A Methodology for Holistic Lifecycle Approach as Decision Support System for Closed-loop Lifecycle Management

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to Filiz, Eyyub & Fatma Zehra…
çekirdek aileme…

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Abstract

Sustainability of their products and practices provides companies with a competitive set of methods and tools to maintain, improve and expand customer and supplier relationships and to ensure access to strategic markets. Companies pay a lot of attention to produce more sustainable products and contribute to the overall sustainability. Most of the companies manage to use lighter materials or change the material with a recyclable one or try to decrease the energy used for manufacturing. However most of these attempts are related to only one part of the life cycle or one aspect of sustainability. In spite the fact that sustainability is thought to be related with the environmental aspects of the product, it is a broad concept and has economic and social dimensions. This makes the evaluation of sustainability a very complex matter. On top of that, to achieve a certain level of sustainability, it is necessary to take into account the whole life cycle of products (life cycle perspective) from material extraction and manufacturing to use and disposal when a decision has to be made about sustainability performance. Life cycle thinking or life cycle perspective takes into account the whole life cycle of the product. The main feature of life cycle thinking is to avoiding problem shifting. This helps not only to take into account all necessary aspects in evaluation of sustainability but also make a more accurate assessment. The proposed methodology, holistic life cycle approach, combines a number of life cycle evaluation methodologies; life cycle assessment (LCA), life cycle costing (LCC), and social life cycle assessment for (S-LCA), in order to evaluate the sustainability performance of the products.

Since the forementioned methods are data intensive procedures and constrained with the availability of data, it is necessary to have an information and knowledge management system for collection and aggregation of life cycle data and distribution of feedback information. Product lifecycle management system help to manage product related information through its life cycle. However, generally the capabilities of PLM systems are limited to the operations of one company or in some cases it might have been extended to their 1st degree partners. Additionally, the information flow of the product is often restricted to the beginning of life (BOL) phase. Closed-Loop Lifecycle Management is a more recent concept which goes beyond the limits of traditional PLM systems and is targeting seamless information flow across all phases of the life cycle. Closed-loop PLM systems use product embedded identification devices (PEIDs) and enables to gather and distribute life cycle information through the life cycle of a product more precisely. This information is prerequisite for evaluation of the products sustainability performance. Closed-loop PLM systems are capable of gathering life cycle data and processing it in order to make informed decisions towards sustainability. Closed-loop Lifecycle Management contains four main components, PEIDs' for collecting data, middle-ware to combine different applications and collect and distribute life cycle data, a decision support system (DSS) to transform the collected data into usable information and a product knowledge and management sys-tem (PDKM) to manage the information and knowledge generated through the life cycle of the product. In automotive industry PLM systems are used to manage the life cycle data but these systems are somehow separate from each other. It is needed to develop a middleware to combine the separate PLM systems, a DSS to transform gathered data into necessary information and knowledge for specific applications and a PDKM to manage the information and knowledge. Holistic life cycle approach takes into account the whole life cycle of the product and generates performance characteristics, which might be configured in order to evaluate the sustainability performance of the product. A Closed-Loop Lifecycle Management system containing a DSS configured with the holistic life cycle approach will be an efficient tool to evaluate and improve the sustainability performance of products.

The proposed methodology benefits from the comprehensiveness of the life cycle thinking and integrates the tools for evaluation of all aspects of sustainability. It has been applied to three test cases and validated. The first two test cases belong to EC FP7 SuPLight project, where the effect of using recycled material on high-end automotive and aeronautics components made of wrought aluminum alloys was investigated. Through the life cycle of the automotive components, the BOL phase is prevailing in which using recycled material reduces the environmental impact of the components drastically. On the other hand, MOL phase is the dominant phase for aeronautics components. Reducing the weight of the component could be more effective than using recycled material. The third test case belongs to Eco-Innovera SuWAS project, in which recycling and incineration of waste ink from flexographic printing are compared. The environmental impact of both scenarios are comparable where recycling offers economic benefits and job creation through innovation. Finally, the results of this work have been published in conferences and journal papers.

Keywords

Holistic lifecycle approach, life cycle thinking, sustainability assessment, closed-loop lifecycle management, decision support system, life cycle assessment, life cycle costing, social life cycle assessment.

Résumé

La durabilité de leurs produits et pratiques offre aux entreprises un ensemble compétitif de méthodes et d'outils pour maintenir, améliorer et d'élargir les relations avec les clients et les fournisseurs et à assurer l'accès aux marchés stratégiques. Les entreprises paient beaucoup d'attention pour produire des produits plus durables et contribuer à la durabilité globale. Beaucoup d'entreprises parviennent à utiliser des matériaux plus légers ou changer le matériau avec un qui soit recyclable ou tenter de diminuer l'énergie utilisée pour la fabrication. Cependant, la plupart de ces tentatives sont liées à une seule partie du cycle de vie ou un aspect de la durabilité. Malgré le fait que le développement durable est considéré comme lié avec les aspects environnementaux du produit, il est un concept plus large et a des dimensions économiques et sociales. Cela rend l'évaluation de la durabilité très complexe. En plus de cela, pour atteindre un certain niveau de durabilité, il est nécessaire de prendre en compte l'ensemble du cycle de vie des produits (perspective du cycle de vie) de l'extraction des matériaux et la fabrication à l'utilisation et la fin de vie lorsque une décision doit être prise concernant la performance en matière de durabilité. La notion de cycle de vie ou la perspective du cycle de vie prend en compte l'ensemble du cycle de vie du produit. La principale caractéristique de la notion de cycle de vie est d'éviter le déplacement du problème. Cela permet non seulement de prendre en compte tous les aspects nécessaires à l'évaluation de la durabilité, mais aussi de faire une évaluation plus précise. La méthodologie proposée, holistic life cycle approach, combine un certain nombre de méthodes d'évaluation du cycle de vie; l'évaluation du cycle de vie (ACV), calcul du coût de cycle de vie (CCV), et de l'analyse sociale du cycle de vie (ESCV), afin d'évaluer la performance de la durabilité des produits.

Depuis les méthodes forementioned sont données procédures intensifs et contraint à la disponibilité des données, il est nécessaire d'avoir un système de gestion de l'information et de la connaissance pour la collecte et l'agrégation de données de cycle de vie et de la distribution d'informations en retour. Le système de gestion du cycle de vie du produit aide à gérer les informations liées au produit à travers son cycle de vie. Cependant, en général les capacités des systèmes PLM sont limitées aux opérations d'une entreprise ou, dans certains cas, cela peut être étendu à leurs partenaires de 1er degré. En outre, le flux d'information du produit est souvent limité à la phase BOL. La gestion du cycle de vie à boucle fermée est un concept plus récent qui va au-delà des limites des systèmes PLM traditionnels et vise les flux d'informations continus à travers toutes les phases du cycle de vie. Les systèmes PLM en boucle fermée utilisent des PEIDs et permet de recueillir et distribuer les informations du cycle de vie à travers le cycle de vie d'un produit plus précisément. Cette information est une condition préalable pour l'évaluation de la performance des produits de la durabilité. Les systèmes PLM en boucle fermée sont capables de recueillir des données de cycle de vie et les traiter en vue de prendre des décisions éclairées envers la durabilité. La gestion du cycle de vie en boucle fermée contient quatre composants principaux, les PEIDs pour la collecte de données, l'inter logiciel pour combiner différentes applications et recueillir et distribuer les données de cycle de vie, un système d'aide à la décision (DSS) pour transformer les données recueillies en informations exploitables et un système de gestion de données et de connaissances de produit (PDKM) pour gérer l'information et les connaissances générées à travers le cycle de vie du produit. Dans l'industrie automobile, les systèmes PLM sont utilisés pour gérer les données de cycle de vie, mais ces systèmes sont en quelque sorte séparés les uns des autres. Il est nécessaire de développer un inter logiciel pour combiner les systèmes PLM séparées, un DSS pour transformer les données recueillies en informations et connaissances nécessaires pour des applications spécifiques et un PDKM pour gérer l'information et la connaissance. Une approche holistique du cycle de vie prend en compte l'ensemble du cycle de vie du produit et génère des caractéristiques de performance, ce qui peut être configuré afin d'évaluer la performance de la durabilité du produit. Un système de gestion du cycle de vie en boucle fermée contenant un DSS configuré avec l'approche holistique du cycle de vie sera un outil efficace pour évaluer et améliorer la performance de la durabilité des produits.

La méthodologie proposée bénéficie de l'exhaustivité de la pensée cycle de vie et intègre les outils d'évaluation de tous les aspects de la durabilité. Elle a été appliquée à trois cas d'étude et validée. Les deux premiers cas d'étude appartiennent au projet SuPLight, où l'effet de l'utilisation de matériaux recyclés sur les composants automobiles et aéronautiques en alliages d'aluminium forgé a été étudié. À travers le cycle de vie des composants automobiles, la phase BOL prévaut et dans laquelle l'utilisation de matériaux recyclés réduit l'impact environnemental des composants de façon drastique. D'autre part, la phase MOL est la phase dominante pour sur les composants aéronautiques. La réduction du poids du composant pourrait être plus efficace que l'utilisation de matériaux recyclés. Le troisième cas d'étude appartient au projet Eco-Innovera SuWAS, dans lequel le recyclage et l'incinération des déchets d'encre d'impression flexographique sont comparés. L'impact environnemental des deux scénarios sont comparables où le recyclage offre des avantages économiques et permet la création d'emplois grâce à l'innovation. Enfin, les résultats du travail de la thèse ont été publiés dans des actes de conférences et des revues scientifiques.

Mots-clés

L'approche holistique du cycle de vie, perspective du cycle de vie, l'évaluation de la durabilité, La gestion du cycle de vie à boucle fermée, l'évaluation du cycle de vie, calcul du coût de cycle de vie, l'analyse sociale du cycle de vie.

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Abbreviations

LCA	Life cycle assessment
LCC	Life cycle costing
S-LCA	Social life cycle assessment
LCSA	Life cycle sustainability assessment
EC	European commission
FP7	7th Framework programme
BOL	Beginning of life
MOL	Middle of life
EOL	End of life
PLM	Product lifecycle management
PEID	Product embedded information device
RFID	Radio frequency identification
DSS	Decision support system
PDKM	Product data and knowledge management
TBL	Triple bottom line
WeEE	Waste electrical and electronic equipment
RHSS	Registered Hazardous Substances Specialist
DfX	Design for X
DfE	Design for environment
NGO	Non-governmental organization
CL2M	Closed-loop lifecycle management
UNEP	United Nations environment programme
SETAC	Society of environmental toxicology and chemistry
CAD	Computer aided drawing
CAM	Computer aided manufacturing
CAE	Computer aided engineering
CIC	Corporate intellectual capital
LCM	Life cycle management
PDM	Product data management
BOM	Bill of materials
FEA	Finite element analysis
ERP	Enterprise resource planning
SCM	Supply chain management
CRM	Customer relationship management
PDA	Product digital assistant

EIA	Environmental impact assessment
SEA	Strategic environmental assessment
SA	Sustainability assessment
EMS	Environmental management system
CSR	Corporate social responsibility
RA	Risk assessment
SFA	Substance flow analysis
MFA	Material flow analysis
CBA	Cost benefit analysis
EF	Ecological footprinting
CF	Carbon footprinting
HIA	Health impact assessment
IIA	Integrated impact assessment
IA	Impact assessment
AA	Appropriate assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
FLCA	Front lower control arm
DC	Direct-chill casting
BDH	Baggage door hinge

Chapter 1 Introduction

Several definitions of sustainability have been proposed, over time. The World Commission on Environment and Development declaration reads: “sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are made consistent with the future as well as present needs” [1].

There is now a well-recognized need for achieving overall sustainability in industrial activities, arising due to several established and emerging causes: diminishing non-renewable resources, stricter regulations related to environment and occupational safety/health, increasing consumer preference for environmentally-friendly products, etc. In particular, the manufacturing sector, which lies at the core of industrial economies, must be made sustainable in order to preserve the high standard of living achieved by industrialized societies and to enable developing societies to achieve the same standard of living sustainably [2].

Over the years, this definition of sustainable development has earned some criticism for not being specific enough. Therefore, great many scientists, researchers, and organizations have proposed new definitions to concretize the notion sustainable development. The perhaps most widespread definition used today has emerged from the book "Cannibals with forks", in which John Elkington first describes the triple bottom line (TBL) concept. The triple bottom line concept basically describes sustainable development in a business context. In this context, companies should change their performance towards the economic, social, and environmental bottom lines (also known as people, planet, profit) which are mutually interdependent on each other: “society depends on the economy, the economy depends on the global ecosystem, whose health represents the ultimate bottom line”, Figure 1 illustrates this common definition of sustainability. The basic idea is taken from traditional business accounting [3]:

1. Profit: The *economic* bottom line concerns e.g. accounting for the traditional physical and financial capital, and for long-term economic sustainability.

2. Planet: The *environmental* bottom line concerns e.g. which forms of natural capital (critical, renewable, replaceable, or substitutable) that will be affected by the planned business activities, and if planned activities will affect the balance of nature. The environmental bottom line is also about long-term environmental sustainability.

3. People: The *social* bottom line concerns e.g. human capital, but also society's health and overall wealth creation. It is about community relations, product safety, training initiatives, charity, and philanthropy, i.e. the social and ethical aspects from the business activities.

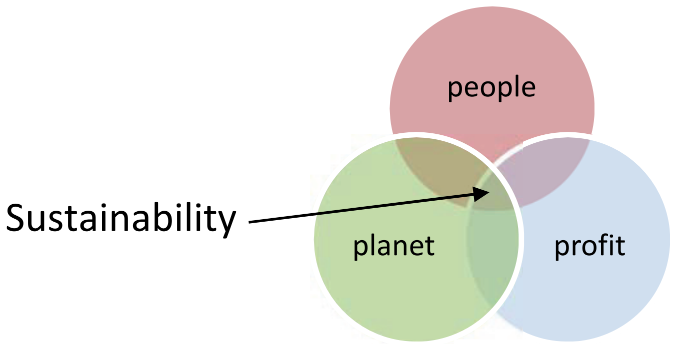


Figure 1 Elkington's triple bottom line concept simplified [3]

Sustainability issues are usually complex because beyond their inherent challenges, there are conflicts among stakeholders within organizations and between organizations; hence, more useful methods are required for effective solutions. As the importance of sustainability issues and sensitivity to them are increasing in industries and society, effective decisions are required to foster effective sustainability planning and control. Issues and concerns of sustainability have been reported in the fields of marketing, production scheduling, new product design, and others. Global companies and academic researchers are studying the importance of sustainability, focusing on ways to improve sustainability [4].

There are regulations and directives (WeEE, EOL vehicles, RhSS etc.), strategies and initiatives (Integrated Product Policy, Extended Producer Responsibility, Corporate social responsibility and etc.), and methodologies and tools (DfE, DfX) which have sustainable development as a basis and intend to improve the sustainability performance of the products. Governments and NGO focuses on sustainable development for policy making and assessing projects. Policy makers within industry are paying increased attention to implementing the sustainable development concept into business activities due to fierce competition in the global market, and strict environmental regulations. The manufacturing industry focuses on producing more sustainable products/*sustainable manufacturing* not only to be in line with the regulations and policies but also make their own contribution to the attempts for SD.

Sustainability focuses on providing the best outcomes for both the human and natural environments now, and into the indefinite future. Sustainability relates to the continuity of economic, social, institutional and environmental aspects of human society, as well as the non-human environment. [4] These three aspects are called as the triple bottom line or three spheres of sustainability and it is represented in Figure 1. According to Seaman, the term "sustainable product design" means to reduce environmental impacts throughout the life cycle of products by maintaining the company's position on the market and its place in society [6].

There are three important aspects that should always be considered when talking about sustainability. First of all, sustainability has a holistic nature. When talking about sustainability or sustainable products it is necessary to take into account not only the environmental, economic and social aspects which states the triple bottom line for sustainable development, but also the whole life cycle of the product from raw materials extraction, and use, to eventual disposal and reuse. This is called life cycle thinking or having a life cycle perspective. The most essential benefit of life cycle thinking is to recognize all important and necessary issues concerning the products and avoid problem shifting between life cycle stages. Improvements made in one part of the life cycle may result in negative impacts in other life cycle stages. Secondly, the concept of 'sustainability' is normative and cannot be defined singularly or categorically. When we talk about the sustainability of a product, we can compare it with another one that has the similar function or serves the same purpose. Finally, it should be noted that sustainability is a moving target and there is 'no state to be reached' [7].

