”[13].

Examples of companies that have proved to be successful in closing the manufacturing loop through remanufacturing are presented as follows.

#### 2.6.1 CATERPILLAR

Caterpillar represents a prominent example of manufacturing firms that have put into practice not only the concept, but also the principles of circular economy. They are considered one of the leaders among

companies that have given stimulus to return and reuse practices, without involving leasing, or buying products as services, to keep control over the sold products.

Caterpillar does manufacturing and remanufacturing of construction equipment. Their incentive strategy consists of a great deal of advantages, such as guaranteed buy-back from the end users, with the final price based on the part’s condition. By doing this, they assure an incredibly high level of returned cores, lower prices for raw materials, more financially affordable products for happier customers, and increased control over the materials at the product’s EoL (Benoy et al., 2014).

Caterpillar takes care of different processes, from the design to the sales, of machinery and engines. They are among the most famous manufacturers of construction and mining equipment, diesel and natural gas engines, and they supply and remanufacture equipment for the military as well. In the Case Study: Caterpillar, APSRG (2014) state that only 10% of a Caterpillar product is remanufactured, whereas the remaining 90% is usually left as is.

The company started remanufacturing in 1973 and the increasing success involved in the practice has convinced it to keep on collecting cores from the market and remanufacturing them (APSRG, 2014). Only in this way they could detain the ownership of the goods and their related value. Caterpillar have created “Cat® Reman” that returns the cores to conditions equal to those of the new products through remanufacturing and by reducing, reusing, recycling the materials otherwise destined to the landfill. Hence, customers who buy remanufactured products are assured the same quality levels at a cost corresponding to a fraction of the one for a new part.

The evident reductions due to these activities regard waste, greenhouse gas generation, necessity for raw materials, and owning and operating costs, therefore even increasing the profit margins. Although the quality and warranty of a remanufactured product are equivalent to those of a new one, they charge customers a lower price for the remanufactured one, and a “core deposit” extra, which is returned when the core is given back, in which case the product would be even cheaper.¹⁴

The cores sent to Cat Reman are dismantled to the point they lose track of the original product, down to the smallest component obtainable. Every single part that has been disassembled is washed and inspected on the base of rigorous engineering standards to assess whether the part can be recovered or not. When it is verified that a component is worn out and cannot be remanufactured, it is converted into material ready for production. Cat Reman, indeed, recovers and lends value, both technical and financial, to parts that would otherwise not be usable.¹⁵

Caterpillar’s aim towards sustainability and circular economy through remanufacturing has taken the company to reach significant environmental benefits. APSRG (2014) argue that, according to some company’s calculations, the remanufacture of a cylinder head makes it possible to have “an 86% safety advantage, 61% less greenhouse gases, a 93% reduction in water use, an 86% reduction in energy use, a reduction in waste sent to landfill of 99% and a 99% reduction in material use compared to making a new product”. The data just presented talks by itself concerning the extremely high advantages derived by closing the manufacturing loop.

2.6.2 Remanufacturing in Japan

Photocopy machines have a great remanufacturing market in Japan. Among the OEMs that do remanufacturing of this category of products, there are Fuji Xerox, Ricoh, and Canon. Matsumoto and Umeda (2011) have conducted a study to assess motives, incentives, limits, difficulties, and benefits associated with remanufacturing in Japan, concluding with case studies for the above-mentioned companies after interviewing the OEMs’ managers.

Following, results, consequences, and environmental and economic benefits derived from remanufacturing in the OEMs are presented.

1. XEROX

Fuji Xerox began remanufacturing in 1990s and nowadays it is considered the most extensively mentioned and successful remanufacturing firm, that has implemented a whole system that enables it to constantly close the production of printers loop, reaping all the economic and environmental benefits of the process. Due to these activities, the company’s profits have incremented and, at the present time, Xerox does remanufacturing not only in Japan, but also in the USA, the UK, the Netherlands, Mexico, and Australia (Benoy et al., 2014).

Fuji Xerox’s remanufacturing practices have reached such a high level that reused components can always be found in new products and there is neither distinction nor difference between refurbished and new items. It is, however, the result of a high initial cost investment that the company made due to its environmental concerns and responsibility and took about ten years to recover from. Much effort in achieving this goal has been put e.g. in Design for Remanufacturing (DfReman), that widely facilitates the implementation of reused components into new products, which makes them entirely equal. In support of this, there are the rigorous quality controls that prove the idleness of doubts about quality issues (Matsumoto and Umeda, 2011).

Although it is not known which precise business model makes Xerox so successful, it is known that the fundamentals of their business are based on an annuity model. According to it, more than 80% of the revenue comes from contracted services, maintenance of their equipment, consumable supplies, and so forth. The remaining percentage of the annual revenue comes instead from the sales of the equipment. They consider both cash sales and leasing agreements as sales.16

Being a pioneer in closing the manufacturing loop in the electronic equipment industry, Xerox has managed to significantly reduce the waste generated in the production processes and in the procurement of raw materials by establishing effective take-back initiatives, and developing a solid network for reusing, remanufacturing, and recycling used products. This effort translates itself into extremely significant environmental advantages: in 2009, 45,000 metric tons of waste did not end up in the landfill, thanks to Xerox’s waste-free initiatives.17

2. RICOH and CANON

Ricoh and Canon’s first remanufactured products, made out of reused component, were seen on the market in 2000s. As Ricoh stated, the first advantages for both manufacturers and customers were observed in the fact that reused parts composed 93% of the remanufactured photocopier’s weight, and its price was

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50%-70% lower than the one for a new machine. Moreover, since the beginning, remanufactured products’ market has led to more profits than the one for new equipment.

However, remanufactured products are produced using the DfRemfg and labelled so as well, while new items are made by using solely new components. This might be a consequence of customers’ dislike to remanufactured products, which leads to sales at lower prices.

To conclude, although these two companies have not achieved a condition in which they can sell remanufactured and new products without any distinctions, they claim to be satisfied with the profits obtained and in prospect of the long-term economic and environmental incentives (Matsumoto and Umeda, 2011).

2.7 Types of Business Models

The business models that are considered and analysed are ‘Buyback’, ‘Product Service System (PSS)’, and ‘Functional Service’. All the economic models considered imply OEMs’ responsibility to a certain extent.

If this process is to be implemented and OEMs are responsible of the products’ take-back, it is in their own interest not to use toxic materials when manufacturing goods. In the specific case in which they have to include hazardous materials in their products, they are supposed to make sure to integrate them in a way that their extraction and separation would be easy at the EoL of the goods in question. This is, in particular, the case for IT products and some electronics in which extremely expensive and rare earth materials are implemented and cannot yet be recycled.

Making profits out of the re-making of products is one determining goal of the business model associated with the circular economy, but performance might be considered even more important. As Walter Stahel suggests, if all kinds of goods are purchased as services rather than products, then it is performance that is exchanged, exactly like it happens when the business model is based on renting items or sharing goods. It is, indeed, a service, for which users do not have any responsibility. Consumers buy the product’s functionality but they do not own it, hence they buy its performance by using the service that is offered.

Five different business models have been chosen and are shortly presented and described in the sections from 2.7.1 to 2.7.3.

2.7.1 Buyback Model

This business model is often related to the practice of recycling, reuse and remanufacturing. It is based on financial incentives deriving from return and reuse.

In this context, the customer, when buying the product, pays an extra fee that will be paid back once the product at its EoL is returned to the OEM. The customer, in this way, is somehow motivated to return the products that are not considered useful any longer.

The presented business model is about making the returning of appliances back to their original supply chain network, basically in a similar way to the rewarded return of cans, plastic and glass bottles in countries such as Sweden, Germany, and North America.

Therefore, contrary to what happens with a leasing model, the customer does have the ownership of the purchased product for the time period desired rather than to benefit from a service for a fixed period of leasing. In addition, although the reward obtained when returning a used product might be trivial compared
to the price paid in advance, the psychological power involved in the process should not be undervalued when assessing the positive effect in customers’ behaviour. Obviously this business model becomes more successful if the returning process is easy to follow and the consciousness of the advantages that the consumers might have from purchasing remanufactured products gets higher and higher (Benoy et al., 2014).

2.7.2 Product Service Systems

A Product-Service System (PSS) is defined as a joint of tangible products and intangible services that are designed in a way so that what this combination offers is able to fulfil specific customers’ requirements. This business model is often seen as an opportunity to increase competitiveness and promote sustainability at the same time (Tukker, 2004).

The same author indicates the benefits of such a business model in some features adding value. These features include:

- Satisfaction of customers’ requirements in an integrated way and with a high level of customization. The consequence is that customers can focus on their core activities and leave the management of other activities to a company that offers PSS.
- Loyalty is enhanced owing to personal and unique relationships with the customers.
- The continuous analysis of customers’ needs leads to better possibilities of innovation.

The figure below (see fig. 9) clearly shows the different levels and sublevels, which are the eight archetypical models, of PSS.

![Figure 9 Main and Subcategories of PSS (Tukker, 2004)](image_url)
The main categories are briefly described on the basis of Tukker’s analysis:

A: ‘Product-oriented services’

It is a model still conceived as a simple product selling, with the only difference of additional services offered. The additional services can include maintenance, consultancy and advice on product’s use and on the company’s logistics where it is used, take-back programs at the EoL, and so forth.

B: ‘Use-oriented services’

It is still based on the physical product having an important part, but the business model is not based on product selling. Precisely, the provider is the owner of the product that is made accessible in different ways and often it is shared among different customers. The subsystems of used-oriented services are described as follows:

Product Lease

The provider of the product is its owner and is responsible for its maintenance, repair and control. The user pays a fixed fee to benefit from its use. In exchange the user has usually unlimited and individual access to the product (Tukker, 2004).

Equipment leasing can be described as a loan done from a lender that has bought the product and rents it to a customer. At the end of the pre-agreed leasing period, the customer can decide whether to buy the leased equipment or return it or even lease different products.18

Product Renting or Sharing

It is basically leasing, with the same requirements on the provider, yet the product is not always accessible by the user. Therefore several users can use the same product at different times, in sequence.

Product Pooling

It is product renting in which different users use the product at the same time.

C: ‘Result-oriented services’

It is a model that entails an agreement on the final result between provider and customer. Examples of this subcategory are:

Activity management/ Outsourcing

A third party is responsible for the management of a part of a company’s activity.

Pay per service unit

The user does not purchase the product; on the contrary he/she pays for its output based on the level of use. Examples of this model can be seen in the formulas “pay-per-print” or “pay-per-wash”. According to these, it is the device’s producer that has to assure specific functions, such as material supply, maintenance, repair or replacement when needed.

18 http://www.entrepreneur.com/article/52720
Functional result

The delivery of a result is decided and agreed upon between provider and customer. It not connected to specific technological solutions and sometimes it is expressed in abstract deliveries, such as “office’s pleasant climate” (Tukker, 2004).