For example the, photovoltaic solar panels, have minimal impact in production and do not emit any hazardous or greenhouse gasses during use phase (electricity production), and the life cycle of these panels are more than 20 years. They are source of renewable energy and accepted as one the most environmentally friendly type of producing electricity. However, it should not be neglected that when these panels are decommissioned in the future, there will be a disposal issue since these panels contain small amounts of regulated materials (Pb, Cd, .. etc.) which require special treatment and disassembly of these panels is not easy. Hence, there is a need for a collection and reverse logistics framework. Therefore life cycle thinking is essential for sustainability of these photovoltaic panels [8].

The sustainability issues within and between industries pose difficulties in making effective decisions. Generally, conflicts among objectives in sustainability issues occur due to multiple objectives based on different criteria. Moreover, there are multiple decision makers especially in supply networks, such as manufacturers, managers of distribution/logistics center, and retailers, and it would not be simple for a decision to satisfy the different goals and perspectives of each and all decision makers [9].

Most of the companies take into account only the technical and economic aspects when making decision like design, material and EOL option change, or when including a new member into their value chain. Sustainability is just a concept, unless it is accommodated into decision making process. The corporations are compelled with the idea of sustainable development and sustainable product manufacturing, however it is not possible if they cannot evaluate the sustainability of their products and processes [10]. This is where sustainability assessment comes on board. Devuyst et al. define sustainability assessment as "...a tool that can help decision-makers and policy-makers decide which actions they should or should not take in an attempt to make society more sustainable [11]". Kates et al. states that the purpose of sustainability assessment is to provide decision-makers with *an evaluation of global to local integrated nature–society systems in short and long term perspectives in order to assist them to determine which actions should or should not be taken in an attempt to make society sustainable* [12].

In order to make a sustainability assessment it is required to combine a number of assessment methodologies. Kloepffer proposed Life cycle Sustainability Assessment in which Life Cycle Assessment (LCA) for environmental aspects, Life Cycle Costing (LCC) for economic aspects, and social life cycle assessment (SLCA) for social aspects; are combined in order to evaluate the negative impacts and benefits towards sustainable products throughout their life cycle [13]. The most difficult part is not only to combine the methodologies in order to have a comprehensive and integrated framework but also attain, elaborate and process life cycle data for assessment.

During the life cycle of the product a huge amount of data is created and stored by the life cycle actors. However a little amount of this data is transformed into information and knowledge and this knowledge can only be used by the life cycle actor who created it. Product lifecycle management (PLM) system help to manage product related information through its life cycle. Closed-Loop Lifecycle Management uses PEIDs and enables to gather and distribute life cycle information through the life cycle of a product more precisely. One of the components of the Closed-loop PLM is the decision support system. A decision support systems (DSS), in general, is a computer-based system that combines data and decision logic as a tool for assisting a human decision-maker. It usually includes a user interface for communicating with the decision maker. A DSS does not actually make a decision, but instead assists the human decision-maker by analyzing data and presenting processed information in a form that is friendly to the decision-maker [14].

Holistic life cycle approach takes into account the whole life cycle of the product and generates performance characteristics, which might be configured in order to evaluate the sustainability performance of the product. A Closed-Loop Lifecycle Management system containing a DSS configured with the holistic life cycle approach will be an efficient tool to evaluate and improve the sustainability performance of products.

1.1 Motivation

PLM intends to manage the product life cycle information from raw material extraction through product manufacture, use, and disposal. However, generally the capabilities of PLM systems are limited to the operations of one company or in some cases it might have been extended to their 1st degree partners.

Additionally, the information flow of the product is often restricted to the BOL phase. Closed-Loop Lifecycle Management is a more recent concept which goes beyond the limits of traditional PLM systems and is targeting seamless information flow across all phases of the life cycle. On top of that, Closed-Loop Lifecycle Management also aims to contribute to sustainable development by doing so. The capabilities of Closed-Loop Lifecycle Management varies from evaluating and improving the technical performance of the products, to increase the reuse and from re-manufacturing of the EOL parts and to manage maintenance operations, etc. Although it possibly has wider use of information management and monitoring capability, Closed-Loop Lifecycle Management has not been used to evaluate the sustainability performance of the products so far.

There are methodologies and tools for appraisal of the sustainability of the products. However those intermediaries are constrained with the available data which is quite difficult to obtain within the current practices. As an innovation Closed-Loop Lifecycle Management offers more systematic data gathering, aggregation, interpretation and storage opportunities. The benefits of sustainability can be comprehended only if the organisations engage sustainability assessment in decision making process. One of the components of Closed-Loop Lifecycle Management system is decision support system. DSSs provide feedback to the decision makers to make informed decisions and reduce the risk of decision making. The motivation of this thesis is to provide a methodology for sustainability assessment as a DSS for Closed-Loop Lifecycle Management systems.

The motivation of this thesis/study came through EC FP7 SuPLight project, which aimed to increase the use of recycled material in production of high-end structural components made of wrought aluminum alloys. Wrought aluminum recycling is difficult due to the fact that the amount of alloying elements is very low and the aluminum scrap is often mix of wrought and cast aluminum alloys which is not suitable for wrought aluminum alloys production. In order to ensure the technical sufficiency, environmental friendliness and economic feasibility of the components containing recycled aluminum, an evaluation procedure was required. We have developed the holistic life cycle approach in accordance with this requirement. Further, we noticed that if we could include the evaluation of the social aspects, we could cover all the aspects of sustainability and the approach could be used for sustainability assessment.

1.2 Research Questions and Objectives

The main objective of this thesis is to propose a methodology for technical, environmental, economic and social evaluation of a product system that takes into account its whole life cycle. The proposed methodology is applied to three case studies for validation.

1- How can a product or a system be superior to another one?

The comparison should be made based on the required function of the product. Based on this function a product may be technically superior (stronger, harder, more flexible, lighter, efficient and etc.), more environmentally friendly (less material usage, energy consumption, emissions to air, lower waste production, better EOL treatment and etc.), cost efficient (less acquisition and processing costs, value recovery through reuse and recycling), socially responsible (better work conditions, fair employment, good relations with local community and etc.). These characteristics represent the three pillars of sustainability.

2- What are the essential elements of sustainability assessment?

The whole life cycle of a product should be taken into account in order to avoid burden shifting. A number of methodologies should be should be combined in order to assess the 3 pillars of sustainability. The impact assessment methodologies should be selected so as to compute the desired performance characteristics. Additionally, since sustainability is not a singular subject, we can only compare alternative scenarios and determine which one is better than the others based on some indicators. This could be used to make informed decisions or support the decisions made by the designers/managers/EOL actors.

3- What are the benefits of holistic system thinking over the traditional approach (end-of-pipe problem solving)?

Holistic system thinking avoids problem shifting between the processes, and helps to identify exact causes of the impacts. Traditional approach may cause undesired outcomes when trying to solve a problem on one end. Life cycle thinking is a holistic system thinking approach, in which the life cycle of the product is considered as a system.

4- How can a Closed-loop Lifecycle Management system contribute to sustainability assessment?

In order to evaluate the sustainability of the products, it is necessary to collect information regarding all the activities of the life cycle actors. Closed-loop PLM system enables not only to collect life cycle information but also to transform the life cycle information into performance characteristics, which may further be used to compare the sustainability performance of alternative products.

5- How is the material and information flow defined?

In order to define the material flow inputs (material, energy, etc.) and outputs (product, co-product, waste) of each process and material transfer among the life cycle actors are documented. This is used to generate the through the life cycle inventory. Information flow definition is determination of source of necessary data for evaluation and content of the information that is necessary for the life cycle actors to pursue their business and feedback information to assess their activities.

6- How can we define (sustainability) performance characteristics?

The performance characteristics may be generic which could be applied to any product, or specific which makes sense for a product category or industry. The performance characteristics should be defined in a way that they cover all related aspects of the product, processes and lifecycle actors.

1.3 Document Structure

In Chapter 1, an introduction to the thesis is given, the motivation and research questions are identified. A general outline of the proposed approach is presented. In Chapter 2, an introduction to Closed-loop life cycle management, decision support systems and sustainability assessment is provided. The former DSS systems designed for the case studies of PROMISE project are summarized. Literature review for life cycle assessment, life cycle costing and social life cycle assessment are presented. In Chapter 3, the holistic life cycle approach for sustainability assessment, and performance characteristics for evaluation of products are presented. A conceptual Closed-loop lifecycle management system is proposed. The case studies for validation of the proposed approach are presented in Chapter 4 – 5 – 6. In Chapter 4, front lower control arm case study is presented. In Chapter 5, baggage door hinge case study is presented. In Chapter 6, flexographic printing case study is presented. In Chapter 7, the conclusions of this thesis and the future extension possibilities are presented.

Chapter 2 State of the art

This chapter provides a brief introduction to Closed loop PLM, and its potential use in sustainability assessment. Secondly, state of the art of decision support systems and the DSS used in earlier Closed-loop PLM systems are summarized. And finally, sustainability assessment and the methodologies (life cycle assessment, life cycle costing, and social life cycle assessment) that are necessary to combine in order to evaluate sustainability of products, are presented.

2.1 Product Lifecycle Management

Usually, when talking about products we mean tangible products i.e. goods. The term goods refers to physical, tangible products that can be owned, traded, and distributed to different places at different times without changing their identity. However, a product in a modern world can also be something very intangible such as a piece of software, a piece of knowledge or an algorithm or a formula [15].

The whole product lifecycle consists of a set of processes, which are functions or tasks to create, transform, and deliver products. These processes include product market strategy, product portfolio planning, product platform planning, customer requirements, product specification, conceptual design, detailed design, design analysis, prototyping and testing, process planning, inventory management, sourcing, production, inspection, packing, distribution, operation and service, disposal and recycle. Past efforts to process management were primarily driven by the desire to improve the efficiency of an enterprise and reduce costs. Successful process management should create processes that meet product developer's expectations, but also support developer value proposition, provide competitive differentiation and contribute to the desired product lifecycle [16].

In general, the product lifecycle is defined as "a series of stages that a product goes through from its concept generation to its disposal." Life cycle stages of a product has been presented differently in the way of thinking and the objective of the study. In marketing perspective, the product life cycle consists of 5 stages; development, introduction, growth, maturity and decline, as depicted in Figure 2. It is depicted as a graph showing the sales volume or profit over time. This type of representation is used to analyses degree of product acceptance by the market overtime and interpret product and market dynamics [17].

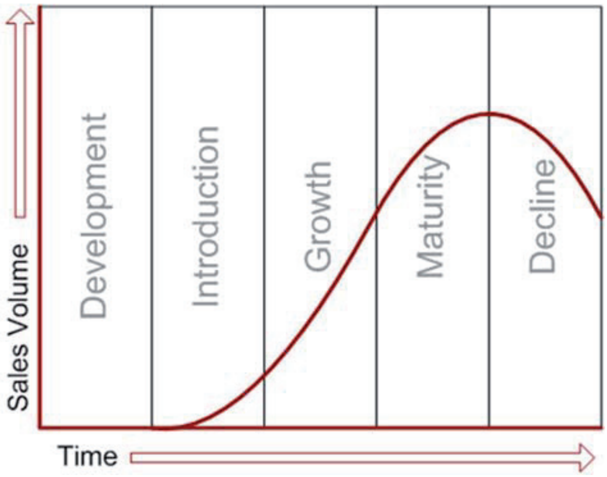


Figure 2 Life cycle stages of a product (marketing perspective) [17]

Figure 3 presents a simplified scheme of the product life concept, which is usually referred to as a ''life cycle,'' as it includes loops between the several life phases. In the figure the full arrows represent material and energy flows, while the dashed arrows represent information flows. Examples of such loops are the reuse and recycling of post-consumer products (originating in the end-of-life phase) or recycling of production scrap [18]. From the global resource viewpoint, there's an environmental product lifecycle in which a natural resource (e.g. an ore, or oil) is extracted from the earth, the resource is processed, the resource is used in the manufacturing of the product, the product is used, and when the product is no longer needed, the resource/waste is managed – perhaps reused, recycled or disposed of.

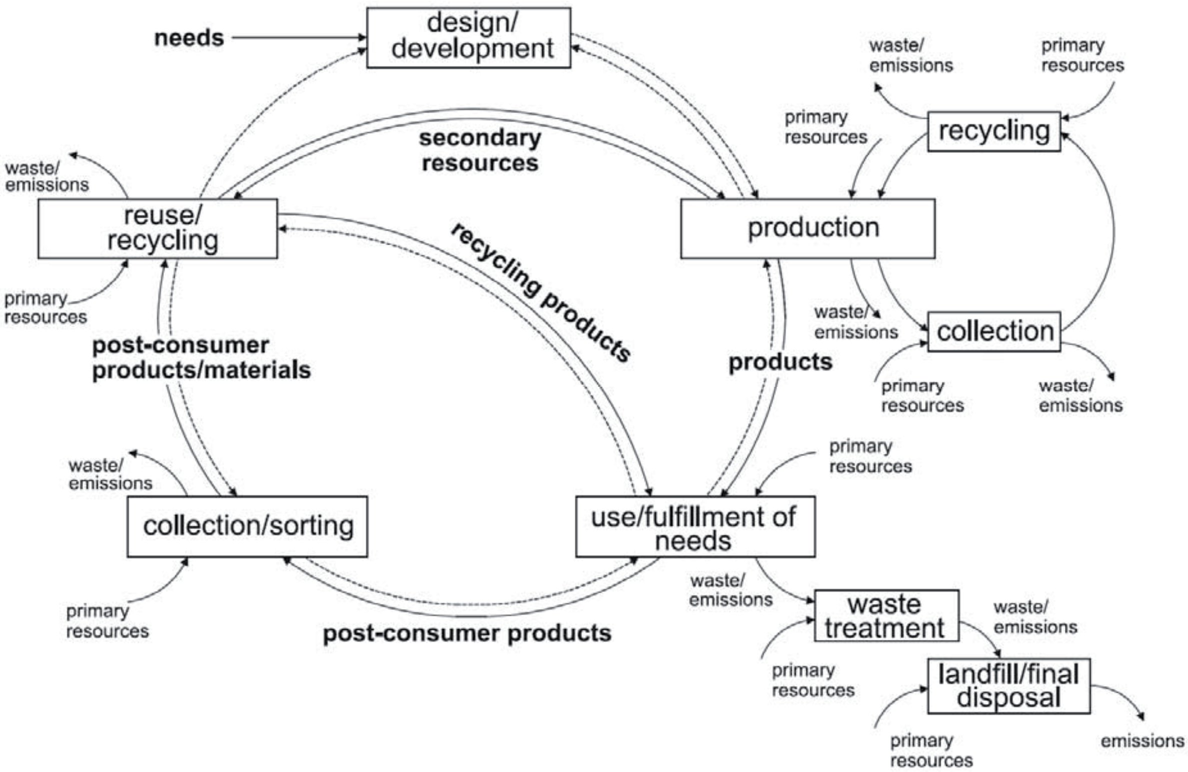


Figure 3 Schematic representation of a generic life cycle of a product [18]

The linear 'take, make, and dispose' model relies on large quantities of easily accessible resources and energy, and as such is increasingly unfit for the reality in which it operates. Working towards efficiency (a reduction of resources and fossil energy consumed per unit of manufacturing output) will not alter the finite nature of their stocks but can only delay the inevitable. A change of the entire operating system seems necessary.