2.7.3 Functional Product

Functional Product (FP) business models are more related to B2B than to B2C settings and often entail the ownership and product’s responsibility for the manufacturer. At a first analysis, there is a strong relation between FP and industrial PSS that are ‘result-oriented services’ (Reim et al. 2014).

The FP conception is based on the fact that the product’s function is delivered on a continuous base and it always has to respect some performance criteria that have been decided prior to the agreement. The actors involved in the process are the manufacturer of the capital good and the customer. The former owns the physical product that is utilized to fulfil the customer’s expectations with its service. In addition, the provider of the service, namely the manufacturer, has the responsibility for the maintenance and operations of the goods offered (Lay et al., 2009).

In order to meet specific service characteristics, typical of this business model, Reim et al. (2014) argue that product design will need to respect specific properties, such as reuse, upgrading, easy to maintain. These properties will increment the chances for the FP model to be successful.

Moreover, the services that are offered with these tactics will enhance cost efficiency because the amount of products used will be lower. The incentives to reduce resource consumption and maximize resource utilization are high since the savings will directly benefit the manufacturer (Reim et al., 2014).

The different aspects and tactics of the FP model are shown in fig. 10.

In summary, the customers neither buy nor own the product with its services; on the contrary they purchase the performance of it for a period of time and at the performance requirements that are agreed upon with the manufacturer at the beginning of the contract agreement. This solution appears to be highly customer-oriented because the customers determine the service offered. It follows that the degree of customization and flexibility must be high.

In addition, this business model appears to be an extension of “Pay per service unit” model, with a difference in the time frame, since FP seems to be more based on the agreed performance level and “Pay per service unit” seems to be more related to the amount of times the product is used. In both cases, however, the manufacturer has the responsibility for the offered product-service.
To conclude, the business models that have been shortly described have all specific features that lead to the success of a company. Obviously, although a business model appears excellent on itself, it might work for certain products and/or markets, yet it might be disastrous for others. It follows that, according to an extensive study of the characteristics of the specific activities, the most suitable business model can be proposed.

Moreover, it must be pointed out that the OEM’s responsibility increases when moving from ‘Buyback’ to FP models, therefore the incentives of reducing the resource consumption increase as well as the economic benefits for the OEM and the environmental benefits for the earth. The increasing OEM responsibility is shown in figure 11.
2.8 Research Hypotheses and Assumptions

2.8.1 Assumptions on the business model in the Master Thesis

The assumption regarding business models made in the present work is based on the consideration that the manufacturers are responsible and accountable for the entire take-back process. Therefore, OEMs are assumed to actively cooperate in fulfilling the success of resource conservation challenge (Rashid et al., 2013).

The OEM is called for controlling the sold items through direct links with the customers, so that the recovery activities on the returned product will be easier to perform. As mentioned above, forward and reverse supply chains must be part of the same enterprise to favour the closest cooperation and coordination. In addition, if the OEMs have the ownership of their products, it will be easier to trace their responsibility and to establish a closer linkage with their customers.

Although the leasing model has turned out to be advantageous for some OEMs in achieving the benefits of controlling the life stages of the product and its EoL activities, the success of the business models depends not only on the efficacy of the model itself, but on other parameters as well.

In particular, factors to consider when choosing the model are:

- Type of product
- Customer segments
- Location of the OEM and the selling market
- Type of design
- Reverse supply chain design
- Information and communications technology (ICT), connectivity OEM - customers

The presented parameters are to be set in order to define how efficient and successful a business model would be. On the other hand, it is clear that the choice of the most suitable business model at a company’s level should be the result of an extensive study; therefore the present Thesis work will consider different business models as a mere strategy undertaken by the company. In brief, it is proposed that it will be the customer’s decision, when an agreement has to be achieved, whether to opt e.g. for a buyback rather than PSS.
In support of the decision on this assumption, Walter Stahel would say that the most important decision that companies aiming at closing the supply chain loop would make is the choice of the business model that allows for products’ take-back and remarket. To enable this, according to him, the products should be designed for their full lifecycle/s, thus including the reverse flow from the consumer back to the producer/remanufacturer. He advises the use of standardized components through modularity, and system solutions instead of ownership of products.

Moreover, the simple ‘product selling’ economic model is not taken into consideration because it does not imply any responsibility from the manufacturer part and fails in motivating customers to reduce their waste. It is believed that in order to permit the development of an economic model, in which the triple bottom line of sustainable development -economy, ecology, and society- is stationary in the forefront, a change in the society’s mentality should be achieved. Hence, only the business models implying OEM’s responsibility are considered in the current thesis.

On the other hand, manufacturing companies are adopting service-focused operations rather than product-focused more and more compared to the past (Lay et al., 2009).

2.8.2 Assumptions on the Acceptance of Remanufacturing Practices

It is assumed that the demand of remanufactured items is not compromised by strategic or quality issues, such as possibility of cannibalization or fear that the remanufactured product would have lower quality, thus would be more prone to less reliability and earlier breakdown.

Customers’ behaviour as well as manufacturing practices need motivation to change. Supporting this desirable view there is the company Xerox that built its success on remanufacturing its copiers and printers, which was made possible in a considerable portion due to a modified consumers’ behaviour. Xerox was the pioneer of the practice of recovering office equipment, and, since 1991, their activities of remanufacturing and recycling have thwarted more than 2 billion pounds of potential waste to end up in the landfill. These practices have led to a high reduction in waste and cost savings over the years, however King et al. (2007) highlight how sometimes the barrier of the consumer behaviour is impenetrable. Thus, they stress on the need “to change the present culture of fashion obsolescence driving new sales”. Nevertheless, Xerox has managed to render recovered products as desirable to customers as the new products.

2.9 Modular upgradability in an adaptable design

ResCoM advocates the need of a design approach for closing the loop by intention rather than by chance when the desired output is the assessment of the feasible number of lifecycles that the product would and should have. In order to make these decisions at the design stage, it is necessary to design the product accordingly.

In this section it is evaluated whether or not it would be even more helpful to have an adaptable design that accommodates the possibility of upgrading not only the software, but also the hardware of the appliances. Since an integrated design does not allow for hardware upgrades, but solely for software improvements, the use of modularity as a substitute of the traditional product structure is suggested. With the aim of increasing the life span of the product, extensive reuse and remanufacturing of the product’s

19 http://www.emg-csr.com/blog/circular-economy/
subsystems is advisable. Therefore, the use of modularity for the achievement of resource conservation through a closed loop supply chain is the key path to go.

Modular upgradability, by allowing for independent substitution of subsystems prone to become obsolete faster rather than discarding the whole product, might improve the environmental performance. Indeed, the waste impacting the environment during the production and disposal stages can be decreased by modular upgradable architectures. This is especially the case for several consumer electronics, such as computers, and network equipment. Indeed, a handful of firms, such as Dell, HP, IBM, Cisco, and Xerox, have implemented modular upgradability as a DfE strategy (Agrawal and Ülkü, 2012).

The common knowledge regarding modular products is that their structure is usually bulkier due to the presence of a higher number of interfaces, as Agrawal and Ülkü (2012) highlight; however consumers’ thinking should be remodelled in accordance with the environmental and economic objectives that are desirable. Celona et al. (2007) instead argue that, although it is believed that modular products are heavier and larger than the integral rivals because the former need more space and weight for accommodating more interfaces, there is no quantitative proof supporting the belief.

They conclude that the additional space used in modular products is not due to the product’s functionality; there is often unnecessary space, not needed; it is basically a matter of efficient use of space. Celona et al. reach a significant result for product design: modular products do not have to be bulkier compared to their integral counterparts, but the space must be utilized better; it follows that the valuable benefits coming from modularity should not be sacrificed. A need for innovation in design is hence recommended.

Modular design has been presented as a viable solution to have products that are more responsive to the changing circumstances of the global market. Indeed, when the design requirements change owing to a change in customer needs, environmental standards, and/or technology improvements, either the product or the design needs to be adjusted in order to fulfil the new requirements. Modular design, for instance, perfectly accommodates ‘product adaptability’, as defined by Gu et al. (2009), by permitting easy replacement and/or addition of modules, when needed and as desired, so that the modified product actually conforms to the new specifications. This represents the point at which the so-called ‘Adaptable Design’ comes into play.

Adaptable Design is defined as “a design methodology for ease of adaptation of design or product considering changes in requirements” (Gu et al., 2009). Therefore, the design has to have characteristics of adaptability, in the sense that an existing design can be adjusted to generate a new or slightly different design when the requirements on the product have been changed. An adaptable design used to create a novel design helps significantly reduce time and effort in the product development process and the main advantages can be seen in the environmental and economic elements. Gu at al. (2009) accentuate the difference between traditional and adaptable designs. In details, the former aims at reaching the desired levels of product’s functionality through maintenance and repair actions, whereas the latter aims at improving the functionality through upgrading.

The adaptable design approach leads to economic benefits with regard to the savings in time and cost in the product development, and consequent faster time to market, with higher profits for the manufacturer. In parallel it has environmental valuable advantages owing to the high degree of reuse of product’s parts.

Designs that take into account product adaptability, magnified by modularity, reduce the waste not only in the manufacturing stage, but also in the remanufacturing and recycling operations, since less modules must be replaced to adapt to the new technical and aesthetic specifications thanks to both design and product
adaptability that obviously increase the length of the product’s life (Gu et al., 2009). The authors present an image to visualize the different practices with different impacts on the environment (see fig. 12).

Figure 12 Methods to reduce environmental impact (Gu et al., 2009)

As it appears from the picture, product adaptability would have the minimum negative effect on the environment, therefore it might be a clear indication that modular approach, which is the one favouring this adaptability, should be extensively implemented.

The degree to which this kind of design is helpful for the achievement of resource conservation depends on the ease of assembly, disassembly, and reassembly, since the modules are meant to be added, removed, and exchanged for upgraded ones. This assembling ease depends on the level of interactions between separate modules and between modules and interfaces; hence the design of interfaces is extremely important in order to reduce to minimum the effort of adaptation of the product.

It can be deduced, indeed, that ResCoM might be highly favoured by an adaptable design, based on modular, platform, interface, and product family design because this new design approach accommodates a better product adaptability, hence the reduction of resources’ waste during the disassembly phase before deciding on the EoL strategy to opt for. The reduction of resources wasted is owing to the fact that the number and the type of modules that are going to be reused, remanufactured, and/or recycled is determined already in the design stage. It follows that the product, at its EoL, is disassembled according to a dismantling sequence carefully calculated right at the design phase, and waste of energy, materials, unnecessary effort from the manpower are minimized. Therefore, modularity leads to high levels of efficiency for a CLSC.

In conclusion, adaptable modular design approach can be used in industrial engineering field in order to have flexible manufacturing systems, so that manufacturing cells or modules can be readily added, removed, and reconfigured or repurposed. Indeed, as the researchers Gu et al. (2009) pointed out, adaptable products, compared to the traditional practices of remanufacturing and recycling, can further expand the life of the product and reduce the damage to the environment.
2.9.1 Re-purposing

It is concluded that the choice of having an adaptable design is mostly appropriate for the ‘Re-purposing’, thus when a product that has specific functions can be transformed in a product with the same base structure, but with totally different functions.