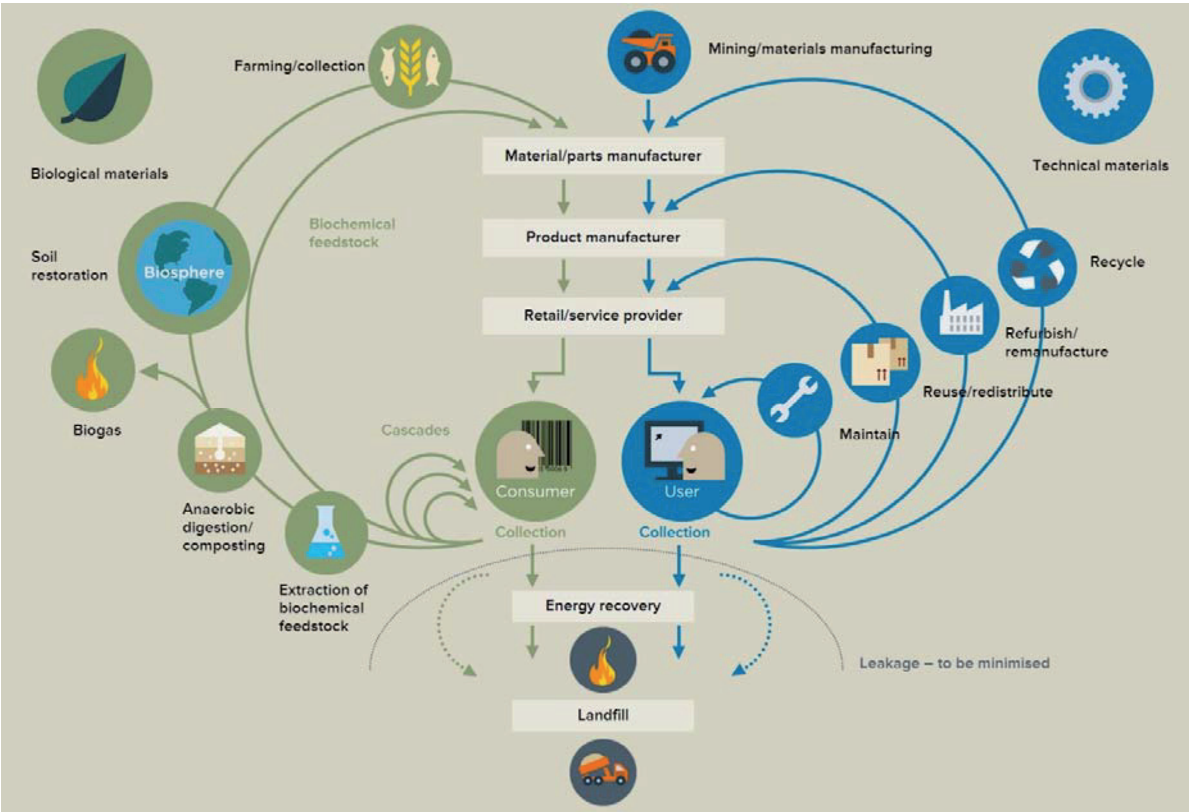


Figure 4 Circular economy [19]

A circular economy, presented in Figure 4, is one that is restorative by design, and which aims to keep products, components and materials at their highest utility and value, at all times. Circular economy;

- is a global economic model that decouples economic growth and development from the consumption of finite resources,
- distinguishes between and separates technical and biological materials, keeping them at their highest value at all times,
- focuses on effective design and use of materials to optimise their flow and maintain or increase technical and natural resource stocks,
- provides new opportunities for innovation across fields such as product design, service and business models, food, farming, biological feed stocks and products,

and establishes a framework and building blocks for a resilient system able to work in the longer term [19].

In engineering point of view, life cycle of a product is divided into phases/stages in order to recognize the distinct activities among the stakeholders. According to Kiritsis et.al, the product lifecycle may be categorized in three major phases; beginning of life (BOL) including conceptualization, definition and realization, middle of life (MOL) including use, service and maintenance, and end of life (EOL) characterized by various scenarios such as: reuse of the product with refurbishing, reuse of components with disassembly and refurbishing, material reclamation without disassembly, material reclamation with disassembly and, finally, disposal with or without incineration [20], illustrated in Figure 5.

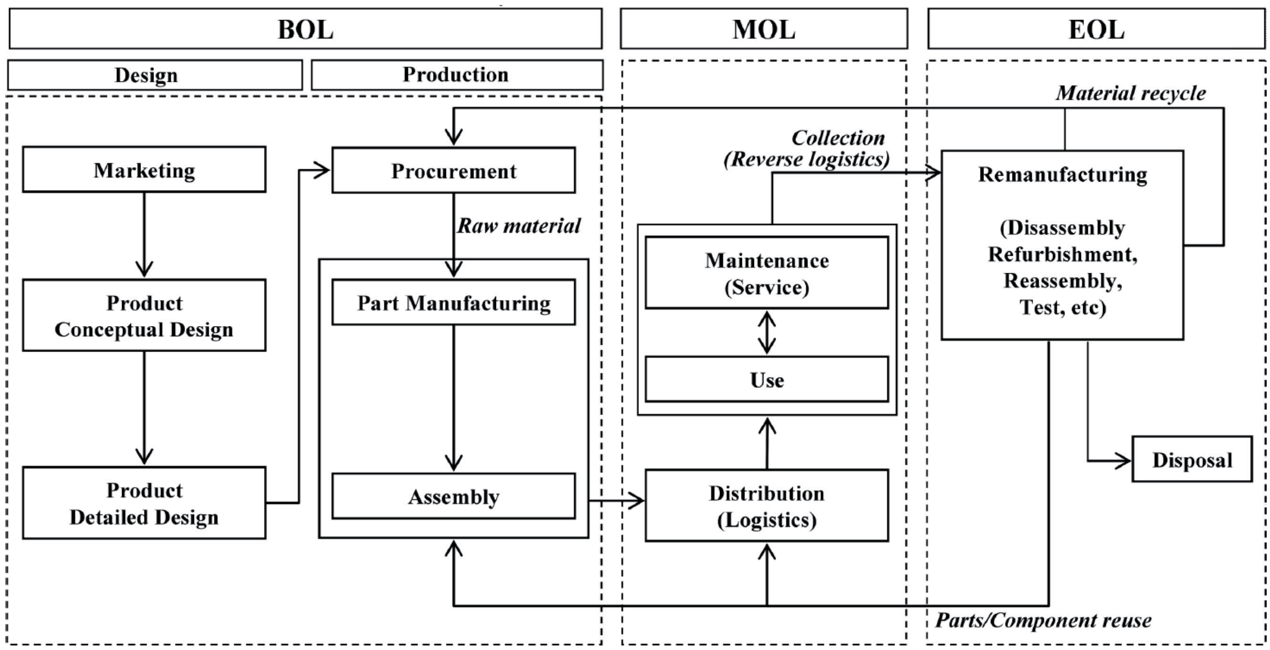


Figure 5 Whole product lifecycle [30]

2.1.1 Life Cycle Thinking

In recent years, an urgent need for implementation of the life cycle thinking into business processes has been highlighted [22]. Effective integration of life cycle thinking into existing business routines is considered as a critical success factor for more sustainable business models [23]. A good example of legislative measures that try to take life cycle thinking into business processes is EuP directive [24], which sets the eco-design requirements for the life cycle performance of energy-using products. Similarly, the life cycle assessment (LCA) community has taken initiative to focus increasingly on life cycle management [25].

As the Life Cycle Initiative is an opportunity for UNEP to bring strategic Life Cycle Thinking to the attention of decision- makers' worldwide, while harmonizing efforts and advancing the development of tools as practical steps towards a life cycle economy, the initiative was finally called an ambitious programme on approaches and best practice for a life-cycle economy. The objective of this initiative is now, "To develop and disseminate practical approaches for evaluating the opportunities, risks, and trade-offs associated with products over their whole life cycle to achieve more sustainable products". This includes the generation, standardization and integration of environmental information and approaches that facilitate Life Cycle Management activities. A further aim of this initiative is to bring Life Cycle Thinking to the attention of a global audience addressing governments, industry and organisations [26].

Any environmental, economic, or social assessment method for products has to take into account the full life cycle from raw material extraction, production to use and recycling or waste disposal. In other words, a systems approach has to be taken. Only in this way, trade-offs can be recognized and avoided. Life cycle thinking is the prerequisite of any sound sustainability assessment. It does not make any sense at all to improve (environmentally, economically, or socially) one part of the system in one country, in one step of the life cycle, or in one environmental compartment, if this 'improvement' has negative consequences for other parts of the system which may outweigh the advantages achieved. Furthermore, the problems shall not be shifted into the future. The second point is that life cycle thinking is not enough, since in order to estimate the magnitude of the trade-offs, the instruments required have to be as quantitative as possible. Since we are living in a global economy (which from the European perspective started in the 15th century, not as recently as often claimed), the system boundaries used in the methods have to be global as well. In this context, the life cycle initiative jointly launched by UNEP and SETAC deserves high attention and support [27].

2.1.2 Product Lifecycle Data

Product lifecycle data indicate all objects that are created, updated, deleted, and stored during whole product lifecycle, such as conceptual ideas, CAD/CAM/CAE models, technical documents, manufacturing data, logistics data, usage information, disposal information, and so on. Depending on their characteristics, they can be classified into some generic types: product definition, product history, and best practice; content and meta-data, internal and external, and stationary and dynamic. The product lifecycle data has been classified by four dimensions. First, the lifecycle data can be classified into three groups depending on its characteristics: product, process, and organisations (resource). Second, the lifecycle data can be grouped into static data and dynamic data by degree of variation. Third, depending on the chronological order of lifecycle phase, these can be divided into three groups: BOL data, MOL data, and EOL data. Finally, depending on degree of abstraction, these can be divided into content data and meta-data [21].

There are many product, process, and organisations related data that are generated during product life span. These are called product, process, and organisations data, respectively. Static data indicate the data that do not change during product lifecycle. Most are determined and fixed at BOL phase: e.g. specifications of products and End-of-Life information such as disassembly sequences. However, dynamic data implies the data that can change during product lifecycle: e.g. service/maintenance history information. BOL is the phase where product concept is generated and its physical model is realized. Therefore, there are many BOL data related to product generation such as CAD/CAM data, technical documents, and so on. MOL is the phase where products are distributed, used, maintained, and serviced by customers or engineers. For example, usage conditions, failure, and maintenance or service events are MOL data. EOL is the phase where products that that have use their use value are collected, disassembled, refurbished, re-assembled, recycled, reused, and disposed. Hence, there are many EOL data with regard to conditions of retirement and disposal of products. Meta-data implies the data to describe the content data while content data means tangible data occurring over whole product lifecycle. Table 1 shows examples of meta-data of product data [21].

Meta-data description	Meta-data
Who created you?	*Creator*
Who owns you now?	*Owner*
What kind of a product are you?	*Type*
Do you contain hazardous materials?	*Hazardous_materials*
What has been happening to you?	*History*
Where are you going?	*Next_destination*
What is your destination?	*Final_destination*
When should you arrive at your destination?	*Due_date*
To which order do you belong?	*Order_number*
To what shipment do you belong?	*Shipment_number*

Table 1 An example of meta-data of product data [21].

"Corporate Intellectual Capital is the sum of retained knowledge that an organisations accumulates in the course of delivering its objectives." Corporate Intellectual Capital (CIC) consists of the following:

- Product Definition: All the information relating to what the product (or service) is, its specification, how it is designed, manufactured, delivered and supported.
- Product History: Any information relating to what the organisations has done in the past that is of relevance for the delivery of the organization objectives, e.g. audit trails required for legal or regulatory purposes, or archives relating to past products.
- Best Practice: This encapsulates experience gathered by the organization in the course of delivery of its objectives.

Note that these definitions apply to any organization regardless of what its products/services are, how it conduct its business, who it is collaborating/partnering with, and how it is delivering its products/services to its customers. Also the definitions do not incorporate any description of technology, system functionality, or processes which may make the definition time dependent [28].

2.1.3 Life Cycle Management

During the life cycle of the product a huge amount of data is created and stored by the life cycle actors. However a little amount of this data is transformed into information and knowledge and this knowledge can only be used by the life cycle actor who created it. Life cycle management organizes the interaction of the life cycle partners to achieve the maximum benefit from each technical product. Life Cycle Management has been defined by the SETAC Europe Working Group on LCM as "an integrated framework of concepts, techniques and procedures to address environmental, economic, technological and social aspects of products and organizations to achieve continuous environmental improvement from a life cycle perspective" [26]. The three main fields influencing the activities of the partners are environment, regulations and standards, as well as the constraints of economy. In order to achieve the best practice, the partners have to cooperate and tap into the know-how of all parties at all life cycle stages, and to minimize the risks and to secure the maximum result, all of them should be part of the value adding processes depending on the extent of the value they contribute [29].

Due to ascending product complexity, globally dispersed product design and manufacturing activities and extended company responsibility on their products, the companies are forced to invest in concepts like product life-cycle management (PLM) supporting their operations management in reducing managerial complexity in new product development. PLM expresses the engineering point of view of the product life-cycle concept and integrates the aspects of people, processes, and data [15]. For example, the lack of a well- defined PLM process is seen as a key factor in companies missing targets in new product introduction and therefore causing delayed market entry, as was the case of the AirbusA380. Similarly, Toyota's massive vehicle recalls were caused due to the cars' complexity and might have been avoided by implementing a thorough PLM concept [30].

In modern product development, as the complexity and variety of products increase to satisfy increasingly sophisticated customers, so does the need for knowledge and expertise for developing products. Co-located and monolithic design teams can no longer efficiently manage the product development effort in its entirety. In order to avoid lengthy product development cycles, higher development costs and quality problems, collaboration across distributed and multidisciplinary design teams has become a necessity. Today’s knowledge-intensive product development environment requires a computational framework which effectively enables capture, representation, retrieval and reuse of product knowledge. This is the essence of Product Lifecycle Management (PLM). PLM, in simple terms, is a business strategy for creating a product-centric environment. Rooted in computer aided design (CAD) and product data management

(PDM) systems, PLM is aimed at connecting various product stakeholders over the entire lifecycle of the product from concept to retirement. As a technology solution, it establishes a set of tools and technologies that provide a shared platform for collaboration among product stakeholders and streamlines the flow of information along all the stages of product life cycle. But, what makes PLM distinct from many other technology solutions is not its state-of-the–art tools. Instead, it is the establishment of a sustainable corporate strategy via PLM [31].

2.1.4 PLM Definition

Product lifecycle management (PLM) is a systematic, controlled concept for managing and developing products and product related information. PLM offers management and control of the product (product development, productizing and product marketing) process and the order-delivery process, the control of product related information throughout the product life cycle, from the initial idea to the scrap yard. Almost without exception, the PDM and PLM abbreviations also refer to information systems developed to manage product lifecycle and product related data [32].

The core of product lifecycle management is the creation, preservation and storage of information relating to the company's products and activities, in order to ensure the fast, easy and trouble-free finding, refining, distribution and reutilization of the data required for daily operations. In other words, work that has once been done should remain exploitable, regardless of place, time or – within prescribed limits, naturally – data ownership. At the same time, the idea is to convert data managed by the company's employees, skilled persons and specialists into company capital in an easily manageable and sharable form-as bits [32].

PLM is a knowledge management solution which supports different processes throughout the product lifecycle within the extended enterprise. It should be stated that, in modern product development practices, knowledge management is becoming a necessity. No matter how knowledge management supports different lifecycle processes, its underlying intention is always the same. Knowledge management, in its core, is about integrating different processes and their corresponding agents through a shared body of knowledge. To investigate why integration is such a critical issue for the enterprise, a historical perspective on the evolution of design and manufacturing is beneficial [31].

The PLM is ideally an information processing system. It supports the management of all information such as CAD drawings, technical documents, and structured and unstructured information created, changed, transferred, stored, managed, and converted by along the lifecycle of a product, from its design to end of life. It becomes the backbone for managing product related information in an enterprise. Physically, product data and information are dispersed along a variety of information systems, generated and used in the diverse phases of the lifecycle by many different actors. Thus, PLM should enable several internal and external actors (i.e. stakeholders) to do collaborative creation, modification, dissemination, and search of information throughout product lifecycle. It entails modeling, searching, manipulating, exchanging, and using of lifecycle information over the whole lifecycle. The scope of information to be managed increases as the product lifecycle evolves. As a result, a great deal of lifecycle information is generated during the whole product lifecycle. Since the information is usually created and consumed by various stakeholders in a certain sequence, lots of information flows are generated. Because of emerging information and communication technologies, it is no doubt that there are more complex information flows over the whole lifecycle. Querying and sharing product knowledge is becoming a key issue in enterprise information systems. Hence, the success of PLM lies in identifying what kind of information are available in the other phase, and how we can use them in or-der to streamline business processes [33].

2.1.5 The Evolution of PLM

With the advent of Computer Aided Design (CAD) systems in the early 1980s, engineering design entered a new era. CAD systems enabled the creation of a geometric model of the product in the computer, to be reused and manipulated by the designer, with extremely rich features and functions for detailed design work. In parallel with the development of Computer–Aided Design, Manufacturing and Engineering (CAD/CAM/CAE) tools, Product Data Management (PDM) systems appeared during 1980s to control and manage the product information created by various information authoring tools. The core functionality of early PDM systems was to provide users with required data through their central data repository and to insure integrity of the product data by continual updating as well as controlling the way people create and modify the data.

Over time, PDM solutions were supplemented with new functionalities like change management, document management, workflow management and project management that promised concurrent engineering and streamlined product development processes within the enterprise. The first generation of PDM systems, although effective within the engineering domain, failed to encompass non-engineering areas within the enterprise such as sales, marketing and supply chain management as well as the external agents like customers and suppliers. The information managed by early PDM systems was limited to the engineering information like geometric models, BOM and FEA models, and working with PDM systems was not always easy and usually required an engineering/technical background.

In the 1990s, PDM vendors began offering systems with web-enabled front-end together with more powerful and user friendly visualization tools to broaden the user base. Due to the universal, inexpensive and ubiquitous nature of the Internet, web-based PDM systems became more accessible throughout the extended enterprise. Nevertheless, their core functionalities remained focused on managing engineering documents.

Almost concurrent with the evolution of PDM systems, the first wave of enterprise applications such as Enterprise Resource Planning (ERP), Customer Relationship Management (CRM) and Supply Chain Management (SCM) were introduced. These were aimed at further streamlining and improving the manufacturer’s business practice. These solutions, each focusing on some specific lifecycle process, are quite dependent on product information. However, PDM systems could not provide the necessary support for ERP/CRM/SCM (unlike CAD/CAM/CAE) simply because the internal piping of PDM systems was designed specifically for handling engineering data [29].

The concept of Product Lifecycle Management (PLM) appeared later in the 1990’s with the aim of moving beyond engineering aspects of a product and providing a shared platform for the creation, organization and dissemination of product related information (cradle to the grave) across the extended enterprise. PLM seeks to extend the reach of PDM beyond design and manufacturing into other areas like marketing, sale and after sale service, and at the same time addresses all the stakeholders of the product throughout its lifecycle. It extends PDM functionalities to include the creation of product definition information as well management and control of such information. In other words, whereas PDM is focused on the management of data created by information authoring tools, PLM also includes the authoring tools. PLM seeks to fill the gap between enterprise business processes and product development processes. In addition, PLM has one major identifier: it is all about knowledge management. Unlike PDM systems which focus on managing data, PLM, at its core, is a process which supports capture, organization and reuse of knowledge throughout the product lifecycle [29].

In the figure below, the development of isolated computer applications were merged to form basic product data management (PDM) systems in the 1980–1990s, and then advanced by supplementing them with additional web and visibility tools; while the development of early PLM occurred with the incorporation of separate systems such as ERP, CRM and SCM, into PDM in the new millennium - a process still continuing and being refined with additional supplementations today. Vendors have built their reputation on their ability to integrate these widely varying systems into coherent, inter-organizational PLM solutions, with differentiation between them depending very much upon the variety of PLM ‘extras’ that they can offer to their customers [34].

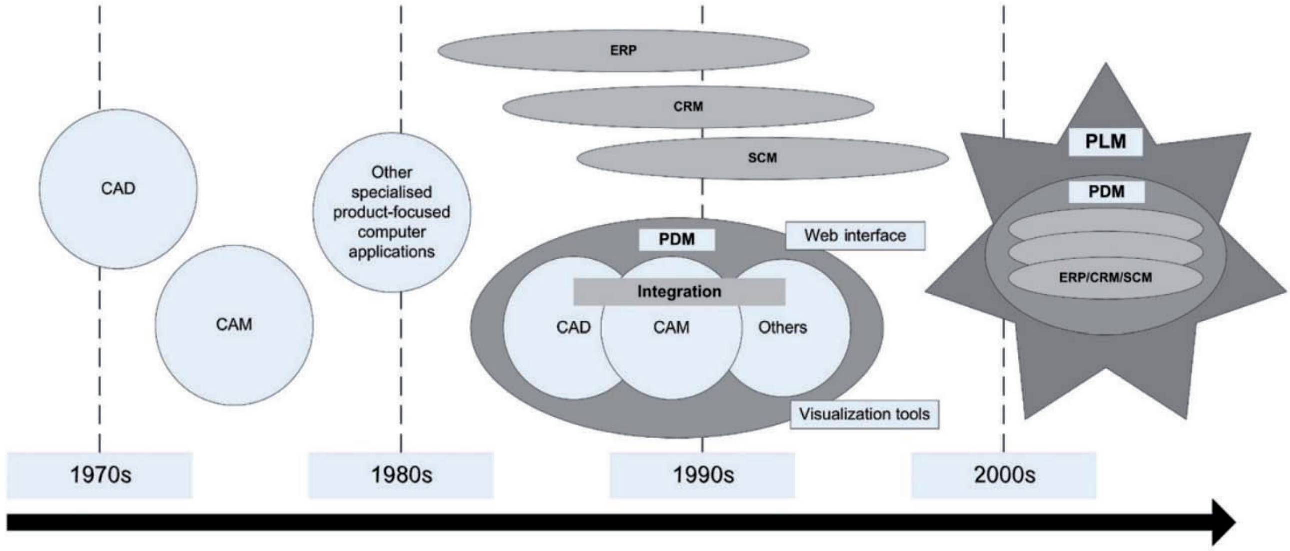


Figure 6 The development of PLM, described as an evolution of computing applications [34]

2.1.6 Internal and External Forces for PLM

There are internal and external forces that channel a company to pay attention to PLM in order to achieve competitive advantage over their competitors and to cope with the universal trends. Reducing operational costs through increasing operational efficiency used to be a powerful means of achieving competitive advantage. However, that is no longer the case. Today product innovation and customer intimacy together with operations excellence have become the most important areas of focus for a corporation that wants to gain competitive differentiation. Over the last few years, universal trends like globalization, environmental awareness, shrinkage in product lifecycle, increase in product complexity and the push into supply chain have posed new challenges for corporations [31].

CIMdata mentioned three core concepts of PLM; universal, secure, managed access and use of product definition information, maintaining the integrity of product definition and related information throughout the life of the product or plant, and managing and maintaining business processes used to create, manage, disseminate, share and use the information [35].

PLM has become one of the key technological and organizational approaches and enablers for the effective management of product development and product creation processes in engineering and in the manufacturing industry. Available PLM methods and tools can be clustered in three groups [36]:

- Information management (e.g. method for identifying, structuring, classifying, modelling, retrieving, sharing, disseminating, visualizing and archiving product, process and project related data).

- Process management (e.g. methods for modelling, structuring, planning, operating and controlling formal or semi-formal process like engineering release processes, review process, change processes or notification processes). The strong link between the different process stages and the resulting product models are covered by so called configuration management methods and tools.
- Application integration (e.g. methods for defining and managing interfaces between PLM and different authoring application like CAD, CAM, CAE and integrated enterprise software such as ERP, SCM or Customer relationship management systems.

The main weaknesses of existing PLM solutions are the poor support of product lifecycle activities outside the product development, as well as the missing integration of mechanic, electronic and software components. Another problem is their very high complexity and the necessary, huge customizing efforts. In spite of intensive standardization activities, general accepted industry standards for PLM meta-data models and for PLM processes are still missing. As PLM is a very complex, multi-layered and multidisciplinary topic, a taxonomy of this multi-dimensional development space is necessary. This space considers the development directions general instantiation approach for different industries or application domains, considered PLM users and actors or partners, covered phases of the product lifecycle, supported process types and the covered product types. The main focus of PLM developments is within one manufacturing company including various distributed sites. Some research activities address the integration between producers and suppliers. Current PLM models and methods were extended in order to integrate this customer feedback into the product development processes (e.g. change management processes), into the product structure and into the classical PLM configuration management. Generic PLM models, methods and tools cover the whole product lifecycle. Specialized models and methods from existing PLM solutions are focused on the product development [36].

PLM facilitates the innovation of enterprise operations by integrating people, processes, business systems, and information throughout product life cycle and across extended enterprise. It aims to derive the advantages of horizontally connecting functional silos in organizations, enhancing information sharing, efficient change management, use of past knowledge, and so on. To this end, the PLM system should be able to monitor the progress of a product at any stage in its life cycle; to analyze issues that might arise at any product life cycle phase; to make suitable decisions to address problems; and to execute and enforce the decisions. In spite of its objective, PLM has not received much attention until so far from industry because there are few efficient tools to gather product life cycle data after product sales [37].

The product life cycle management by a PLM solution allows including, not only all the necessary elements to ensure its traceability, like modeling, document management, numerical analysis, know-how capitalization, etc. but all the information system components making it possible to ensure the product monitoring from its manufacture to its marketing until its disappearance or likely its recycling. In PLM applications, the technical data are organized within configurations. The configuration management is used to manage products complexity and knowledge diversity resulting from various business cases in the company. Indeed, the growing number of PLM applications users, the technical data volume and the various evolutions associated to these data require; controlling and checking the exchanged technical data consistency, unicity and safety, and taking into account data evolutions and all their effects on the product and its components. This is why the configuration management is a fundamental component in PLM applications, making it possible to control and manage complexity related to the data [38].

2.2 Closed-loop Lifecycle Management

The development of product identification technologies such as RFID and AUTO ID has made the whole product lifecycle visible and controllable. Several types of product embedded information device (PEID) are available in the market. These new technologies become a major driving force that is needed in the propagation of product lifecycle management (PLM) because they can tackle the problems of PLM that have been obstacles to be propagated. The PLM under new environment allows all actors of the whole product lifecycle to access, manage, and control product related information, especially, the information after a product delivery to the customer and up to its final destiny, without temporal and spatial constraints. This information can be used to streamline operations of MOL and EOL. This information also goes back to the designer and producer at BOL so that the information flow can be horizontally closed over whole product lifecycle. In addition, the control of information flow is vertically closed. This means that based on gathered data, we can analyze product related information and take some decisions on behaviors of products, which will affect data gathering again [39].

Currently, there is the lack of study on information flows to be identified across product lifecycle operations. Although some studies dealt with information flows in PLM, many of them addressed the framework or protocol for communicating information flows, not information flows themselves. As a result, very little attention has been paid to clarifying the product lifecycle information flow. The unavailability of explicit flows of product lifecycle information leads to a certain degree of inefficiency in performing lifecycle operations. Thus, the methods to efficiently represent, control, and search information flows are critical. It requires the identification of information flows and their efficient management, which can play an important role in analyzing and making decisions of several operational issues in the product lifecycle [33].

PLM facilitates innovation by integrating people, processes and information throughout the product lifecycle and across the extended enterprise. It aims to derive the advantages of horizontally connecting functional silos in the organization, enhancing information sharing, efficient change management, use of past knowledge, and so on [40]. The *closed-loop PLM* focuses on the complete lifecycle of a product with more emphasis on tracking and managing of information of whole product lifecycle, and possible feedback of information to each product lifecycle phase. There are many lifecycle information flows among BOL, MOL, and EOL, as shown in Figure 7. Product lifecycle data, such as usage conditions, failure, and maintenance or service events, etc., can be gathered by the PEID that is embedded in each product over the whole product lifecycle. These data play an important role in analyzing and making decisions of several operational issues in the product lifecycle. Based on the feedback information, *closed-loop PLM* can support the decision making of several operational problems over the whole product lifecycle. It gives us opportunities to improve several operations over whole product lifecycle [39].

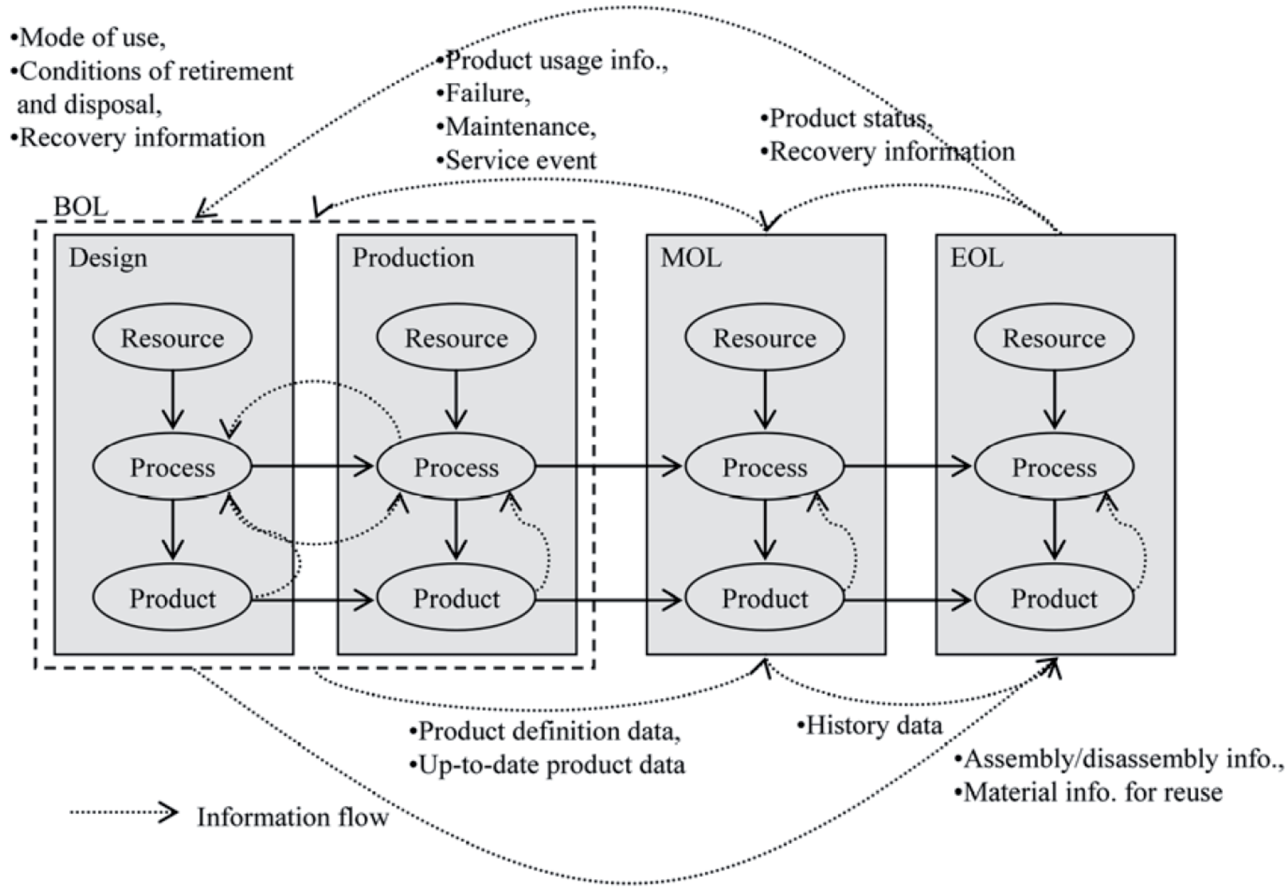


Figure 7 Product information flow [39]

There are several closed-loops among BOL, MOL, and EOL as shown in Figure 7. Some of them have direct links. For example, most forward information flows can be directly used as inputs for streamlining the operations of next phases. However, some of them such as feedbacks from MOL and EOL to BOL must be indirect links. However, the feedback information can be used as knowledge for streamlining the design and production of the same or similar types of products. Table 2 shows available inputs of each product lifecycle in forward and backward chains.