In this way, functions might continuously be modified, added, and replaced. In order to deal with the adaptable design complexity, Gu et al. (2009) suggest that modelling of functions at different levels is done, and all the correlations of independency between functions must be determined carefully.

By adopting this approach, when customers choose to modify or add new functions to their product, new modules with new/different functions are put into place into the old product. Hence, one single product, thanks to function-based modularity, can allocate several different or alternative functions.

The chance for customers of having products that have optional functions implemented in the same structural platform would lead to a new level of production and disparate customer segments might be satisfied at the real same time. It would be important, however, to have the same space for modules’ interfaces so that new modules with different functions than the previous models can be as well allocated in the old interface slots. Therefore, when it is requested to fulfil different functions in different products of the same family, the platform design approach can be used, as suggested by Gu et al. (2009), and modules having specific functions will be attached to the platform, after a reconfiguration of the different attachment modules.

In order to be more concrete, an example of a product having an adaptable design obtained by using platform design and product family design approach is offered by the Black and Decker’s modular power tool 21. The power tool at issue consists of a principal module, containing the motor, handle, and battery, to which it is possible to attach one of the seven different accessories, among drill, jigsaw, circular saw, and so forth.

Another example of adaptable design, offered by Gu et al. (2009), would be a hand vacuum cleaner, to whose basic interface it is possible to attach various accessories, e.g. one for wet spills and one for dry dust.

3. Approach and Methodology

The present chapter presents an overview of the method chosen to analyse the assigned case-study-based product, namely the semi-commercial washing machine “Cylinda Sverigetvätten N”. The analysis is done at the design level in order to explain firstly the reasons for modularization’s need and, secondly, how to apply modularity in the context of resource conservation.

Since a specific methodology that takes into account modularity within the ResCoM vision has never been documented, the present thesis is based on the evaluated case studies done on similar products and in similar contexts. More precisely, the context in which the analysis is performed is based on traditional forms of resource conservation. Therefore this thesis project aims at giving suggestions to define a method that would assess economic and environmental impact of ResCoM when using a modular design and that could be replicated by following standardized procedures.

The suggestions that will be given are based on internal surveys taken at the consultancy company Modular Management22, Stockholm, Sweden, and on the author’s personal opinions due to the research

22 https://modularmanagement.com
done. Therefore, this section consists more of an approach that leads to disparate results rather than the application of a predefined method to a case study.

### 3.1 Modular design to enable the reuse of carryover modules

The main reason why modularity is proposed as a design solution for the washing machine under investigation is that this type of design might enhance the reuse of modules over time and guarantee an efficient ResCoM, since prolonging one single lifecycle leads to the possibility of having multiple lifecycles for the same product.

In order to survive to the fierce competitiveness of the fast changing market, the companies’ approach to product development should be revised in a way that allows them to improve quality, keep the costs low, and speed up the time to market. In the attempt of being more efficient, the solution has been seen in the adoption of lean principles in engineering not only in the production and administration, but also in the product development stage. However, at the beginning of this process, the finished product is still unknown, despite of the application of lean principles (Lorenz et al., 2015).

To achieve excellent benefits from lean engineering, what counts is “doing the right things”, namely being effective, and “doing things right”, namely being efficient (Leine, 2013). Lorenz et al. (2015) state that “Efficiency is driven by fully utilizing modularized product design across all product lines”. Therefore, modularity is considered as an enabler for the application of lean methodologies in engineering practices.

In MFD, it is called “Carryover” the module whose design remains the same from one generation to the next. Thus, it is the case of a part or subsystem that will not be subjected to any design changes during the lifetime of the product platform.23

If the utilization rate for carryover parts is maintained high, the need for alternative designs is reduced, solution-oriented designs are preferred, and this complex of solutions entails a more efficient set of processes within the company. Indeed, standardization and modularization of processes leads to the identification of defined sequences with a constantly known output, so that the eventual recognition of bottlenecks is doable at an early stage and waste is removed faster (Lorenz et al., 2015).

As Lorenz et al. (2015) highlight, companies that have chosen modularity as the main approach, by having different functions in distinct modules and reusing their design across other product variants, can decrease costs, achieve better quality, increment product variety, and speed up the development process.

From their results, it is also shown that companies that are leaders in modularization manage to achieve shorter development time and to plan more accurately compared to those companies that do not implement any modular product systems or do not reuse existing modules according to their potential. From the study results it is deduced that the lean champions among the companies participating at the survey employ modular design in the complete product portfolio across all the product lines. These companies manage to reduce engineering effort and resources’ consumption by designing modules that can be reused in an easy way, so that unnecessary product requirements that do not satisfy customers are avoided. In addition, suppliers are actively involved in the early modules’ definition process, in order to increase the cooperation and successfully close the supply chain loop.

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23 [https://modularmanagement.com](https://modularmanagement.com)
3.2 Case Study: Washing Machine Cylinda Sverigetvätten N

3.2.1 Case study - Reasons

Some surveys regarding the lifetime and life performance of a household washing machine, conducted in the past two years, show that some low-end appliances seem to last up to five years, or no more than seven, contrary to the past observation of appliances lasting for more than ten years, sometimes twenty. It is questioned whether some parts inside the machine are deliberately designed to last for a predetermined number of washing cycles or the combination of low quality materials and techniques easier to implement might lead to a reduced lifespan of the device at issue. In the former case, it might be due to a specific business strategy that economists would call “Planned Obsolescence”, and in the latter it might be owing to the need of using cheap materials, which at times break down faster, in order to market the appliances at a lower price so that more people can afford them. In both cases, this acknowledgement is in contrast with the past years in which producers used to sell long-lasting appliances and offer repair and service for the whole time they lasted.

Some manufacturers choose to adopt an integral design rather than a modular one, and it might happen that when a fault occurs, it might be hard to replace just one part or component. Therefore, consumers might need to substitute the whole set of assemblies, in order to favour the repair. It might be the case of the motor replacement: when it is not bolted, but spot-welded, it is impossible to take it apart. Pumps’ parts are difficult to find, therefore, when needed, the part must be replaced with a new pump. Usually drums’ bearings cannot be removed, so the whole tub must be substituted with a new one, in which the bearings represent a whole with the tub itself. Sometimes, outer drums are welded together and it makes it impossible to separate them. It is still not clear whether this is resulting from the fact that modern washing machines are built by using cheap materials, so that their price is lower and the majority of people are able to afford them, or to impede repairing. Another reason might be that manufacturers want to have low levels of inventory of spare parts, thus they make it expensive to repair a faulty machine, and consumers, consequently prefer buying a new one.

Whatever the reason is, the earth is suffering from lack of resources owing to extremely high production rates, and a solution must be proposed. Therefore the main interest has been to investigate the possibility of building washing machines that are designed to have multiple lifecycles. This possibility might depend on the ease of repair and replacement of faulty or obsolete subsystems and the remanufacturing of parts, with no meaningful distinction between new and remanufactured products, alongside with a supportive ad hoc business model.

The washing machine Cylinda has been chosen as a mere example of design. It is analysed by a design viewpoint in order to understand both the weak and strength points and which are the possibilities of increasing the life span when different, namely integral and modular, design solutions are implemented.

The reasoning behind this investigation lies in the attempt of showing commercial washing machines’ manufacturers that it is possible to reutilize existing modules when developing new products or new product variants.

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24 http://www.whitegoodshelp.co.uk/how-long-should-a-washing-machine-last/
25 http://www.economist.com/node/13354332
26 http://www.whitegoodshelp.co.uk/how-long-should-a-washing-machine-last/
### 3.2.2 State-of-the-art of Washing Machines

From a recycling perspective, since the majority of electrical devices nowadays are formed by a wide variety of different materials, they do not allow for an easy recycling process. For instance, in a regular washing machine, it is possible to find a range of materials that includes parts manufactured from sheet metal, sometimes coated with zinc, stainless steel, iron with porcelain coating, plastic, which is extremely good rust resistance, aluminium, glass, and so forth. The disassembly operation after the collection of used products is a requirement established by law (WEEE Directive) for the EoL strategy, either if it is recycling or remanufacturing.

Washing machines are rarely modular and are not optimized for remanufacturing. Although several parts of these appliances might be profitably reused because still technically valid, there is missing a solid inverse logistics with acceptable costs. Therefore, modularity is proposed as a solution to this necessity since it creates the circumstances of having functionally separated modules that would overcome the obstacles to reuse. The functional building blocks\(^\text{27}\) (modules) are considered as assemblies of components contributing to the fulfilment of the same function. Hence, by grouping components with comparable and/or related life characteristics, e.g. ease of maintenance, and repair, the EoL scenarios do not appear burdensome to deal with (Tchertchian et al., 2009).

---

**Energy Information and Technical Data - Sverigetvätten N\(^\text{28}\)**

- **Energy efficiency class:** A+++
- **Maximum washing capacity:** 8 kg
- **Annual energy consumption:** 196 kWh per year
- **Annual water consumption:** 10340 litres per year
- **Water consumption per wash (Normal programme, 60°C, 40°C, full load):** 55 litres
- **Centrifugal efficiency class:** B
- **Maximum spin speed:** 1400 rpm
- **Residual Moisture:** 53%
- **Wash drum and liquid compartment material:** Stainless steel
- **Outer casing material:** Powder-coated and hot-galvanized sheet steel or stainless steel
- **Water connection:** 1,5 m PEX (Cross-linked polyethylene) pipe
- **Drain:** 1,7 polypropylene hose
- **Average product’s lifetime:** 30,000 washing cycles, with an average washing cycle of 2 hrs, assuming that the machine runs for twelve hours per day, which equals an average lifespan of 13 years.

Both annual energy and water consumption are based on 220 standard washing cycles for Normal cotton programme at 60°C and 40°C, with full and half loads. They last respectively 2:50 hrs (2:20 hrs for half load) and 2:40 hrs (2:20).

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\(^{27}\) [https://modularmanagement.com](https://modularmanagement.com)

3.2.3 Reasons for Modularization Need in Washing Machine product families

An interesting survey, conducted by Lorenz et al. (2015), in which several companies in the automotive and engineered-product industries participated, shows that modular product systems are actually implemented in some companies, but they are used solely for some product lines. Moreover, the reutilization of previously used modules is not a deeply explored possibility. They argue that the use of carryover parts compared to all parts is unusually low. In fact, the average for automotive OEMs is 30\% and only 15\% for suppliers.

Similar data from modular washing machines manufacturers is not known; therefore there is an additional need of investigating the impact of an alternative design for washing appliances.

When dealing with washing machines manufacturing, most often the situation, clarified with the help of Modular Management Expertise, consists of mass production with one product family per line. This situation leads to the complexity of matching demand and capacity, especially for multi-brand manufacturing firms.

Indeed, some production lines might be under-utilized, resulting in the need for the company to sell at discount prices through e.g. seasonal promotions, and in being cost inefficient. On the other hand, some lines might be over-exploited due to the high demand and this situation might result in negativities for the firm, such as lack of product availability and lead times that are longer than customers would expect. In both cases, the company might lose their customers.

Another highly important parameter is the need to have more variance among a product family and innovate to drive higher volumes. Variance is a fundamental factor, especially for white goods, in order to make the customers perceive the difference between products that do actually look the same.

The solution for the exposed problems would be the implementation of modularity, in particular in a multi-brand firm manufacturing different kinds of white goods, such as fridges, dishwashers, laundry and kitchen equipment, and so forth. Modularity would, indeed, help merge several existing families into a broader architecture, with the advantage of producing different products on the same line. The advantageous result a decreased development time and wider variance, in terms of product’s characteristics, aesthetics, and configurability to increase the sales for the company. Figures 13 and 14 show the main benefits of the modular approach over the traditional one.
## Traditional vs Modular approaches to Product Management (II)

<table>
<thead>
<tr>
<th></th>
<th>Traditional approach</th>
<th>Modularization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technological leaps</td>
<td>New technologies often are not implemented across the complete range, which drives variance</td>
<td>New technologies are implemented in development modules only, often no need to redefine architecture</td>
</tr>
<tr>
<td>Lead time in product development</td>
<td>Often one year to develop and test a new variant</td>
<td>Less than one half of traditional lead time</td>
</tr>
<tr>
<td>Lead time in production</td>
<td>Relying on fabrication to express model mix</td>
<td>Relying on assembly to express model mix</td>
</tr>
<tr>
<td>Launch rate</td>
<td>Low to medium - new generation of products often implies complete redesign</td>
<td>High - planned future launches can be taken into account in modular design</td>
</tr>
<tr>
<td>Quality control</td>
<td>Highly demanding - controls performed on finished product; disrupts flow and results in high cost</td>
<td>Greatly simplified - modules can be tested separately. Many carryover modules</td>
</tr>
<tr>
<td>Service and upgrading</td>
<td>Difficult, with many parts of the product involved. Typically one service instruction per variant</td>
<td>Options, upgrades, and service items can be isolated to specific modules</td>
</tr>
</tbody>
</table>

Figure 13 Traditional versus Modular (Modular Management AB, Stockholm, Sweden)

## The modularization staircase

**How far have we reached?**

- **Core competencies:** Modular architecture used to build differentiated, structured way to define, create and manage core competencies
- **Strategic integration:** Architectures seen as way to integrate technology, marketing and business strategy
- **Knowledge management:** Architectures used as framework for knowledge management and organizational learning
- **Speed to market:** as source of competitive advantage
- **Configurability:** as enabler of product strategy
- **Cost rationalization:** through standardized components and processes

Figure 14 The Modularization Staircase (Modular Management, Stockholm, Sweden)
In order to understand more clearly the benefits of modularization in a product such as the washer at issue, Electrolux-Wascator, which is a Modular Management Case Study, might give a valuable insight.

When Electrolux-Wascator asked for Modular Management help, their aim was to expand in an already highly mature market like the laundry equipment industry. They aimed at addressing new market segments with customized and unique solutions. These proposals would have been extremely expensive and time consuming to implement if a case-by-case approach was to be taken. Therefore they claim that:

“By using a modular approach the opportunities to create these customized solutions exist. The complexity of the potential product variation requires a new approach in both marketing, sales, development and production processes, but the effort has proven its worth! The products are greatly appreciated by the market, and we can provide solutions to almost every textile laundry need as we live up to the Electrolux-Wascator slogan ‘because every laundry is different’.” (Bert Nordholm, President Electrolux Laundry Systems).

The main advantages that Electrolux-Wascator has achieved through modularization are:
- Reduction of set-up time from several hours to less than one hour
- Cut of electrical system work by 90%
- Reduction in lead-time in drums’ production from 10-12 days to 2.5 days
- Reduction of delivery times
- Reduction in development lead-times by 50%
- Reduction of fault detection in the final assembly; increased quality
- 5% increase in the market share
- Time to develop a complete new platform (with modularity) is the same to develop one product (without modularity)

3.2.4 Case study: Approach

Assuming that the washing machine of the case study is a candidate for remanufacturing, a methodology for assessing which modules are interesting for upgrading, exchange, reuse, and recycling, at the end of each lifecycle, is evaluated.

The MFD methodology is considered as the means that allows for the modularization of the assortment of washers. The main focus will be on the reuse possibility, in terms of reuse, remanufacturing and recycling, of modules. In any way, before suggesting a specific clustering of technical solutions that will constitute a module, it is needed to leave aside the common rules prevailing in the application of regular MFD. Indeed, as Tchertchian et al. (2009) point out, since modular design takes into account mostly the characteristics enhancing assembly, maintenance, and upgrading, it is necessary to determine in advance which modules satisfy which criteria, in terms of lifetime, functionality, and technological stability.
Refurbishing or Replacement?

In the time frame spanning about one year, from October 2008 and December 2009, the Waste & Resources Action Programme (WRAP, 2010) has made an investigation regarding the benefits of refurbishing compared to those of replacing a domestic washing machine.

The answer to the question ‘Which is the best environmental option?’ generally depends on the energy efficiency of the model that might represent the replacement. Briefly, it is more environmentally efficient when the replacement is with a more energy efficient machine, e.g. when the switch is from a C or A rated machine to a A++ rated one (see fig. 15). Indeed, according to the WRAP statistics (2010), the global warming potential, namely the amount of heat that a greenhouse gas ensnares in the atmosphere, when replacing an appliance in the presented case is 1940 against 2150 when refurbishment is done and the machine is used for nine more years. On the other hand, refurbishing a C rated machine instead of switching to an A rated one is more environmental convenient (see fig. 16) (WRAP, 2010).

<table>
<thead>
<tr>
<th>Machine rating change</th>
<th>Immediate replacement with A++ rated</th>
<th>Refurbished, used for 3 years, then replaced with A++ rated</th>
<th>Refurbished, used for 6 years, then replaced with A++ rated</th>
<th>Refurbished, used for 9 years, then replaced with A++ rated</th>
</tr>
</thead>
<tbody>
<tr>
<td>A → A++</td>
<td>1940</td>
<td>2030</td>
<td>2090</td>
<td>2150</td>
</tr>
<tr>
<td>C → A++</td>
<td>1940</td>
<td>2060</td>
<td>2160</td>
<td>2250</td>
</tr>
</tbody>
</table>

Figure 15 Comparison of Global Warming Potential values (in kg CO2 eq) of refurbishment and replacement with A++ machine (WRAP, 2010)

<table>
<thead>
<tr>
<th>Machine rating change</th>
<th>Immediate replacement with A rated machine</th>
<th>Refurbished, used for 3 years and replaced with A rated</th>
<th>Refurbished, used for 6 years and replaced with A rated</th>
<th>Refurbished, used for 9 years and replaced with A rated</th>
</tr>
</thead>
<tbody>
<tr>
<td>A → A</td>
<td>2420</td>
<td>2390</td>
<td>2330</td>
<td>2270</td>
</tr>
<tr>
<td>C → A</td>
<td>2420</td>
<td>2420</td>
<td>2400</td>
<td>2370</td>
</tr>
</tbody>
</table>

Figure 16 Comparison of Global Warming Potential values (in kg CO2 eq) of refurbishment and replacement with A machine (WRAP, 2010)
It follows from the study that refurbishment is the most, environmentally wise, beneficial solution in half of the cases. There must be said, however, that the machines that were investigated were characterized by a rather low energy efficiency compared to those on the market nowadays. The authors of the WRAP study actually suggest the replacement when new upgraded machines with lower energy and water consumptions are available on the market. They also advise to further analyse cost effective refurbishment possibilities for both the models available at the time being and the future ones. In fact, if the future developments on the energy consumption are not significant, the only way of reducing the environmental impact of the production of the washing machine will actually be remanufacturing with guaranteed increased lifespan (WRAP, 2010).

Since the washing machine at issue is rated A+++, which is the latest introduced grade, the substitution with a potential more efficient item cannot be considered. Moreover, the machines considered in the study are most probably characterized by an integral design. For these and other reasons discussed in the above sections, such as section 2.4, remanufacturing is a primary solution to adopt, and a modular design is expected to enhance recovery possibilities at the planned EoL, but also to facilitate upgrading, especially in terms of energy efficiency and lower consumption solutions.

In any case, the impacts of the washing machine at each stage of its lifecycle must be taken into account. According to the findings of the study undertaken by WRAP (2010), it is stated that besides the solid waste generated at the disposal of the product, the washer’s use phase has the greatest impact on the environment. During the production and assembly phases, the contribution to global damage is described in terms of non-renewable resources diminution, acidification and photochemical oxidation; moreover, their impacts are to be quantified also with regards to the amount of plastic, ferrous and non-ferrous materials for the production and the use of electricity and gas for the assembly. If the washer is refurbished, these impacts are considerably lower, with a greatly significant reduction in the production and assembly phases. Figure 17 represents the results of their study findings in regards to the different lifecycle’s stages of the chosen washer.
Figure 17 Global Warming Potential Impact (in kg CO2 eq) when a single A rated washer is replaced with another A rated or refurbished (WRAP, 2010)

Another study conducted for the LCA of a washer (ETH, 2011) shows that although more modern washing machines have higher energy efficiency, hence a better performance during the use phase, compared to machines produced ten years ago, they have a worse impact owing to the material used. In fact, the more modern washers present a higher amount of electronics and plastics that, it is known, are more difficult to recycle.

The authors Agrawal and Ülkü (2012) state, on one side, that modularity drives innovation and permits upgrades to be part of the new product, so that both the subsystems and the whole product are more competitive. On the other side, the same authors remark that the up-to-date arguments concerning the environmental benefits of modular upgradability are usually related to the production and disposal impacts of the products, and not to the effect that their usage during the whole lifetime might have on the environment. They also specify that the washers have usually a worse environmental impact owing to their use rather than to their production and disposal. It might be true, but the unbearable waste produced when these devices are scrapped, with highly limited effort in recycling is a squandering that earth can no longer accept.

In fact, according to the BBC study\(^{29}\) on the necessity of leasing washing machines rather than owning them, it is stated that a number between 40% and 70% of the 40kg of steel contained in an average washer is actually lost in the landfill when the device is being scrapped. If Ellen MacArthur Foundation proposes a model\(^{30}\) that entails leasing the washing machines with a full service for the whole duration of the contract, the present thesis proposes an offer of different business models, as outlined in the introductory sections and as it will be presented in the following ones.