Information flow	Category	Main data
Forward		
BOL to MOL	BOM information	Product ID, product structure, part ID, component ID product/part/component design specification, etc.
	Information for maintenance/service	Spare part ID list, price of spare part, maintenance/service instructions, etc.
	Production information	Assemble/disassemble instruction, production specifications production history data, production routing data, production plan, inventory status, etc.
BOL to EOL	Product information	Material information, BOM, part/component cost, disassemble instruction, assembly information for remanufacturing, etc.
	Production information	Production date, lot ID, production location, etc.
MOL to EOL	Maintenance history information	Number of breakdowns, parts/components' IDs in problem, installed date, maintenance engineers' IDs, list of replaced parts, aging statistics after substitution, maintenance cost, etc.
	Product status information	Degree of quality of each component, performance definition, etc.
	Usage environment information	Usage condition (e.g., average humidity, internal/external temperature), user mission profile, usage time, etc.
	Updated BOM	Updated BOM by repairing or changing parts and components, etc.
Backward		
MOL to BOL	Maintenance and failure information for design improvement	Ease of maintenance/service, reliability problems, maintenance date, frequency of maintenance, MTBF[a], MTTR[b], failure rate, critical component list, root causes, etc.
	Technical customer support information	Customer complaints, customer profiles, response, etc.
	Usage environment information	Usage condition (e.g., average humidity, internal/external temperature), user mission profile, usage time, etc.
EOL to MOL	Recycling/reusing part or component information	Reuse part or component, remanufacturing information, quality of remanufacturing part or component, etc.
EOL to BOL	EOL product status information	Product/part/component life-time, recycling/reuse rate of each component or part, etc.
	Dismantling information	Ease to disassemble, Reuse or recycling value, disassembly cost, remanufacturing cost, disposal cost, etc.
	Environmental effects information	Material recycle rate, environmental hazard information, etc.

Table 2 Main data information flow in closed-loop PLM [42]

To properly manage the full product lifecycle, it is necessary to develop a seamless data flow through all three phases, which requires a PEID to store information and communicate with local and centralized databases, as well as a product data model capable of structuring this information for easy access and updating. During BOL (between design and manufacturing), and partly into MOL, the information flow is quite complete and supported by intelligent systems like CAD/CAM. Product Data Management (PDM), and Knowledge Management systems are effectively and efficiently used by the industry and, through their influence, by their suppliers. The information flow becomes far less complete when moving from the MOL phase to the final EOL scenario. For most of today's technological products, and especially for consumer electronics, household machines, vehicles etc., it is fair to say that the information flow breaks down after the delivery of the product to the customer. The fact that the information flow in most cases is interrupted shortly after product sales prevents the feedback of data, information and knowledge, from service and maintenance and recycling experts back to the designers and producers. In general, relevant activities and information flows have complex interactions during the lifecycle. Therefore, it is important to control and steer the process and information flow of the product lifecycle. For this purpose, modelling issues related to product lifecycle activities and lifecycle information are considered [21].

The concept of closed-loop PLM can be defined as follows: "A strategic business approach for the effective management of product lifecycle activities by using product data/information/knowledge which are accumulated in the closed-loops of product lifecycle with the support of product embedded information device (PEID) and product data & knowledge management (PDKM)." Its objective is to streamline product lifecycle operations, based on the seamless product information flow, through a local wireless connection to PEIDs and through remote internet connection to knowledge repositories in PDKM, after its delivery to the customer and up to its final destiny (disassembly, re-manufacturing, re-use, recycle, disposal, etc.) and back to the designer and producer [41].

To implement the concept of closed-loop PLM, the following are necessary conditions.

- Every product has a PEID to manage its lifecycle data. If necessary, sensors can be built in products and linked to the PEID for gathering its status data.
- Each lifecycle actor accesses to PEIDs with its reader or accesses to a remote PLM system for getting necessary information.
- Closed-loop PLM should have decision support systems, and PDKM systems for providing lifecycle actors with suitable advices at any time.

In closed-loop PLM the information and control flow are horizontally and vertically closed, respectively. The *closed-loop PLM* focuses on the complete lifecycle of a product with more emphasis on tracking and managing of information of whole product lifecycle, and possible feedback of information to each product lifecycle phase [25]. The information flow is horizontally closed, which means that information flow is closed over product lifecycle phases: BOL, MOL, and EOL.

- Designers will be able to exploit expertise and know-how of the other players in the product lifecycle such as the modes of use, conditions of retirement, and disposal of their products and thus improve product designs.
- Producers will be provided in a real-time way with not only operation data of shop floor but also usage status of product until disposal phase.
- Service and maintenance experts will be assisted in their work by having not only product design information but also an up-to-date report about the status of the product during product usage.

- Recyclers and re-users will be able to obtain accurate information about 'value materials' arriving through end-of-life (EOL) routes by the analysis of modes of use and conditions of product [42].

Moreover, the information control flow is vertically closed, which means that information are gathered and controlled in the vertical loops of hardware, software, and business process [42].

- PEID gathers product related data under specific conditions or periodically or in a real-time way over the whole product lifecycle.
- PEID sends gathered data to database under specific conditions or periodically or in a real-time way.
- Based on gathered data, information and knowledge are generated and stored at knowledge repository in PDKM system. They are based on decision making of lifecycle actors.
- Based on analysis and decision making, if there is any need to update product information, PLM server sends updated information to PEID directly or via PLM agents.

The core of closed-loop PLM is the information management of lifecycle objects such as product related data, processes, and resources over the whole lifecycle since it can support the ability to analyze data and make decisions with fast and consistent ways. For this, closed-loop PLM should support; management of whole product lifecycle activities, management of product related data and resources, collaboration between customers, partners, and suppliers, and enterprise's ability to analyze challenges and bottlenecks, and make decisions on them [28].

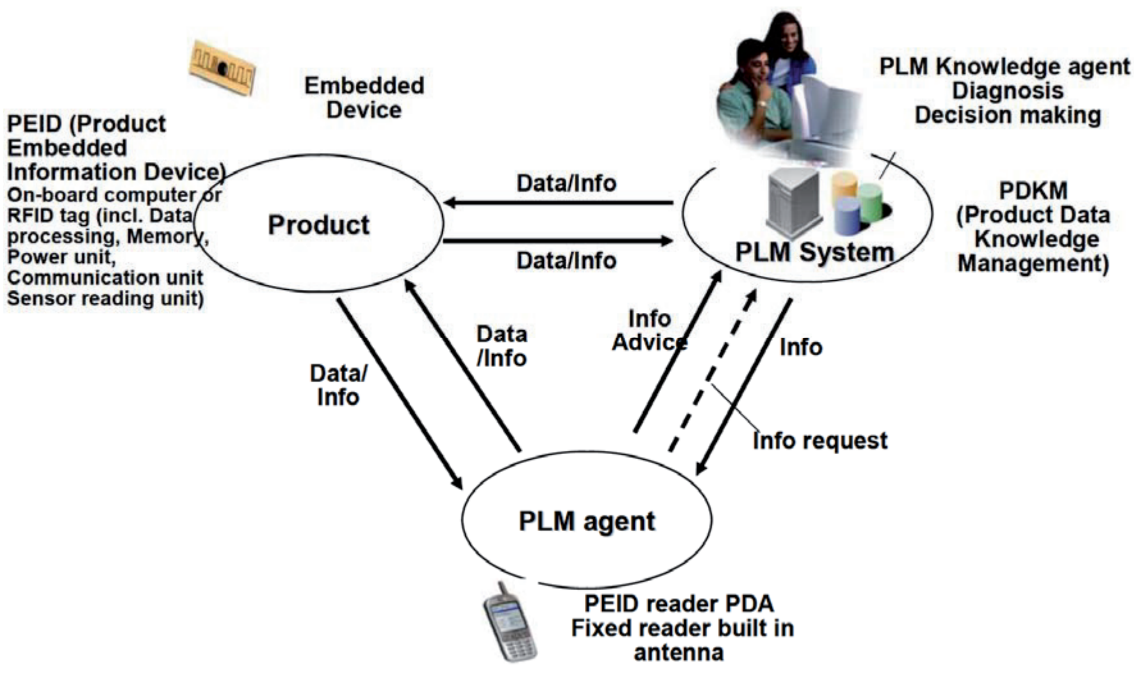


Figure 8 Closed-loop PLM concept [42]

In PLM, all activities performed along the product lifecycle must be coordinated and efficiently managed in theory. Figure 8 shows the business architecture of a closed-loop PLM. The operations in the closed-loop PLM are based on the interactions among three organisations (PLM agent, PLM system, and Product). The PLM agent can gather product lifecycle information from each product at a fast speed with a mobile device such as a personal digital assistant (PDA) or a fixed reader built in antenna. It sends information gathered at each site (e.g. retailers, distribution sites, and disposal plants) to a PLM system. It enables a PLM system to manage lifecycle information reported at each site (e.g., retailers, distribution sites, and disposal plants) by reading the RFID tag via an information network. The PLM system provides lifecycle information or knowledge made by PLM knowledge agents through an information network whenever requested by related persons and organisations. The following figures show BOL, MOL, and EOL business architecture which describe business applications and information flows.

The components of a closed-loop PLM system and their relations are presented in the five layers of the system architecture schema shown in Figure 9. These layers are mainly classified into business process, software, and hardware. PEID is an important hardware component for facilitating the closed-loop PLM concept. Furthermore, software related to applications and middleware layers, and their interfaces play important roles in closed-loop PLM. Following are some more details about the components of whole closed-loop PLM system: PEID, middleware, DSS, and PDKM [44].

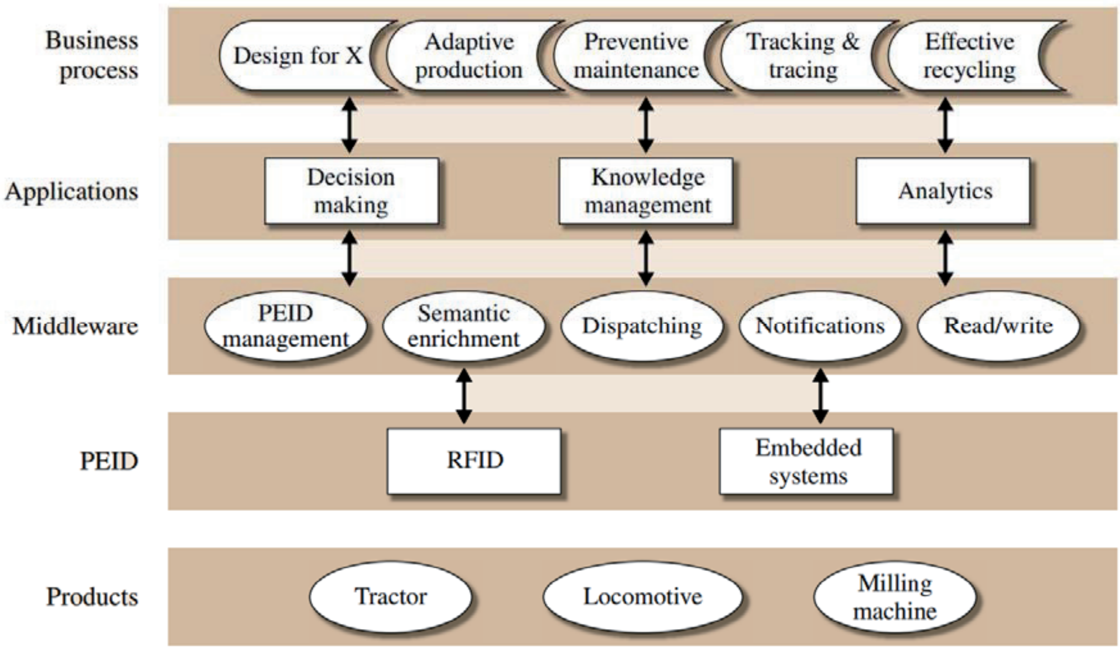


Figure 9 Overall system structure for closed-loop PLM [44]

- *PEID* stands for product embedded information device. It is defined as a device embedded in (or attached to) a product, which contains product related information (e.g. product identification), and which is able to provide the information whenever requested by externals during product lifecycle. There are various kinds of information devices built in products to gather and manage product information, for example, various types of RFID tags and onboard computers. A PEID has a unique ID and provides data gathering, processing, and data-storage functions. A PEID should have a processing unit, communication unit, sensor reader, data processor, and memory. Depending on the combinations of these functions, the PEID has several types such as passive RFID tag, active RFID tag, and onboard computer. In particular the manufacturing cost of the PEID is greatly affected by power management and data function specification. Hence, the PEID should be carefully designed considering application characteristics.

- *Middleware* takes a role of converting raw data gathered by PEID to necessary information and knowledge. It can be considered as intermediate software between different applications. Developing middleware is one of the most challenging areas in the closed-loop PLM since it is the core technology to efficiently gather and distribute PEID data. It plays a role as the interface between different software layers, e.g., between PEIDs and PDKM. It is used to support complex and distributed applications, e.g., applications between RFID tags and business information systems, to communicate, coordinate, and manage data by converting the data in a proper way. In the closed-loop PLM, it has a role to map the low-level data gathered from PEID readers to more meaningful data of other high-level application such as field DB/PDKM and PLM business applications. There are several issues to be resolved: data security, consistency, synchronization of data, tracking and tracing, exception handling, and so on.

- *Product data and knowledge management (PDKM)* manages information and knowledge generated during product lifecycle. It is generally linked with decision support systems and data transformer. PDKM is a process and technologies to acquire, store, share and secure understandings, insights and core distinctions. PDKM should link not only product design and development such as CAD/CAM but also other backend software (legacy systems), e. g., enterprise resource planning (ERP), supply chain management (SCM), and customer relationship management (CRM) to achieve the interoperability of all activities that affect a product and its lifecycle.

- *Decision support system* (DSS) streamlines the lifecycle operations by providing suitable information and knowledge through analysis of gathered lifecycle data. DSS software provides lifecycle actors with the ability to transform gathered data into necessary information and knowledge for specific applications. To this end, diagnosis/analysis tools for gathered data and data transformer are required. There can exist several types of decision making/support: automatic, semi-automatic, and manual. There are a lot of decision support areas which are highlighted in the closed-loop PLM; for example, main areas in decision support for MOL include assisting efficient maintenance diagnosis and prognosis, whereas in EOL this includes efficient waste management. Figure 9 shows the overall architecture of the middleware developed in the PROMISE project.

2.3 Decision Support Systems

The essence of management is making decisions. Managers are constantly required to evaluate alternatives and make decisions regarding a wide range of matters. Just as there are different managerial styles, there are different decision making styles. Decision making involves uncertainty and risk, and decision makers have varying degrees of risk aversion [45].

Decision support systems (DSS) are defined broadly as interactive computer-based systems that help people use computer communications, data, documents, knowledge, and models to solve problems and make decisions. DSS are ancillary or auxiliary systems; they are not intended to replace skilled decision-makers, and are not automating decision-making [46].

In pursuing the goal of improving decision-making, many different types of computerized DSS have been built to help decision teams and individual decision-makers. Some systems provide structured information directly to managers. Other systems help managers and staff specialists analyze situations using various types of quantitative models. Some DSS store knowledge and make it available to managers. Some systems support decision-making by small and large groups. Companies even develop DSS to support the decision-making of their customers and suppliers [47].

The history of DSS reveals the evolution of a number of sub-groupings of research and practice. The major DSS sub-fields are [48]:

- Personal Decision Support Systems (PDSS): usually small-scale systems that are developed for one manager, or a small number of independent managers, to support a decision task;
- Group Support Systems (GSS): the use of a combination of communication and DSS technologies to facilitate the effective working of groups;
- Negotiation Support Systems (NSS): DSS where the primary focus of the group work is negotiation between opposing parties;
- Intelligent Decision Support Systems (IDSS): the application of artificial intelligence techniques to decision support;
- Knowledge Management-Based DSS (KMDSS): systems that support decision making by aiding knowledge storage, retrieval, transfer and application by supporting individual and organizational memory and inter-group knowledge access;

- Data Warehousing (DW): systems that provide the large-scale data infrastructure for decision support;

- Enterprise Reporting and Analysis Systems: enterprise focused DSS including executive information systems (EIS), business intelligence (BI), and more recently, corporate performance management systems (CPM). BI tools access and analyze data warehouse information using predefined reporting software, query tools, and analysis tools.