\(^{30}\) [http://www.ellenmacarthurfoundation.org/business/toolkit/in-depth-washing-machines]
3.2.5 Multiple Lifecycle Analysis

The assessment of the possibility of having modularized washing machines that could have multiple lifecycles could be done through a LCA, as also demonstrated by Tchertchian et al. (2009) in section 2.5.2. However, in order to perform a LCA of the product, some important characteristics must be known. As mentioned above, remanufacturing is considered as the primary option after mere reuse, since recycling is only the last option to take into account. In order to perform this study, it is necessary to know:

- Product lifetime
- Each component’s lifetime
- Number of reusable components
- Electricity consumption
- Logistic scenario
- EoL scenario, with indication of recycling rate, reuse, incineration, landfill
- Failure rate, price, lifetime, and technical stability of each product’s component
- Indication of the environmental impact at different stages, such as manufacturing, transportation, usage, and EoL of the machine
- Product disassembly time after take-back, location of disassembling (transportation cost)

However, the lack of real data from Cylinda manufacturer makes it impossible to assess a proper LCA in this case. Therefore, the actual benefits, in terms of both ecology and economy, of using a modular design to favour ResCoM cannot be assessed in a deterministic way.

3.2.6 Modules Identification for Remanufacturing

In order to make the case-based study more effective in the evaluation of the arguments concerning the EoL scenario, modules that are potentially reusable and remanufacturable are chosen. Since the main concern is to create products that would allow for the recirculation of resources and, in the meantime, the most desirable changes for the product at issue regard the energy consumption during use phase and reliability, modules that favour these improvements through upgrading are most likely to be the candidates for the exchange process.

As Barthel and Götz (2013) point out, in order to ameliorate energy and water efficiency, it is necessary to aim at controlling important parameters, such as ‘energy used for heating’, whose amount depends on the temperature required and the quantity of water utilized; ‘mechanical action’, based on functioning time and spinning cycles; ‘water pumping’; and ‘heat loss’ owing to metal drums, glass doors. Therefore, their suggestion regards the implementation of specific design options that favour the improvements in energy efficiency.

In addition, Ellen MacArthur Foundation, in their study “In depth – Washing Machines” 31, denote that the standardized components that most commonly are the cause of breakdowns are the motor, pump, and plumbing, with the addition of belts, seals, and so forth. Therefore, after the collection of the device, the components that might be subjected to a deeper analysis are, besides the motor and the pump, the bearings, front panel, and printed circuit board.

It follows that after each recollection, if the product is modular, not all the modules will be substituted, yet solely the ones that need technical and environmental improvements, and eventual styling changes.

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The Motor Module, addressed as ‘Drive System’, includes the following components: motor, motor pulley, motor harness, drum pulley, and belt. Figures of the components belonging to the presented module can be found in appendix A. A figure representing, on a general level, the ‘Drive System’ Module can be seen as follows (see fig. 18).

![Figure 18 Drive System](image)

The ‘Drive System’ module is responsible for converting electric energy to torque and transfer it to the drum in order to make it rotate.

As presented above, the module considered consists of different technical solutions, namely components, each of which is a physical entity designed to embody product properties and perform a specific product function. For instance, the complex of motor and motor pulley provides mechanical agitation combined with water extraction to laundry; the motor harness provides the link between electrical components.

The motor in the current design is a Brushed DC Motor and its lifetime, considering that the machine is a top-end device, equals an average of twelve years. These engines are likely to last many years, and they would not burn just from running. In this kind of motor, depending on usage, the elements that are more prone to wear out are the brushes and the commutator; the latter is the one that usually gets worn out first, wearing out the brushes faster, which ruin the commutator even more, leading to damage of the axle bearings also.

Hence, at the time of the machine returning to the OEM, the motor, following an accurate testing, might be replaced with a remanufactured one, in which there might be new bearings, new brushes, and a refurbished commutator. Otherwise, the motor, after testing, might be considered still perfectly functional and not damaged, so that there might only be cleaning of the commutator so that even the brushes last longer, or it could be used in a different product variant.

The belt, on the other hand, is likely to endure for about five years, so that, at the time of recollection, it might be replaced with a new one or it might be changed during the ordinary lifetime’s maintenance.

The ‘Drive System’ module is a set of components on its own, but it interfaces to several different modules, such as the cabinet, wash unit, noise insulation package, motor control unit, CCU motherboard, different sensors, and so forth.
At the same time, this module might be seen as a candidate for remanufacturing and as a module for planned development. Therefore, the motor module could be re-valued by periodical restoring as long as the technology is somewhat stable; when there are technological improvements and new motor models are considered more energy efficient, then they will be replaced and the refurbishment will take place on the new model.

Another module candidate for reuse and/or remanufacturing deals with the outer casing of the washing machine. The outer casing material is powder-coated and hot-galvanized sheet steel or stainless steel. The duplex system, which is formed by powder coating over hot-galvanized steel, offers corrosion protection by far better than one of the two systems used independently and not in combination. The obtained material allows the casing to endure for several years. Therefore, the other candidates for the similar EoL purposes are suggested as follows.

The ‘Cabinet’ module, which, on the whole, encapsulates the machine by the sides and the rear part, gives stability, damp the noises, and consists of different elements (see Appendix B):

- Cabinet that functions as a carrier of all the components and styling, and as sealing for the noise;
- Rear cover, which prevents from unnecessary access and allows for immediate service, and carries external connections, such as holders for hoses, transport bolts and braces;
- Side reinforcements or panels that act as safety covers, and are a support for noise insulating materials;
- Cabinet bottom, which carries the feet system and the entire machine; it prevents the house from flooding in case of any leakages or malfunctions;
- Foot nuts;
- Damper reinforcement;
- Feet system that has the function of levelling and carrying the weight of the machine, while preventing the device from “walking” when it is functioning.

The components that constitute this module are firstly carryover and common unit.

The ‘Front Panel’ module acts as an aesthetic part sealing the front of the machine for safety reasons. It is part of the chassis structural strength and carries the pump’s cover at its bottom left. The front panel consists of one part that is an integrated powder-coated over hot-galvanized sheet steel. It has different functions that go from aesthetic to safety protection. In fact, it carries styling, yet it supports the door, giving shape to it, the pump access flap, and the detergent container spot.

The ‘Top Aesthetics’ module has the same material of the rest of the chassis. It is a visible and structural part sealing the top of the machine, the so-called ‘table top’. Its functions are safety, enclosure offered by the cover, splash protection, avoiding water leakages in the control unit, and support for laundry detergents and baskets. This module, as the previous ones, follows the drivers carryover and common unit.

The module drivers characterizing the above-presented modules are common. The styling requirements on the chassis, front and top panels regard mainly the colours that the customer wants, hence, according to the customers’ requirements, after the recollection, the aesthetics might be changed by painting. Therefore, these three modules, following the collection of the appliance, might be removed to assure the absence of worn out parts, cleaned, painted, if needed, and reassembled to constitute a remarketable washing machine.

However, in the ‘Cabinet’ module, the nuts, holders for hoses, bolts and braces might be replaced, depending on their condition.

The module ‘Functional Door’ that consists of door glass, inner ring, hinge, and hook, has the function of sealing and lock the tub while the machine is operating. Precisely, it keeps water and clothes into the washing unit when the device is functioning; it enables loading and unloading of the laundry washed and to be washed; and it carries door aesthetics and permits to see the load at any time, which might be useful in some cases, e.g. to detect the presence of an inappropriate amount of detergent.

This module follows carryover and common unit module drivers. It means that the same design is kept for different generations and that it is a part having the same physical form for different product variances.

Therefore, this module is proposed as a candidate for remanufacturing since the design as well as the physical components can be assumed to be the same as the previous generation. However, the rubber seal, which represents one of the main causes of leakages and reason to call the service organization for a repair, can be changed in occasion of every collection’s period or during eventual repair or maintenance. Otherwise, given that the interface is the same, the rubber seal door might be replaced by its updated version, such as a door with “Smart Seal” technology that allows for less leakages and residual detergent, no cleaning and/or repair needed.

The module ‘Wash Unit’ contains several components with similar materials with high resistance and durability that might be used for the whole machine’s lifecycle. Its main functions are to expose the laundry to a mix of water and detergent, to transfer motor rotation to mechanical agitation on the laundry, and to transfer motor torque to high-speed rotation for water extraction. The comprehensive module’s components are:

- Inner drum, namely spin tub, including front, rear and wrapping, in stainless steel. It contains and agitates the clothes during different operations
- Lifters, which improve the wetting process by carrying and realising water, agitate clothes and help distribute the load evenly during spinning
- Cross piece that carries the (inner) drum and transforms torque and rotation from shaft
- Drum shaft that carries the drum and transmit torque and rotation to it
- Shaft sealing that seals the drum and the shaft
- Bearings and bearing cross that allow the drum to rotate and support the shaft
- Outer drum, namely washing tub, including front, rear, wrapping, sump and reinforcement braces, in stainless steel. This tub contains water and it carries the spin drum, motor, counter weight, bellow and part of suspension
- Heater
- Temperature sensor to measure water temperature and for safety reasons in order to avoid overheating
- Motor fixation that protects the cabinet from swinging washing unit during operation
- Counter weights to balance the wash unit and position the centre of gravity
- Suspension System (dampers, springs), whose function is to absorb vibrations coming from spinning with unbalanced load
- Bellow, whose function is to seal door-tub-cabinet, to minimize the gap between the inner and outer drums for safety reason and also to avoid laundry to get stuck
- Exhaust pipe

The ‘Wash Unit’ module is mainly driven by Planned Development, that answers to the internal company’s need of changing some attributes according to an existing product plan, and Common unit, since the module’s components are common to different product variances. It follows that eventual technical improvements and development are planned internally, so that the required changes in the product can be planned in advance and scheduled for the time of recollection. Since both the inner and outer drums are made of stainless steel, they are much more resistant, durable, and reliable compared to the same drums made of different materials, such as plastic or enamelling iron with porcelain coating. Therefore they can be reused for different lifecycles of the washer, even until the moment of eventual disposal of the product, when remanufacturing is no longer possible and recycling is the last resort.

In fact, the stainless steel drum, given its resistance to stain or rust, owing to the high chromium content, and higher durability compared to the rival tubs (in steel with a porcelain enamel finish or in heavy-duty polymer plastic\(^{34}\)), will not need to be replaced with a new one; therefore, it represents a module destined to reuse, after inspection and proper cleaning. Stainless steel drums’ main advantages are easy cleaning, durability, economy, sanitary design, and good corrosion resistance\(^{35}\). It can be deduced that, in this specific case, remanufacturing mainly needs washing, and cleaning and the disassembling operations are considerably easy.

The ‘Aquastop tray’ module consists of connected components, such as the tray itself, aquastop switch with floater (optional), and leakage guide. Its function is to detect eventual water leakages inside the machine and collect the water in the tray. If necessary, it guides the internally leaked water to the inlet hose and valve connection in order to expel it.

It is a Carryover and Technical Specifications module, since it is influenced by the dimensional requirements of the machine’s detergent dispenser. Moreover, since the material of the tray is plastic, it might be reused with high chances for more than one lifecycle, meaning that, once collected, it might solely need cleaning and superficial treatments for removal of soap and calcareous sediments.