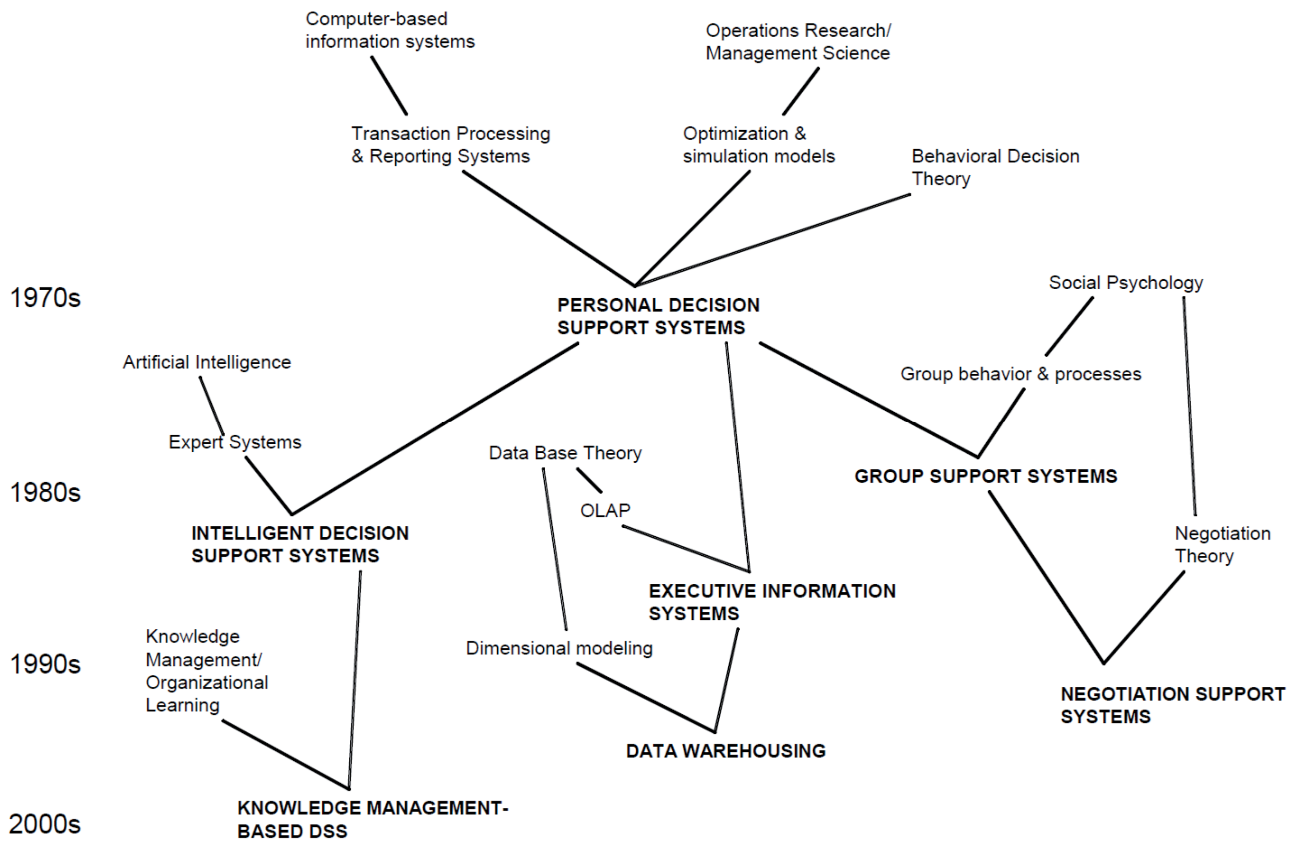


Figure 10 The evolution of the decision support systems field [48]

The following expanded DSS framework, illustrated in Figure 11, helps categorize the most common DSS currently in. Some DSS are integrated or hybrid systems with more than one major DSS subsystem. The framework focuses on one major capability dimension with five categories and three secondary dimensions. The term driver is used as a common or shared descriptive adjective in the expanded framework. Driver refers to the capability, tool or component that is providing the dominant functionality in the DSS. The five categories explained below are communications-driven, data-driven, document-driven, knowledge-driven, and model-driven [47].

- *Communications-Driven and Group DSS* includes communication, collaboration, and decision support. A group DSS is an interactive computer-based system intended to facilitate the solution of problems by decision-makers working together as a group; such systems often derive functionality from a model more than from supporting collaboration and hence are model-driven DSS.

- *Data-Driven DSS* emphasize analysis of data. These systems include file drawer and management reporting systems, data warehousing and analysis systems, executive information systems (EIS), and data-driven spatial decision support systems (SDSS). A data-driven DSS provides access to and manipulation of large databases of structured data and especially a time series of internal company data and external data. Data-driven DSS with online analytical processing (OLAP) provide the highest level of functionality and decision support that is linked to analysis of large collections of historical data.

Dominant DSS component	**User groups: internal, external**	**Purpose: general, specific**	**Enabling technology**
Communications *Communications-driven DSS*	Internal teams, now expanding	Conduct a meeting Bulletin board Help users collaborate	Web or client/server
Database *Data-driven DSS*	Managers, staff, now suppliers	Query a data warehouse	Main frame, client/server, web
Document base *Document-driven DSS*	Specialists and user group is expanding	Search web pages, find documents	Web
Knowledge base *Knowledge-driven DSS*	Internal users, now customers	Management advice, choose products	Client/server, web
Models *Model-driven DSS*	Managers and staff, now customers	Crew scheduling Decision analysis	Stand-alone PC

Figure 11 An expanded DSS framework [47]

- *Document-Driven DSS* is evolving to help managers retrieve and manage unstructured documents and web pages. A document-driven DSS integrates a variety of storage and processing technologies to provide complete document retrieval and analysis. The web provides access to large document databases including databases of hypertext documents, images, sounds, and video. A search engine is a powerful decision-aiding tool associated with a document-driven DSS.

- *Knowledge-Driven DSS* suggest or recommend actions to managers. These DSS have specialized problem solving expertise. The *expertise* consists of knowledge about a particular domain, understanding of problems within that domain, and *skill* at solving some of these problems.

- *Model-driven DSS* includes systems that use accounting and financial models, representational models, and optimization models. Model-driven DSS emphasize access to and manipulation of a quantitative model. Simple statistical and analytical tools provide the most elementary level of functionality. Some OLAP systems that allow complex analysis of data may be classified as hybrid DSS systems providing modeling, data retrieval, and data summarization functionality. Model-driven DSS use data and parameters provided by decision-makers to aid them in analyzing a situation, but they are not usually data intensive. Very large databases are usually not needed for model-driven DSS, but data for a specific analysis may need to be extracted from a large database.

The DSS's in closed-loop PLM systems-scenarios are used to make decisions taking into account the condition of a component in order to choose the best disposal option (reuse, recycle, landfill, or incinerate) in EOL, or modify the maintenance plans in MOL. One of the DSSs was using the information from MOL and EOL phases in design of the product and manufacturing processes. There is not a DSS for evaluation of sustainability. A Closed-Loop Lifecycle Management system containing a DSS configured with the holistic life cycle approach will be an efficient tool to evaluate and improve the sustainability performance of products.

2.3.1 DSSs from the PROMISE Project

PROMISE project aimed to consolidate the information generated during all phases of life by products, that are able to sense and communicate their condition and environment, (closing the lifecycle information loops) and transformed into knowledge in order to support decision making. The former decision support systems which were developed in PROMISE project, had focused on the technical performance of the products or subsystems of the products. Few examples of the decision support systems are given in this section.

- DSS for End-of-life Vehicles: The product information collected from MOL (mission profile information and statistics about the use of the vehicle and components, environmental conditions, temperature in the engine area, history of all maintenance activity and specifically replaced parts and corresponding dates) is used the determine if the components and subsystems worth reusing/remanufacturing.

- DSS for EOL option: Depending on the physical condition (wear state) of the engine components reached to the EOL, product information from MOL, DSS helps to decide that the parts are disposed, re-cycled, re-used or re-manufactured in order to increase whole lifetime of engine components, reduce EOL costs and improve the EOL supply chains (logistics, scheduled orders...).

- DSS for predictive maintenance: DSS evaluates degradation profile of some selected critical components and incipient failures, and informs the user in order to enable condition-based predictive maintenance of the trucks in order to increase in vehicle's availability and decrease in service cost. Condition-based predictive maintenance offers component replacement when required by the level of wear out and due to the real type of usage, and the possibility to organize the “optimal” set of interventions for the incoming coupon, minimizing the total time of truck stop. The Decision Centre requires a computational resource to receive the information, analyze the data, render a diagnosis (whether by automated analysis or expert technician), store and archive the data, and make the data available for a variety of engineering analysis.

- DSS for preventative maintenance: DSS helps make decisions preventive maintenance considering remaining life of the estimated based on physical measures by using new devices attached onto the structures indicating fatigue damage of local points. It enables inspection, reparation and part change could be scheduled to avoid machine downtime and further costs due to failures on structures. BOL improvements (manufacturing & design of structures) where design guidelines will come to light by comparing field results to design criteria.

- DSS for on-site maintenance assistance: When a failure is detected, DSS compares the state of the equipment with similar cases from the PDKM and suggests a number of solution alternatives for the technicians in the field. The designers are also informed about the causes of the failures and possible design changes. The collected data will be gathered into the PDKM system, and further aggregation will be implemented in the DSS. During maintenance procedures technicians on the field will be supported in diagnosis and problem-solving by utilizing the information resides on DSS. Finally, vital information residing on the PDKM and DSS will be available to designers for product improvement efforts.

2.4 Sustainability Assessment

Sustainability/sustainable development has caught a growing interest in the last 20 years and has been a major issue for governments, NGOs and manufacturing industry. Since all these organisations have different agendas and point of views, they have different definitions for sustainability. Afgan et al. presented five different definitions of sustainability.

a) for the World Commission on Environment and Development (Brundtland Commission) “development that meets the needs of the present without compromising the ability of future generation to meet their own needs”,
b) for the Agenda 21, Chapter 35 “development requires taking long-term perspectives, integrating local and regional effects of global change into the development process, and using the best scientific and traditional knowledge available”,

c) for the Council of Academies of Engineering and Technological Sciences (Declaration of the Council Engineering and Technological Sciences 1995) “it means the balancing of economic, social, environmental and technological consideration, as well as the incorporation of a set of ethical values”,
d) for the Earth Chapter (The Earth Chapter 1995) “the protection of the environment is essential for human well-being and the enjoyment of fundamental rights, and as such requires the exercise of corresponding fundamental duties”, and
e) Thomas Jefferson, Sept. 6 1889 (Jenkinson 1987) “then I say the earth belongs to each generation during its course, fully and in its right no generation can contract debts greater than may be paid during the course of its existence”.

As they stated, all five definitions stand for the emphasis of specific aspect of sustainability. Definition (a) and (e) implies that each generation must bequeath enough natural capital to permit future generations to satisfy their needs. Definitions (b) and (c) are more politic ply for the actions to be taken at global, regional and local levels in order to stimulate United Nation, Government and Local Authorities to plan development programs in accordance with the scientific and technological knowledge. In particular it should be noticed in definition (c) the ethic aspect of the future development actions to be taken to meet sustainable development. Definition (d) is based on the religious believes playing the responsibility and duties toward the nature and Earth [49].

Sustainable manufacturing must respond to; economic challenges, by producing wealth and new services ensuring development and competitiveness through time; environmental challenges, by promoting minimal use of natural resources (in particular non-renewable) and managing them in the best possible way while reducing environmental impact; social challenges, by promoting social development and improved quality of life through renewed quality of wealth and jobs [50].

Sustainability helps to create and maintain conditions under which humans can coexist in harmony with nature, while fulfilling economic, social, and other requirements of present and future generations. Sustainability is important for ensuring that we will continue to have all the resources, especially water and materials, to protect human existence, growth, and the environment [51].

The problem of finding a balance between the economic, social, and environmental values of human development is now at the heart of the debate that involves men of culture, men of faith, economists and politicians, who are working together to tackle the problems of globalization. At the center is a reflection of the responsibilities of politics and economics that is related to the imbalance of the world’s social and economic order, putting in danger the ultimate goal for a civil society which is to guarantee an acceptable human condition that may be ‘shared’, starting from the common membership of a network of international relationship that is central to our age [53].

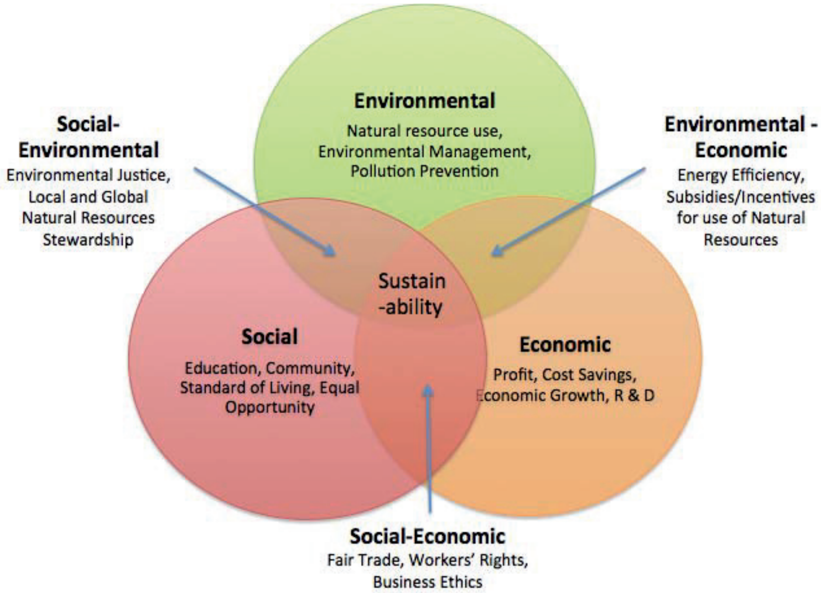


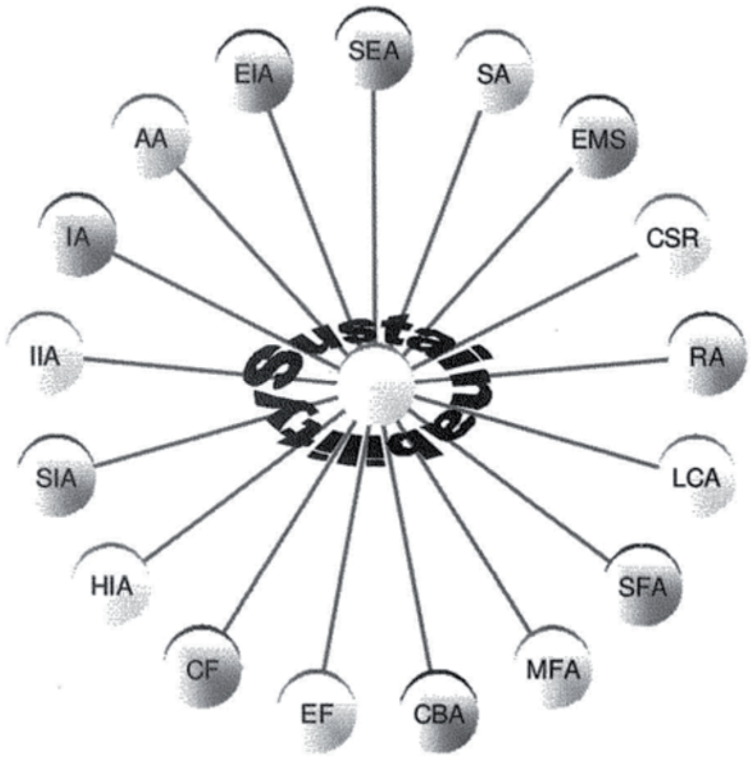
Figure 12 Three spheres of sustainability (triple bottom line) [53]

As discussed before, sustainable development involves the simultaneous pursuit of economic prosperity, environmental quality, and social equity. Therefore, these three main criteria (environmental, social and economic sustainability) were selected to explain the general sustainability issues, shown in Figure 12. In each criterion, there are several key factors, as shown in Table 3 [54]. Specific key sustainability indicators could be identified and generated specific to the stakeholder, industry or product category.

Criterion	Factors
Environmental	Total solid wasted (%)
	Specific energy consumption
	Specific emission rate (mmg)
	Risks and recoverability (%, %)
	Other environmental treats and potential disasters
Social	Employee satisfaction
	Quality of life
	Expenditure on peripheral development
	Diversity & opportunity
	Reputation and visibility
Economic	Gross margin ($)
	Turnover ratio
	Net profit ($)
	Average capital employed
	Total income or revenue; market share ($, %)

Table 3 Key sustainability factors [54]

The concept of sustainable development is charged with complexities as it involves and balances several different goals, content types, approaches, aspirations and desires. If it is to be analyzed and carried out on the basis of a decision-making process, sustainability must be measured. As a multifaceted concept, sustainability requires aggregate measures, based on the integration of the different sustainability domains, that in due course define whether a system is sustainable or not [55]. In order to leverage from the concept of sustainability it is necessary to involve it in decision making process in the supply chain. It is essential to have an evaluation procedure so as to involve it in decision making. Sheate (2009) listed 17 environmental assessment tools and methods which have sustainability as an underlying purpose [56].