### 3.2.7 Future Improvements in Washing Machine Technology

Barthel and Götz (2013) sum up efficiently the technological improvements that have and/or could be adopted in a washing machine in order to reduce water and energy consumption while washing clothes. Some features are presented as follows:

Existing load, water and temperature sensors should represent the base for electronic advancements that allow for a fuzzy logic, so that the machine is able to choose the optimum parameters for the washing programme, behaving similarly to a human being. According to the load and textile of the clothes being washed, the machine should be able to decide on the amount of water, temperature, and detergent to be used.

The relatively new Steam technology might improve the regular washing performance and provide an additional sanitizing effect, while reducing energy consumption by 21% and water consumption by 35%, in comparison with a class ‘A’ washing machine.

The discussed design options are basically short-term solutions leading to significant energy savings. A long-term solution regards the use of polymer pellets, which is considered the real innovation in the laundry industry, after the less incisive ultrasonic washer or the detergents that are biodegradable and vegetable-based rather than petroleum-based. The polymer-based washing machine has been developed by Xeros and

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they show the amount of water that could have been saved if the U.S. laundry industry had switched to polymer beads cleaning in 2013\textsuperscript{36}. Indeed, a great amount of water is replaced with millions of polymer beads, which can be reused up to 500 times, after a periodical regeneration and only about a cup of water is needed in each washing cycle (Barthel and Götz, 2013). It follows that the water reduction is of 75%, alongside with reductions in energy, drying time and chemical detergents\textsuperscript{23}.

According to the developers, current washing machines’ design cannot be adapted in the attempt of introducing polymer pellets in a regular water-based washer, yet a completely new design might be needed (Barthel and Götz, 2013). However, the possibility of adjusting a modularly designed washing machine to the one that incorporates the function of polymer beads cleaning might represent a potential future research. It might be interesting for the time being, at least until society is willing to adopt a radical change in the washing habits, therefore a regular washer that offers the option of a different type of cleaning would perfectly meet several requirements.

4. Results

In order to assess the reuse potential of the washing machine’s modules and the applicability of modularity as empowerment for ResCoM, some modularity drivers must be identified.

Firstly, the market segmentation needs to be clear because the requirements for the washer might vary according to the types of customers that use it. Therefore different customer values are taken into consideration. Secondly, a business model that would allow for the success of this system must be presented, alongside several assumptions, one of those being the OEM’s full responsibility of the product.

4.1 Market Segmentation

In the attempt of highlighting the product areas in which remanufacturing is the activity to perform, two very different product categories have been chosen. From the scoring matrix (see table 3) in which two B2C products, namely a mobile phone and a washing machine, are compared, the possibility of reusing some components is evaluated. By making a simplistic evaluation based on common sense, consumers’ questionnaire, and on Modular Management expertise, it is deduced that remanufacturing seems to be profitable and environmental friendly for some products, yet not all.

From a first analysis it appears that the cell-phone is more suitable for recovery since it is subjected to faster technological changes, with new functionalities and applications proposed and implemented. However, the styling changes are not so visible from one cell-phone generation to the next, considering that, most of the times, two generations might come in succession at a high speed rate, sometimes in the same year.

It follows that, although the functions might differ significantly in different, but close in time, generations, the changes regard mostly solely the software, where the hardware is, on the whole, very similar, or eventually the same.

A different interpretation can be given for the B2C washing machine that is already a mature product, designed to be satisfactorily functioning for a great amount of time, which spans from five to fifteen years on average. From simple questionnaires submitted to washing machine’s users, it is highlighted that styling and

\textsuperscript{36} http://www.xeroscleaning.com
additional washing features are not considered of high importance, as long as the washer is functioning when needed. What consumers are looking for in a washer is that different types of clothes are cleaned properly and kept in good quality, and that the machine is not disturbing when running, is easy to use and to maintain.

Moreover, very different customer segments desire a machine that has a long lifetime, and the reason for it might be searched in the fact that a common washer is usually big in size, heavy and bulky and customers are not willing to exchange it unless it breaks down. It is deduced that its EoU is equal to its EoL, so that the machine is discarded only when it is not functioning anymore and not because consumers are interested in implementing any kind of upgrading in either the hardware or the software, especially considering that the rate of innovation is considerably low and new technologies evolve at a slow pace. In addition to these considerations, it has been found that the stoppage or failure in a household washing machine does not represent criticality if it lasts for a few days. In sum, the performance of the washer matters only to specific customer segments, not to all.

<table>
<thead>
<tr>
<th></th>
<th>Cell-phone (B2C)</th>
<th>Washing Machine (B2C)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EoL</strong></td>
<td>Longer</td>
<td>=</td>
</tr>
<tr>
<td><strong>EoU</strong></td>
<td>Shorter</td>
<td>=</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td><strong>Size</strong></td>
<td>Small</td>
<td>Big</td>
</tr>
<tr>
<td><strong>Rate of Innovation</strong></td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

Table 3 Scoring Matrix

It is consequently deduced that the cell-phone would be more prone to exploit remanufacturing since a considerably higher percentage of material can be saved and consumers give importance to trends and fashions related to mobile phones and are more willing to spend more money on a new phone’s generation rather than on a household washing machine.

Therefore, the B2C market for washing machines has been discarded as a matter of further investigation in the present Master Thesis. The analysed scenario pushes towards the investigation of B2B markets. The markets considered are the following:

- Low-low end (LLE): the washer’s expected lifetime for this market segment is about three years;
- Low end (LE): the washer’s expected lifetime is about five years;
- Medium end (ME): the washer’s expected lifetime is at least ten years;
- High end (HE): the washer’s expected lifetime is at least twenty years.

The markets considered worth investigating are the Medium End and the High End for B2B (see table 4). The main reason of this choice lies in the fact that the B2B Medium- and high-end categories seek a different kind of washers. In details, they look for a machine that could last many years, spanning from ten to twenty, and that is always perfectly functioning. In addition, they do not usually give any importance to aesthetic washer’s features.
Examples of consumers in these two categories are small medium enterprise and Industry. In the “SME” segment, different customer categories seek a similar product and, according to the market analysis of washing machines, these translate into high capacity, long life span, ease of maintenance, and care for textiles. The machine’s EoU usually coincides with its EoL.

The segments considered in SME category are identified as follows:

- Day Care
- Sport Clubs
- Restaurants
- Hotels
- Shared Laundry Rooms and Public Laundromats
- Small/Medium Companies (approximately 25 employees)

The customers identified in “Industry” segment are identified in:

- Hospitals
- Laundromats
- Big manufacturing firms (high number of employees)

The main “Industry” segments’ requirements that need to be fulfilled are high uptime, targeted serviceability, continuous maintenance, and minimized stoppage events. These customers are willing to make an investment and agree on specific service solutions when buying or leasing/renting their washing machine because they need that the device is functioning as desired and when needed. In certain cases, it might be needed that the machine runs for 24/7, performing a high number of washes per day.

Moreover, in industry, operators that generally use the device are only users, yet not owners, and it might happen that unskilled operators are the cause of failure in the system. Based on these assumptions and considerations, the EoU of the washer might be shorter than its EoL as well and it might correspond to the time in which the device is not running at its initial capabilities and customers might decide to exchange the machine for a new or remanufactured and more performing one. In the case in which they opt for a remanufactured machine, most probably only the motor, transmission system, plumbing, hoses and software will be changed because they are responsible for the machine’s functional life. On the contrary, the bulky parts are candidates for a longer lifespan since they determine their tangible life, therefore they can be left in place and disqualified for recollection.

In the case in which the reason for the exchange is the need of a more performing motor, the motor previously used might be still respecting the functional engineering standards for what is needed in a different variant of the same products’ family. Assuming that the design is modular and all the variants of the same product family share the same platform, it would be extremely easy to exchange the motor, or other components, from one machine to another.
These considerations are due to the fact that the components that have a high pace of innovation define the life of the washer. Whatever the reason for exchanging modules is, these segments have high requirements on the washing devices and the OEM is called for their satisfaction.

However, a comparison evaluation between washing machines with different designs has been performed and submitted to Modular Management consultants. The results of the survey are shown in figure 19. The current washing machine, with today’s design, has been considered as the reference, to which a modular and an integrated one have been compared. The modular and the integrated designs are conceived in the resource conservation vision; therefore possibilities of recovery are taken into account.

As it is possible to see from the graph (see fig. 19), several parameters have been taken into account and the results can be clearly understood from the comparison.

Factors worth mentioning regard the benefits of a modular design for repair time, repair cost, failure rate, and disassembly time. These are in fact lower compared to the reference and to the integrated design. These advantages are due to the fact that frequently serviced technical solutions are identified and located in modules that are easy to detach.

Speed and energy efficiency are, on the whole, the same because they depend more on the technical performance of specific components rather than on the design.

Product lifetime is the highest for the modular alternative, given that the interface will stay the same over the different products’ generations.

The price is similar for the two alternatives since the possibility of having a product with remanufactured parts in it is taken into consideration.

The cost of first production, including the increment in material cost (dm) and the increment in labour cost (dL), is generally similar for the three options. The exception is for a reduced labour cost in the modular
caused because modularity favours not only the product architecture, but also the operations in the production line. Precisely, the flow optimization possibility is enabled by standardized interfaces. This obviously leads to a reduced production and assembly times that reflect in lower working hours; therefore the labour cost is lower.

Concerning, on the other hand, the cost of remanufacturing, the cost of material for both the modular and integrated alternatives is lower because apparently some parts are reused and fewer raw materials are utilized. The cost of labour in this case is not much lower since remanufacturing usually entails manual processes, on the contrary of the automated ones in the forward supply chain. Therefore, the labour cost is likely to be higher in reality. The logistics costs when remanufacturing are almost twice as higher as the current ones. This is owing to the implementation of a proper reverse logistics network that would allow for the return of the products from the customers back to the OEM.

To conclude, waste at the EoL is considered lower for the modular product because the arrangement of technical solutions in different modules favours their separation not only during their lifecycle, but also when some parts are destined to recycling, or, in the worst case scenario, to disposal. Scrapping needs can be definitely reduced in case the product is modular.

In sum, the modular design presents in theory a much more satisfactory design type when resource recirculation, in the perspective of multiple lifecycles, is to be assured. The analysis that has been performed in section 3.2.6 shows an example of reusing and/or remanufacturing modules, which requires effort and environmental consciousness by both manufacturers and consumers. According to the extensive research done, modularity can extend the lifetime of the products considerably and it reflects into an extension of their lifecycles.

4.2 Assumptions for the OEM and Considerations on Business Models

The chosen customer segments are asked to be part of the supply chain in the sense that they have the option to decide what kind of linkage they aim to have with the OEM, which, on the other hand, is required to have full responsibility of the products. Customers’ involvement in this supply chain is seen in the loyal agreement, in terms of type and time frame they choose to establish with the OEM. In this case, different business models are proposed as a mere example of model that the customer can choose from at the time of purchasing either the product or its service. Therefore, after evaluating the product of the case study, business models at a company’s level have not been taken into account. The range of business models, which have been described in section 2.7, has been considered as a range of offers from the manufacturer to its customers; therefore it is the customers to choose the solution they prefer.

After analysing the various business possibilities, it is clear that some models are successful for some OEMs and not for others. As already highlighted in section 2.7, some models, such as leasing, are useful in controlling the life stages of the product and its EoL activities, and others, e.g. PSS, are suitable to ensure the OEM’s full responsibility. However, the success of the business models depends on the logical combination of factors, such as the right product’s design, the most cost efficient reverse supply chain design, the customer segments, and the ICT to trace and control the linkage between manufacturers and customers.

The business models that entail the ownership of either the customers or third parties have been disqualified because they do not support the basic requirements of ResCoM. In fact, industrial examples that have managed to close the loop successfully have common elements and one of these is the full control of the OEM over the product being sold. This control embraces several different business functions related to
the product, from its development and manufacturing technologies, typical of the forward supply chain, to
the responsibility of taking back the product and recovering its tangible and intangible values.

Hence, since the EOM’s ownership of the product is one of the essential prerequisites, only the modern
business models that imply the OEM’s ownership and responsibility for the product during its all life need to
be considered as candidates to allow the OEM to close the manufacturing system loop.

After a thorough analysis of the washing machine-based case study, it is concluded that the most
successful business model, chosen by the B2B customer as an option offered at the moment of the
purchase/beginning of the agreement with the OEM, would be PSS, with a particular focus on ‘Product
Lease’, or FP. Indeed, these models would most likely accommodate the two different B2B customer
segments considered and would allow for a careful control over the product and its performance. It means
that since the OEM (in FP) and the product-service provider (in Product Lease) have the full and constant
responsibility of the product, which is sold as a service, it would actually be easier to report eventual failure,
faulty or critical modules.

To respect the initial assumptions regarding the OEM being fully responsible of the product that is sold,
it is proposed to assume that the provider of the service even in the leasing service system is the
manufacturer. It means that the manufacturer, not a third provider, is in charge of the leasing strategy.
Consequently, the product’s return to the OEM after the leasing period is assured and it is avoided that it
becomes the provider’s responsibility.

The OEM, while keeping track of the failure rate, would be able to act reactively to solve the problem
and proactively, by making estimates. The result is that the design of the module that shows criticality will
be modified to accommodate the new requirements and technical specifications.

The presented solutions would allow both the customers and the manufacturers to gain from it.
On one hand, the customers will gain because they will:
• have no responsibility of the product;
• will always be assured full functionality and quality;
• will not pay for the product, yet for the service.

On the other side, the OEM will have financial benefits
• due to instant information about the product, enhanced by the full control over it;
• due to the use of a modular design that minimizes the material losses during the lifetime, in case of fault
or repair required, or at the EoL. In fact, modules to be exchanged can be detached independently, so
that the item does not have to be disassembled wholly, incurring in the risk of destroying some parts (as
it would most likely happen with an integrated design)
• due to the salvage of material even in case of initial failure. In fact, sometimes a very high percentage of
material cost can be saved because modularity facilitates the reuse of good modules and the replacement
of the faulty ones.
• due to an increased customers’ loyalty and better public image enhanced by good and prompt service.

More in details, the business models that the author thinks would be more appropriate for the SME
customer segment are:
1. PSS - Use-oriented: in particular ‘Leasing’ model with the OEM’s ownership is suggested for hotels,
whereas ‘Renting’ is considered to be satisfactory for shared laundry rooms.
2. PSS – Result-oriented: in particular ‘Pay per service unit’, such as “Pay-per-wash” formula for public Laundromats. These customers would be more prone to agree on a type of contract that provides services, such as maintenance, repair, and assistance at different levels, including advice on use, and that implies a fixed monthly fee on an agreed performance and type of use (individual, consequential, unlimited).

On the other hand, the business model considered appropriate for the “Industry” segments is the FP model since it would satisfy the higher performance requirements and different usage demands. In this case, Industry would be willing to pay for the result with predefined characteristics that the OEM is responsible to provide for.

4.3 Limitations of the current modular methodologies

The product life cycle goals that the present thesis project has wished to cover are related to re-activities (reuse, remanufacture, recycle) enhanced by modular design architecture. However, if, on one hand, MFD method considers recycling as a module driver, on the other hand, it does not take remanufacturing into account yet.

The possibility of physical reuse is not considered either, yet the module driver “Carryover” entails the transition of a product design from one generation to the next. Although it concerns a non-physical aspect, such as the life of the product platform, it might be seen as a chance of reusing something that has been previously employed in the methodology. This possibility exists for the premature obsolescence issues as well that the majority of consumable products, such as electronic and electric devices, encounter.

The current MFD method aims at including the product strategies, represented by the known Module Drivers, into the process of determining the product architecture (Börjesson, 2014), yet it does not consider any module drivers related to reuse possibility at the product or module’s EoL.

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The theory of module drivers is a brief representation of twelve specific strategic reasons in order for the company to determine standard interfaces so that the company-specific strategy can be succeeded (Börjesson, 2014). According to the impelling need for companies of adjusting their specific strategies to the environmental legislations, they will need to have new, or revised, module drivers, since being environmental friendly will actually represent a strategic aptitude, therefore the need to intervene on the theory of module drivers. Moreover, by adjusting the design approach to fulfil the environmental requirements, the manufacturing industry has a high potential of achieving economic benefits, as also pointed out by Circular Economy thinking and shown by the industrial examples of firms that are successful in closing the manufacturing system loop.

Some items get out of fashion much earlier than the end of their useful technical and physical life and often it is a customer demand for new original models of the product that make the existing ones become cores to be collected ahead of time. Effort and time spent in R&D and consequent market of a new model are significant; therefore one possible solution to shorten and favour these procedures would be to reuse both design and manufacturing processes already built into place for the previous models of the same product. It is, in a notable way, an advantage greatly accommodated by modular architectures, which exploits the standardization of common modules and defined interfaces, and allow in parallel for production efficiency and quality and reduction of total assembly time and cost (Gu and Sosale, 1999).

It might, indeed, be the case of two different mobile phone’s generations that, owing to the high rate of innovation for the software, might come in succession even during the same year. However, the aesthetics
and the dimensions of some components are sometimes kept unchanged. Therefore, these parts might represent a “Carryover” since their design is left unchanged moving from one generation to the next. In the same way, the physical parts might be reused after proper refurbishment, especially considering that they might not be excessively worn out since they might have been used for a few-months-time.

4.4 Need for Modular Approach Re-thinking

The main reason behind the interest of integrating modularity into the production line of washing machines can be explained as a firm’s effort of increasing responsiveness when there is a need of expanding product variance and a desire of maintaining the complexity low in the meantime (Börjesson, 2014). It follows that if a manufacturer of washing machines does agree on using modular design for producing appliances that are able to last several lifecycles, it is necessary for modularity to be subjected to re-thinking. The re-thinking should regard the analysis of module drivers that enable the EoL strategies. However, it has been detected a lack and/or misuse of module drivers that might help achieve this objective. Hence, another goal of the present Master Thesis is to suggest new module drivers that might be used, when implementing MFD, as a reference that drives the design for reuse.

The typical parameters considered when deciding on the size and structure of the modules are the “similarity between the physical and functional architecture of the design”, minimized interaction between physical components (Ericsson and Erixon, 1999), cost, ease of manufacturing, ease of maintenance, and so forth (Kimura et al., 2001). However, when considering modularity as a primary solution for post-life issues and as a factor empowering reuse potential, other module parameters should be considered.

As suggested by Kimura et al. (2001), these are technological stability, functional upgradability, life span, quality level guaranteed, ease of cleaning, disassembly, repair, and so forth. This new requirements’ definition involves a novel mindset that might even imply a different modular approach from the conventional one.

It would probably be too expensive to implement such a novel modular structure, which would support resource conservation through reuse, with traditional modularization parameters that do not consider any reuse possibilities. As also Kimura et al. (2001) suggest, it should represent an opportunity for a new standpoint as well since designers are often used to thinking within the traditional design constraints.

Therefore, the current modular approach is challenged to a re-thinking in order to accommodate the new global requirements on the environment and, in the same time, increase the economic profitability of being environmental conscious.

4.5 Proposal of New Module Drivers

After having done an analysis regarding the approach used in MFD and getting to the conclusion that it would need a re-thinking in order to adjust to the new EoL requirements, it follows a proposal of new module drivers. In MFD, a module driver called “Recycling” does exist already and it provides the possibility of having material purity in a forward-looking effort of differentiating polluting materials into a separate module in order to allow the recycler to perform an easier separation.
Likewise, a module driver called “Upgrading” answers to the need of simplifying adaptation to future customer requirements with the convenience of rendering that module easy to exchange (Modular Management Expertise 37).

Although these two module drivers, Recycling and Upgrading, support respectively the re-use potential of materials and re-use of interfaces, and “Carry Over” supports the design re-use, it is observed that these do not seem sufficient in satisfying the requirement of prolonging the lifespan of the products in the effort of making the resources recirculate and creating products that could be used for more than one single lifecycle.

It follows that new module drivers should be suggested in order for the current modular approach to adapt satisfactorily to the global requirements on the environment and to succeed the process in a cost efficient way.

The author’s suggestions consist of:
1. Renaming the driver “Upgrading” with “Re-purposing”. The reason behind this proposal lies in the original and common meaning of the word upgrading. Indeed it means rising to a higher level or standard. It regards e.g. the replacement of software for getting a more recently released version and/or the replacement of hardware with one with better performance. Hence, upgrading simplifies the adjustment to future technical changes. On the contrary, “Upgrading” driver in MFD is described as a possibility offered to the customers of changing the product in the future, in the sense that the product could be used for another purpose and other functional modules could be added to it, so that the purpose is changed and the performance might be improved. This definition is more similar to what is meant for “Re-purposing”, which has been presented and explained in section 2.9.1.

   Examples of products that can be re-purposed are a modular power tool38 with several exchangeable tools; a food processor39 with the function of a stand mixer, grinding mill, blender, and so forth; a reconfigurable transportation vehicle; a four-machine in one, such as the Troy-Bilt’s flex40 that can be, among different functions, a lawnmower and a snow-blower.

2. A new module driver called “Reuse” will include upgrading. It is named “Reuse/Upgrading” because upgrading is considered to be supportive for reuse possibility of physical components. Upgrade can be regarded as reuse for modules whose technology evolves slowly and slightly. It is possible to add value to the product by changing only one component, namely the one to upgrade and leaving the rest of the module as it is, thus reusing it. It is usually the case of B2B where obsolete components are replaced with more powerful and functional ones, in order to maximize remanufacturing.

3. A new module driver suggested by the author is “Remanufacturing” that would answer to the issue: ‘Are there reasons for which a specific set of technical solutions should be grouped together to favour future restoring of cores?’ This specification should be used as a guide in the design phase so that the different design strategies are integrated to reach the same goal. A core, in order to be remanufactured, must be subjected to diverse actions, such as inspection, disassembly, replacement of some subassemblies, refurbishment, cleaning of all the parts, reassembly, and final testing before remarketing.