EIA	= Environmental impact assessment
SEA	= Strategic environmental assessment
SA	= Sustainability assessment
EMS	= Environmental management system
CSR	= Corporate social responsibility
RA	= Risk assessment
LCA	= Life cycle assessment
SFA	= Substance flow analysis
MFA	= Material flow analysis
CBA	= Cost benefit analysis
EF	= Ecological footprinting
CF	= Carbon footprinting
HIA	= Health impact assessment
SIA	= Social impact assessment
IIA	= Integrated impact assessment
IA	= Impact assessment
AA	= Appropriate assessment

Figure 13 Tools with a common purpose: sustainability [56]

Sustainability assessment is emerging around the world as a key decision-making tool, is best considered an umbrella term encompassing a range of impact assessment practice. Since the whole life cycle of the product should be considered it could also be called life cycle sustainability assessment. The report *Towards a Life Cycle Sustainability Assessment: Making informed choices on products* [57] by the Life Cycle Initiative gives the following description of SLCA:

"Life cycle sustainability assessment (LCSA) refers to the evaluation of all environmental, social and economic negative impacts and benefits in decision-making processes towards more sustainable products throughout their life cycle"

This report provides a comprehensive introduction to the LCSA concept, and can be used as a guideline for decision-maker and others on.

Kloepffer proposed the following scheme for Life cycle Sustainability Assessment (LCSA):

$$LCSA = LCA + E - LCC + \ S - LCA$$

Figure 14 Life cycle sustainability assessment equation

where LCA is the SETAC/ISO environmental Life Cycle Assessment, LCC is an LCA-type ('environmental') Life Cycle Costing assessment and SLCA stands for societal or social Life Cycle Assessment. There are, however, some prerequisites for using this scheme. The most important requirement is that the system boundaries of the three assessments are consistent (ideally identical). This includes, of course, that in LCC the physical (as opposed to the marketing) life cycle is used for modelling the Life Cycle Inventory (LCI). The best solution would be the use of one identical LCI for all three components. It seems, however, that the societal LCI will be much more demanding with regard to regional resolution than LCA and LCC. The reasons the methods have to be life-cycle based is easy to explain and, indeed, involve the same arguments as for LCA, i.e. recognizing and avoiding trade-offs by including the whole life cycle ('cradle-to-grave'). With regard to sustainability, avoiding the shifting of problems into the future is of special importance, due to the request for intergeneration fairness [58].

The following eight points are now safe assertions about the basic insights, at least for the purposes of sustainability assessment [59]:

- Sustainability considerations are comprehensive, including socio-economic as well as biophysical matters, and their interrelations and interdependency over the long term as well as the short term.
- Precaution is needed because human and ecological effects must be addressed as factors in open, dynamic, multi-scalar systems, which are so complex that full description is impossible, prediction of changes uncertain, and surprise likely.
- Minimization of negative effects is not enough; assessment requirements must encourage positive steps towards greater community and ecological sustainability, towards a future that is more viable, pleasant and secure.
- Corrective actions must be woven together to serve multiple objectives and to seek positive feedback in complex systems.
- Sustainability requires recognition both of inviolable limits and of endless opportunities for creative innovation.

- Sustainability is not about balancing, which presumes a focus on compromises and trade-offs. Instead the aim is multiple reinforcing gains. Trade-offs are acceptable only as a last resort when all the other options have been found to be worse

- The notion and pursuit of sustainability are both universal and context-dependent. While a limited set of fundamental, broadly applicable requirements for progress towards sustainability may be identified, many key considerations will be location-specific, dependent on the particulars of local ecosystems, institutional capacities and public preferences.

- In the pursuit of sustainability, the means and ends are intertwined and the process is open-ended. There is no end state to be achieved.

These basic consensus points about sustainability can be translated quite directly into implications for sustainability assessment. Arguably there are four major components [60].The first is that sustainability assessment processes must force decision-makers contemplating potentially significant initiatives to give serious primary attention to sustainability requirements. To do this, the processes must apply decision criteria that establish meeting the core requirements for progress to sustainability as the main test of proposed purposes, options, designs and practices. The processes must put application of these sustainability-based criteria at the center of decision-making, not as one advisory contribution among many.

Second, sustainability assessment must take seriously the obligation to recognize interdependencies and to seek multiple reinforcing gains on all fronts. This is assisted by setting a comprehensive agenda that covers the full suite of core requirements for moving towards sustainability. Yet it is also crucial to establish firm guidance for trade-off decisions, to ensure that sacrifices are made only where there is no viable ‘less bad’ alternative.

Third, sustainability assessment processes must provide means of specifying the sustainability decision criteria and trade-off rules for specific contexts, through informed choices by the relevant parties (stakeholders).

Finally, sustainability assessment processes must apply these insights in the full set of process elements:

- identifying appropriate purposes and options for new or continuing undertakings;
- assessing purposes, options, impacts, mitigation and enhancement possibilities, and so on;
- choosing (or advising decision-makers on) what should or should not be approved and done, and under what conditions; and

- monitoring, learning from the results and making suitable adjustments through implementation to decommissioning or renewal.

The management of trade-offs in sustainability assessment requires good processes that are focused on optimizing sustainability outcomes. Trade-offs are matters of choice. Traditional EIA decision-making permits these choices to be made by decision-makers at the approval stage and traditionally these decisions are taken behind ‘closed doors’. There has long been concern in such impact assessment practice that it is the environment that typically gets traded off for socio-economic benefit in these cases. Gibson et al. have put forward trade-off decision rules designed to ensure that sustainability assessment processes better deal with and account for any sustainability tradeoffs [61]:

1) Net gains: Any acceptable trade-off must deliver net sustainability gains (over the long term).
2) Burden of argument: The proponent of the trade-off must be required to provide justification.
3) Avoidance of significant adverse effects: No trade-off involving significant adverse effect is acceptable unless all alternatives are worse.
4) Protection of the future: No displacement of significant adverse impact from present to future can be justified unless all alternatives are worse.
5) Explicit justification: All trade-offs must be explicitly justified (including a context-specific account of priorities and sustainability decision criteria).
6) Open process: Stakeholders must be involved in trade-off making through open and effective participatory processes.

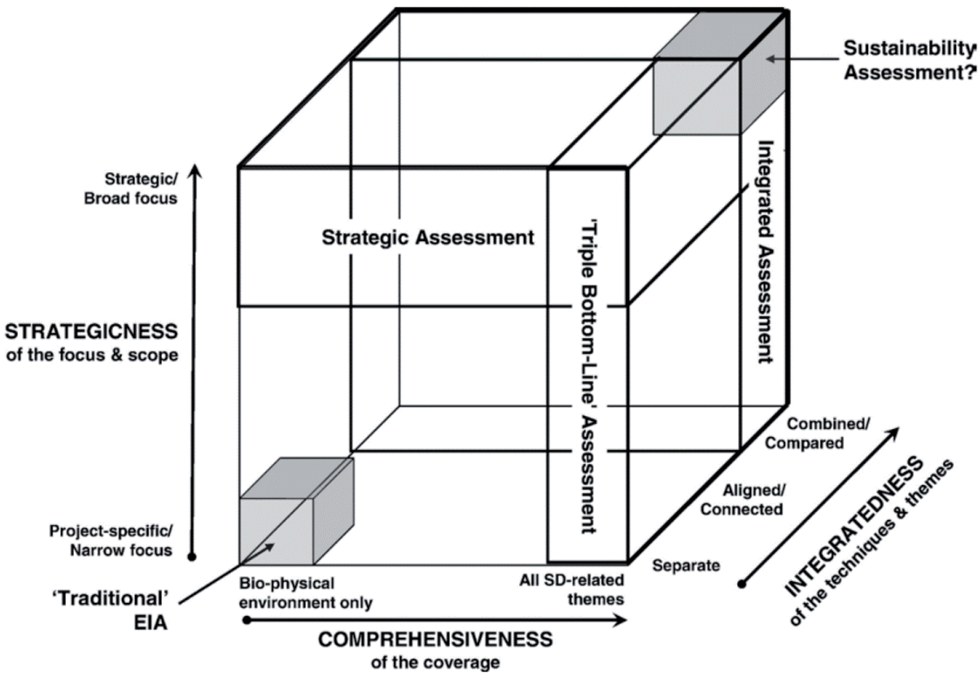


Figure 15 Spectrum of SD-directed features within the assessment process [49]

Figure 15 illustrates the fundamental characteristics of sustainability assessment [62];

- *strategicness* refers to the degree of emphasis on strategy (i.e. the extent to which the focus is broad, considers cumulative effects, is forward-looking, and incorporates intergenerational timescales),
- *integratedness* refers to the extent to which the various assessment techniques used are combined/aligned, and
- c*omprehensiveness* refers to the coverage of issues which, for sustainability assessment, needs to include the three categories or pillars of environmental, social and economic effects as well as indirect effects.

2.5 Life Cycle Assessment

Environmental impact can be defined as "any change to the environment, whether adverse or beneficial, wholly or partially resulting from an organization's activities, products or services" [50]. Traditionally, products were designed and developed without considering their adverse impacts on the environment. Factors considered in product design included function, quality, cost, ergonomics and safety among others. No consideration was given specifically to the environmental aspects of a product throughout its entire life cycle. Since, in developed and modern countries some indices such as sustainability, quality of life, environment and energy have been considered important, finding out how the production of materials and related products, processes and services affect the environment helps sustainable development [65].

The environmental impacts of a product or a service result from substance emissions into the environment and from the consumption of resources, as well as other interventions (e.g. land use) associated with providing goods and services that occur along the process of resource extraction, materials production, product manufacture, use and consumption, and product end-of-life (collection, sorting, reuse, recycling, waste disposal). The awareness of the environmental impacts of the processes associated with extracting, producing, manufacturing and using materials, products and services help to protect the environment. In the past manufacturing firms were concerned with meeting regulations that limited or prohibited the pollution and waste that are generated by manufacturing processes. However, regulations are now focusing on the material content of the products that are sold in an effort to control the substances that enter the waste stream. Organizations that develop new products need to consider many factors related to environmental impact of their products, including government regulations, consumer preferences, and corporate environmental objectives. Although this requires more effort than treating emissions and hazardous waste, it not only protects the environment but also reduces life-cycle costs by decreasing energy use, reducing raw material requirements, and avoiding pollution control. Environmental objectives of an organization are [66]:

1- Comply with legislation: Products that do not comply with a nation's environmental regulations cannot be sold in that nation

2- Avoid liability: Environmental damage caused by a product represents a financial liability.

3- Satisfy customer demand: Some consumers demand environmentally responsible products. Retailers, in turn, pass along these requirements to manufacturers.

4- Participate in eco-labeling programs: Products that meet requirements for eco-labeling are more marketable

5- Enhance profitability: Certain environmentally friendly choices such as remanufacturing, recycling and reducing material use make good business sense and have financial benefits

6- Behave ethically: Being a good steward of the planet's resources by considering the environment during the product development process is the right thing to do.

One of the greatest difficulties in an attempt to reduce the negative impact that a generic activity has on the environment is that of evaluating this impact qualitatively or quantitatively, so as to be then able to undertake appropriate initiatives to contain it. Although the methodologies developed for the evaluation of environmental impact (Environmental Impact Assessment—EIA) are numerous and differ in their identification, measurement and interpretation of the impact, they generally have some significant limitations in common [67]:

- They were developed in relation to specific cases.
- They do not include the possibility of assessing the reliability and stability of the results.
- They do not start from the premise of the life cycle approach in line with the ideas expressed in previous chapters.

Many approaches to environmental protection continue to be based on "end-of-pipe" solutions that focus on a single medium (e.g., air, water, or soil), a single stage in the product's life cycle (e.g., production, use, or disposal), or a single issue (e.g., individual chemical limits). Such strategies do not always lead to a net environmental benefit. Environmental laws and regulations that have a single focus often force the use of pollution control resources in ways that are not optimal for reducing overall impacts. By attempting to solve a single environmental problem without considering the interconnectivity of natural systems, designed legislation, although intended for a specific purpose, has often created additional, unexpected or unintended consequences. Because single-issue approaches are often not designed with a systematic understanding of the trade-offs and their implications, they often diminish opportunities for achieving net environmental improvements [68].

As environmental awareness increases, industries and businesses are assessing how their activities affect the environment. Society has become concerned about the issues of natural resource depletion and environmental degradation. Many businesses have responded to this awareness by providing "greener" products and using "greener" processes. The environmental performance of products and processes has become a key issue, which is why some companies are investigating ways to minimize their effects on the environment. Many companies have found it advantageous to explore ways of moving *beyond* compliance using pollution prevention strategies and environmental management systems to improve their environmental performance. [69].

Life cycle assessment has been defined as;

- a technical, data-based and holistic approach to define and subsequently reduce the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and material usage and waste discharges, assessing the impact of those wastes on the environment, and evaluating and implementing opportunities to effect environmental improvements [70], and
- a tool to assess the potential environmental impacts and resources used throughout a product's lifecycle, i.e., from raw material acquisition, via production and use phases, to waste management [71].

Life cycle assessment is a "cradle-to-grave" approach for assessing industrial systems. "Cradle-to-grave" begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. The unique feature of LCA is the focus on products in a life-cycle perspective. The comprehensive scope of LCA is useful in order to avoid problem-shifting, for example, from one phase of the life-cycle to another, from one region to another, or from one environmental problem to another. The analysis of both consuming raw materials and energy used in these processes and the outputs; products and emissions to the air, water and soil is an approach to evaluate the environmental impacts called life cycle assessment so that in this methodology the production and consumption are considered as the two sides of a single coin as a Cradle to Grave model. This kind of evaluation is performed since without addressing environmental impacts from the entire life cycle of a product, even for the product design, one cannot resolve the environmental problems causing from the production and consumption of the product [65].

By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product and process selection. Thus LCAs are useful in quantifying environmental impact and comparing various process routes for the same product, comparing improvement options for a given product, designing new products, and choosing between comparable products [72].

When conducting an LCA, the design/development phase is usually excluded, since it is often assumed not to contribute significantly. However, one has to note that the decisions in the design/development phase highly influence the environmental impacts in the other life cycle stages. The design of a product strongly predetermines its behavior in the subsequent phases (e.g., the design of an automobile more or less determines the fuel consumption and emissions per kilometer driven in the use phase and has a high influence on the feasible recycling options in the end-of-life phase). Figure 16 illustrates this interdependency between design/development and the other phases of the life cycle. Therefore, if the aim of an LCA is the improvement of goods and services, one of the most important LCA applications, then the study should be carried out as early in the design process as possible and concurrent to the other design procedures. This applies analogously to the design or improvement of a process within a life cycle of a product, especially if interactions with other processes or life cycle stages can occur [73].

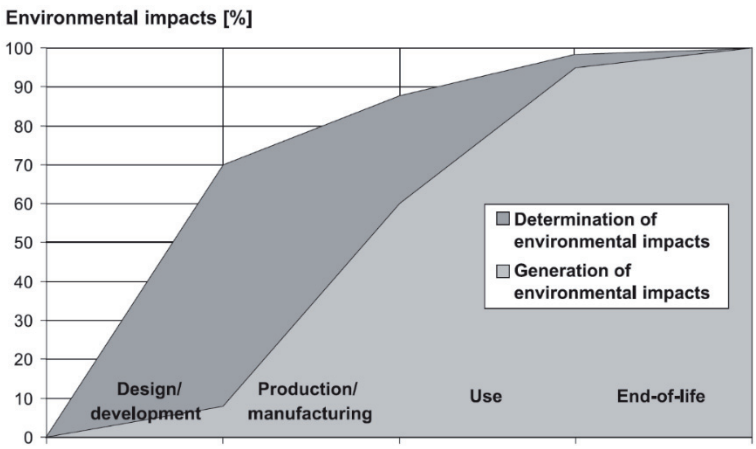


Figure 16 Generalized representation of the (pre)determination and the generation of environmental impacts in a product's life cycle [73].