37 http://modularmanagement.com
38 http://www.blackanddecker.com/products/power-tools
40 http://www.troybilt.com/equipment/troybilt/flex
It is now suggested that the existing module driver called “Separate Testing” would be part of “Remanufacturing” because, in MFD, Separate Testing is defined as the possibility of testing each module before delivery to final assembly. This may lead to quality improvements and it is mainly due to reduced feedback time. On the other hand, complaints and quality loss statistics should be a concern. Since a remanufacturing prerequisite is testing and the OEM is now responsible for the product, quality can be assured with higher degree. In fact, by taking back the products, the OEM has higher chances of getting feedback on the performance, be aware of failure rates and learn from them. So the design can be adjusted to new specifications and the quality can be improved starting from the design, thus reducing the need of intensive quality controls in all the other stages.

4. The last module driver that is suggested by the author regards the possibility of planning the lifetime of the modules. The new module would be called “Module Lifecycle/Planned Development”. It would answer to the question ‘Would be there a reason to plan the lifecycle of each module right from the design stage?’ An analysis based on the MFD methodology used nowadays shows that modular platforms are not developed for products with multiple lifecycles. The only lifetime that is planned from the start of the modularization process is the one of the platform; therefore, its duration is decided according to customers’ needs and module drivers’ definition. Hence, if consultants usually agree on the duration of the modular platform lifecycle, they do not agree on the one of the products or modules. Reuse possibility is considered to be highly dependent on carry over and technology push since if, on one hand, the design is the same from one generation to the next, the module has higher chances to be reused, and, on the other hand, if the module’s technology evolves slowly, this increases the reuse potential.

Technology evolution sets the pace for technology stability, therefore the beginning of a new technological era or shift may determine the end of use of a module, namely the end of its first lifecycle. Technology push can be considered as the external driver of the internal planned development. Planned development is a company’s internal strategic tool that defines when to develop and change some parts in the product and launch new models to satisfy new customers' requirements. These new requirements are usually dictated by the technological evolution. So a foreseen technology shift may allow for estimates on the planned development for the same product’s category. It follows that the lifecycle of the module, alongside the one for the platform, could actually be planned.

5. Summary and Discussion

The modules presented in the Washing machine ‘Cylinda’ case study represent solely a proposal of one arrangement of components within a module, namely an example of modularization to achieve multiple lifecycles products right from the design stage. Although the case study narrows its focus on a specific type of products within the industry of electrical appliances, the statements, which are the results of both literature research and industrial case studies’ evaluation, about the implementation of modular design as an opportunity to close the manufacturing loop are general and might eventually be applicable to different types of industry.

Due to the lack of empirical data concerning the lifetime, price, technical stability, and failure rate of each component, some assumptions on the matters have been done. The assumptions are based on common
knowledge regarding the washing machine’s parts and knowledge concerning mechanical parts gained during university studies.

The investigation undertaken in the current thesis project leads to a re-thinking of traditional remanufacturing that usually consists of the process dealing with products that are discarded and no longer functional. Basically products at their EoL are subjected to traditional remanufacturing with the aim of restoring their functional conditions to as-new conditions. The way remanufacturing is conceived in the current thesis project is far from the conventional understanding. Indeed, remanufacturing is part of a broader scenario that does encompass the whole supply chain’s parties and the ad hoc business model. Its main role is not when the product is discarded, yet during its usage phase, so that it is limited to reconditioning of the features with the additional processes of renovating and upgrading, in order to provide the product with a longer lifetime.

This approach would allow, firstly, for the consideration of remanufactured products in the same way of new ones, and secondly for the use of remanufactured parts into new items and vice versa, with no distinction at all from the consumers’ viewpoint. However, in reality, this discussion would require an extensive practical study of the business model that would potentially enhance what it is advised by the current literature, and a focused evaluation of the supply chain to try to balance the usually unmatched supply-demand, typical of the forward supply chains, when a reverse logistics is put into place and remanufacturing is accepted as a conventional practice.

The main purpose of the model presented in the above sections is to give an example of one of the possible applications of ResCoM philosophy and methodology to come. It can be concluded that the model presented is not conventional and it is most likely subjected to future modifications, yet, if followed properly, starting from the design stage, it might set the foundations for achieving products with multiple lifecycles.

With regards to the washing machine, the modules that would be most likely subjected to remanufacturing are those that show to be less sensitive to changes, both in appearance and technology, or even those that are tested to be reliable for highly longer time than the weakest, non-reusable module in the appliance. Therefore, the former modules should be reconsidered in the ‘manufacturing’ of a new device. It goes without saying that in order to make this kind of assessment at the design stage, it is important to give an estimate of the number of lifecycles that each specific module will most probably have.

To stress the point, modules that are considered candidates for future recovering should consist of components having similar lifecycle length. In this way, when designing the product for the first time, the manufacturers will already foresee how many times each module might be reused in the manufacture of a new product.

Technical solutions that are Carryover and less time and change-sensitive might be grouped together for the Remanufacturing driver. In order to facilitate and maximize remanufacturing, it would be necessary to upgrade and reuse at an individual level, thus but changing single components.

In conclusion, the choice of the most suitable business models depends on several factors that go beyond the mere investigation of the customer segments. Other parameters, such as the location of the selling markets, the location of the manufacturing and remanufacturing facilities, the acceptance of the new system from the society, starting from the buyers, must be considered.

Firstly, the effort of the OEM in setting the foundation so that this novel ResCoM would work lies in different steps:
1. Implementation of a reverse supply chain that is somewhat cost efficient;
2. Modularization of specific assortments of products that would reduce the complexity in both manufacturing and remanufacturing;
3. Reinforce the ICT system to get as much information as possible from each product’s lifecycle in order to increase traceability and know the conditions of the modules before the whole product is disassembled;
4. Embrace new manufacturing challenges that do not operate at the earth’s expense, e.g. the coexistence of remanufactured and new modules inside the same product.

Since the principal driver in an OEM business is economy and the ambition of making profits, manufacturers cannot afford to test business models till they find the most suitable for their enterprise. For this main reason, a simplistic scheme (see table 5) is proposed as a mere example for manufactures to follow when they need to endorse a model rather than other when manufacturing a specific type of products. In the table below, different scenarios are presented, in which the business model is considered in relations to modular design, cost efficiency of the reverse supply chain and ICT to keep track and ensure return of the products to the OEM through the connection between customers and original manufacturers.

The numbers in the table represent a suggestion of the indexes that the parameters being considered should have. The assigned indexes are the result of an internal discussion with Modular Management’s consultants. Each parameter can be gauged in a scale spanning from 1 to 5. These numbers are indicative and do not constitute a precise measure; hence for modularity in design and for ICT, the different levels in the scale can be interpreted as:

- 1= very low
- 2= low
- 3= medium
- 4= high
- 5= very high

Concerning the ‘Cost efficiency of the reverse supply chain’ parameter, the levels are to be interpreted as:

- 1= very low cost efficient, namely very expensive
- 2= expensive
- 3= average expensive
- 4= high cost efficient, namely cheap
- 5= very cheap
From surveys submitted at Modular Management, it is deduced that trying to measure modularity is not an easy task. Its level highly depends on different factors and can vary with different product categories. In some cases, to assess whether a product is more modular than another, the number of modules might help. In other cases, the number is a mere indication, yet it does not label the product as one with a structured modularization.

However, an assortment of products is well modularized when it is possible to guarantee interface stability over the subsequent generations of the same product and when a consistent number of modules are common among the different product variants. Indeed, a level of modularity of a product might be defined as the percentage given by component commonality, namely the number of common units over the total number of components.

If the level of solidity in interfaces and platform is achieved, modularity will accommodate properly and cost efficiently different upgrading needs, whatever the innovation and introduction rates are. Moreover, if the interfaces are kept the same over the years, the modular product will greatly enhance the reuse potential, with the possibility to exchange used and/or remanufactured modules among different variants of the same product family and among products with different lifecycle. Precisely, a module that has been used for a certain amount of years might be replaced with its technically and aesthetically upgraded version. The removed module might be remanufactured and consequently inserted in a product of new generation. However, this is only possible when the interfaces do not change over time.

Therefore, in table 5, the level of modularity needs to be high and very high in the three cases of business models considered. The main reason of this suggestion lies in the fact that a well modularized product enables faster and easier replacement of modules, which is an extremely important element for maintenance, serviceability, repair, and remanufacturing.

With regards to ‘Cost efficiency of reverse supply chain’, when Buyback business model is applied, the reverse flow might be costly. The reason of this is owing to the fact that a solid reverse network does not really exist. In fact, the return of the cores is highly dependent on the customer’s decision, since it is the customer to own the product and they might not be interested in selling back their items to the OEM.
Concerning the ICT, as already highlighted in figure 11, the linkage between customers and OEMs is higher when the latter’s responsibility and ownership for the product is higher.

In conclusion, table 5 presents a mere suggestion for the manufacturing industry when it is interested in implementing a precise business model. Based on the type of product that is manufactured and on the possibility of controlling the product, which is higher for B2B markets, a firm might take into consideration the benefits of modularity, deciding to which extent it should be done.

To conclude, after evaluating the different theoretical and industrial case studies of companies that have managed the close the supply chain loop and after performing the washing machine case study, a graph has been created. In figure 23, the different companies have been placed in a graph in which the level of recovery and the profitability achieved are taken into consideration.

Figure 20 Recovery level in relation to economic profitability
6. Conclusions and Future Research

In order to achieve a level of maturity in manufacturing that would permit to close the loop, it is necessary to evaluate remanufacturing possibilities in different contexts and for different product families. Indeed, the belief that a generalized solution would be both environmentally and economically profitable when different product systems are under analysis is idealistic.

Therefore, the future research on a related topic might consist of the analysis of individual cases in which cost evaluations can show the best environmental and economic opportunities for the specific cases.

In order to assess the total benefits of remanufacturing the washing machine, it is necessary to calculate the environmental impact of the reverse flow in the CLSC involved in the washing machine case. A specific case study should be undertaken, in which the calculations of economic and environmental scores are performed and a better understanding is achieved in relation to its reverse flow’s impact, alongside the ResCoM dynamics. Due to a lack of empirical data and due to an emphasis on the design that the washing machine should have to best exploit its reuse potential, economic and environmental analyses of the reverse logistics, involved in the process, have not been performed. It would be extremely important to understand whether or not products that have already reached a high market maturity and high exploitation of economies of scale, such as washing machines and other white goods, e.g. refrigerators and dryers, are still worth remanufacturing, when the impact of the reverse supply chain is taken into consideration.

Therefore this thesis project aims at giving suggestions to define a method that would assess economic and environmental profits of ResCoM when using a modular design and that could be replicated by following standardized procedures. Future research might be performed to define this new methodology.
References


**Web References**


Modular Management [http://modularmanagement.com](http://modularmanagement.com)