Two different LCA approaches, attributional LCA (ALCA) and consequential LCA (CLCA), were identified and described. ALCA describes the pollution and resource flows within a chosen system attributed to the delivery of a specified amount of the functional unit. CLCA estimates how pollution and resource flows within a system change in response to a change in output of the functional unit. When performing an LCA, in most cases, multifunctional processes are included in the analyzed system. Choices of how to handle co-products, therefore, are inevitably connected with performing an LCA. The distinction between ALCA and CLCA was developed in the process of resolving the methodological debates over allocation problems and the choice of data. A strong connection, therefore, exists between the choice of ALCA and CLCA and the choice of how to handle co-products. Within ALCA, avoiding allocation by using system expansion to handle co-products is optional, while coproduct allocation is most frequently used. Avoiding allocation by system expansion, however, is the only way to deal with co-products within CLCA, as it reflects the consequences of a change in production [74].

The identification of design alternatives that best satisfy environmental demands requires the use of instruments able to quantify the environmental performance of the product under development and guide the ameliorative measures. Moreover, only a systematic vision of the product over its life cycle can ensure that these measures reduce the environmental criticalities and so avoid simply transferring impacts from one phase of the life cycle to another. Life Cycle Assessment (LCA) is an objective procedure used to evaluate the environmental impacts associated with a product's entire life cycle, through the quantitative determination of all the exchange flows between the product-system and the ecosphere in all the transformation processes involved, from the extraction of raw materials to their return into the ecosphere in the form of waste [75].

A complete LCA is structured in four main stages, illustrated in Figure 17:

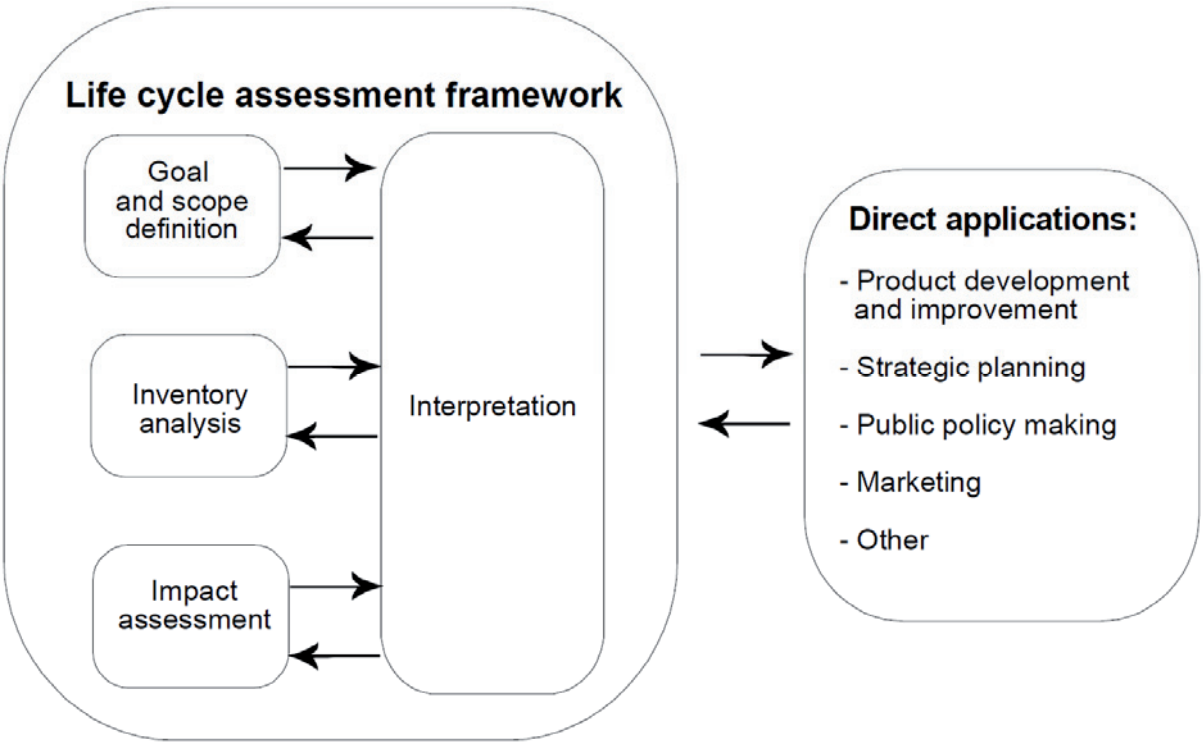


Figure 17 Phases of a life cycle assessment

1- Goal and Scope Definition

The objectives of the analysis and the set of preliminary assumptions according to which it will be conducted are defined in this first phase. This requires the definition of the evaluation typology (aimed at system improvement or comparing alternative systems); the boundaries of the system under examination; the reference functional unit, assumptions, and parameters for inventory and allocation operations; and the categories of impact to be considered [71].

- *“Goal and scope”* stands for the objectives and range of an LCA must be clearly defined and coherent with the intended application. An explicit statement of the purposes of the study is, therefore, essential.
- *“Functional unit”* is a reference unit of measurement used to treat and present the data and information of an LCA. According to the norm, a functional unit constitutes “a measure of the performance of the functional outputs of the product system.” The main aim of the definition of the functional unit is to provide a reference unit to which input and output flows can be correlated.
- *System boundaries* determine which unit processes shall be included within the LCA. A first delimitation is obtained by taking into consideration the physical environments and production processes. It is then possible to exclude those components found to be largely irrelevant or difficult to represent in detail. It is clear, therefore, that the domain of application of an LCA is highly subjective and essentially depends on the intended depth of analysis.

2- Inventory Analysis

The inventory analysis phase includes the compilation and quantification of the inputs and outputs of the entire life cycle. The typical inputs and outputs of a product system are shown in Figure 18. The data can be obtained from various sources such as direct measurement as well as information from databases and the literature [56]. The aim of the inventory is to provide objective data which only later can be elaborated and interpreted to obtain evaluations useful at the decision-making stage.

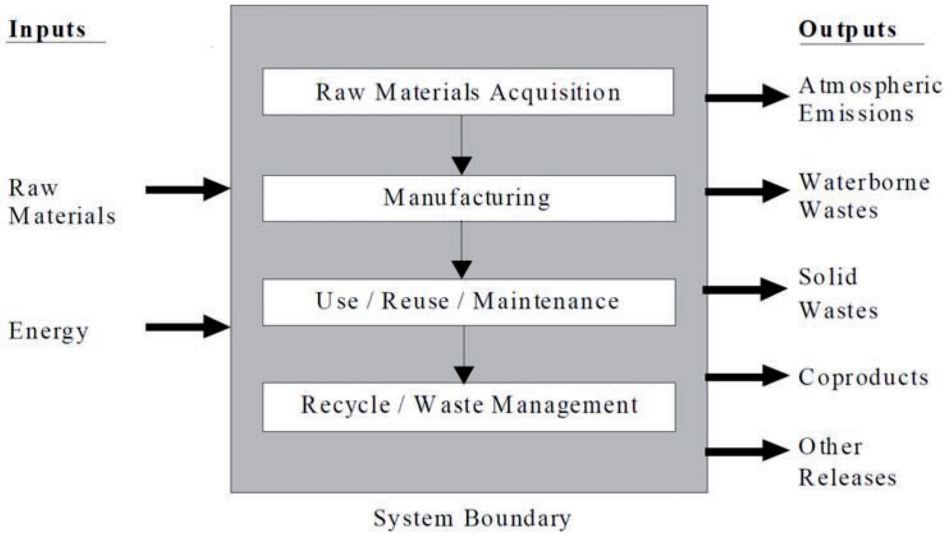


Figure 18 Typical inputs and outputs of a product system [56]

The main steps of inventory analysis are [71]:

- *"Modeling product system"* consists of developing a schematic model in sufficient detail to represent the system of operations performing the process in question. The degree of detail is determined in each case on the basis of the aims of the LCA, and the complexity and difficulty of the measurements that can be made on the system components.

- *"Data collection"* involves the quantitative and qualitative description of the inputs and outputs needed to determine where the process starts and ends, and the function of the unit process. This is achieved using appositely prepared records. The data in question are classified as "primary data," acquired through direct measurement, and "secondary data," derived data generally obtained from the literature.

- *"Allocation procedure"* defines how the materials and energy flows as well as associated environmental releases shall be allocated to the different products of a company since the real industrial processes rarely produce just one output. The procedures of allocation allow energetic and environmental charges to be associated with the various coproducts and byproducts of individual processes. Through these associations it is possible to undertake the study of complex systems using energy and environmental indices summarizing their behavior.

3- Life Cycle Impact Assessment (LCIA)

LCIA constitutes the phase of LCA where the inventory data are translated into potential environmental impacts, evaluating their size and significance [70]. LCIA is directed at the evaluation of environmental impact, revealing the magnitude of the effects produced as a consequence of the consumption of resources and the emissions that result from the entire life cycle. The difficulty of assessment lies in identifying the correlation existing between the operations performed during the life cycle and the effects of these operations on the environment. The environmental effects (greenhouse effect, reduction of the ozone layer, acid rain, eutrophication, photochemical smog, toxicity, impoverishment of resources, etc.) are subdivided into local, regional, or global effects and are understood in terms of impact categories (i.e., classes of impact "representing environmental issues of concern to which LCI results may be assigned"). LCIA is structured in different stages, some obligatory and others optional. The obligatory stages are [71]:

- *"Selection"* consists of choosing the environmental effects to be taken into consideration and the corresponding environmental indicators representing these effects.
- *"Classification"* consists of cataloging the inventory data, correlating it with different environmental effects, and thus associating it with the various impact categories.
- *"Characterization"* is aimed at quantitatively determining the value of environmental indicators (category indicator) relating to the various impact categories. The calculation consists of converting the results of the LCI into common units and aggregating the converted results according to the impact category.
- *"Normalization, Grouping, and Weighting"* consist of elaborating the results of the characterization phase to obtain indices used to perform an overall evaluation of the process under examination. The methods of normalization and weighting are varied and not standardized - each refers to different parameters, often linked to artificial and debatable considerations.

Life cycle impact assessment methods are revised in the end of this section.

4- Interpretation (ISO) or Improvement Analysis (SETAC)

In this final phase, the results of the LCA or LCIA are evaluated in relation to the planned objectives in order to formulate final considerations and directives for improvement [56]. This phase of LCA provides for the interpretation of the data obtained in the preceding phases and, on the basis of this data, identifying the actions to be undertaken with the aim of lessening the environmental impact of the system. The approach is iterative in the sense that, after having modified the process, it is necessary to repeat the LCA to verify that the modification has improved, not worsened, the situation. This phase is usually understood as a step where it is possible to create a valid correlation between the results of inventory analysis and those of impact analysis in order to propose useful recommendations conforming to the aims and objectives of the study. This procedure is highly subjective and the ISO 14043 standard itself advises that the data obtained in the previous phases must be organized in a clear and understandable manner in order to provide useful indications for the unambiguous planning of any intervention of improvement [71].

An LCA can help decision-makers select the product or process that results in the least impact to the environment. This information can be used with other factors, such as cost and performance data to select a product or process. LCA allows a decision-makers to study an entire product system hence avoiding the sub-optimization that could result if only a single process were the focus of the study. This ability to track and document shifts in environmental impacts can help decision makers and managers fully characterize the environmental trade-offs associated with product or process alternatives. By performing an LCA, analysts can;

- develop a systematic evaluation of the environmental consequences associated with a given product,
- analyze the environmental trade-offs associated with one or more specific products/processes to help gain stakeholder (state, community, etc.) acceptance for a planned action,
- quantify environmental releases to air, water, and land in relation to each life cycle stage and/or major contributing process,
- assist in identifying significant shifts in environmental impacts between life cycle stages and environmental media,
- assess the human and ecological effects of material consumption and environmental releases to the local community, region, and world,
- compare the health and ecological impacts between two or more rival products/processes or identify the impacts of a specific product or process, and
- identify impacts to one or more specific environmental areas of concern [70].

Performing an LCA can be resource and time intensive. Depending upon how thorough an LCA the user wishes to conduct, gathering the data can be problematic, and the availability of data can greatly impact the accuracy of the final results. Therefore, it is important to weigh the availability of data, the time necessary to conduct the study, and the financial resources required against the projected benefits of the LCA. LCA will not determine which product or process is the most cost effective or works the best. Therefore, the information developed in an LCA study should be used as one component of a more comprehensive decision process assessing the trade-offs with cost and performance, e.g., Life Cycle Management.

As mentioned earlier, an LCA can help identify potential environmental tradeoffs. However, converting the impact results to a single score requires the use of value judgments, which must be applied by the commissioner of the study or the modeler. This can be done in different ways such as through the use of an expert panel, but it cannot be done based solely on natural science [70].

LCAs are costly and time-consuming because they are inherently complex and data intensive, subject to technological change, and dependent on data which often are proprietary and inaccessible to nonindustrial researchers. Without these data, the researcher conducting an LCA for public use must rely on public data sources. And it is necessary to distinguish carefully between industry and government perspectives on LCAs. Within a firm, LCAs are often used to target opportunities for reducing pollutants for which the firm is responsible under federal and state air, water, and waste regulations. In other words, the system boundaries for the firm may be defined by those pollutants and damages which enter its cost calculus. These, however, represent only a fraction of the total pollutant load-and universe of impacts-that a social accounting might encompass. This distinction is an important one and should be forthrightly discussed in presenting the results of an LCA, along with the many other assumptions underpinning the analysis [76].

The LCIA method determines the output that will be achieved from the Life cycle assessment. LCIA methods aim to connect, as far as possible, each life cycle inventory (LCI) to its potential environmental damages, on the basis of impact pathways (impact pathways are composed of environmental processes like a product system consists of economic processes). According to ISO, LCI results are classified in impact categories and the category indicator can be located at any place between the LCI-results (interventions) and the category endpoint. Based on this format, two main schools of methods developed:

- Classical impact assessment methods (e.g. CML , EDIP) which stop quantitative modeling relatively early in the cause-effect chain to limit uncertainties and group LCI results in what we call here midpoint categories, according to common themes: i.e. common mechanisms (e.g. climate change-global warming) or commonly accepted grouping (ecotoxicity).

- Damage oriented methods such as Eco-indicator 99 or EPS, which try to enhance relevance by modeling (sometimes with high uncertainties) the cause-effect chain up to the endpoint or damage [77].

The LCIA method should be chosen in a way that the desired environmental performance characteristics could be generated. Some of the life cycle impact assessment methodologies are presented in Table 4.

LCIA Method	Definition
CML 2001	It restricts quantitative modelling to early stages in the cause-effect chain to limit uncertainties. Results are grouped in midpoint categories according to common mechanisms (e.g. climate change) or commonly accepted groupings (e.g. ecotoxicity).
Eco-Indicator 99	The product's environmental impacts are evaluated by a damage model and a weighting similar to the LCA. The damages to the resources, the ecosystem and human health are taken into account within the estimation.
EDIP 97/2003/2007	It is a damage oriented LCIA methodology developed by Danish Environmental Protection Agency.
LIME (ILCD)	The Lime method has been developed in Japan, with is an intended purpose of developing lists of midpoint, endpoint and weighting reflecting the environmental conditions of Japan.
IMPACT 2002+	Will be described later in the dissertation.
LUCAS (ILCD)	It was developed with the goal of providing a methodology adapted to the Canadian context. It is based on existing characterization models from existing LCIA methodologies such as TRACI and IMPACT 2002+, which are re-parameterized and further developed to better assess Canadian life cycle inventories.
ReCiPe (ILCD)	It is an LCIA method that is harmonized in terms of modelling principles and choices, offering results at both the midpoint and endpoint level.
Ecological Scarcity Method	It permits impact assessment of life cycle inventories according to the "distance to target" principle. It compares the existing flow of a substance with the critical flow defined by political targets. Eco-factors, expressed as eco-points per unit of pollutant emission or resource extraction, are the key parameter used by the method.
TRACI	It is developed by US EPA with the focus of determining and developing impact assessment tool for life cycle impact assessment, pollution prevention, and sustainability metrics for the US. The methodology has been developed specifically for the US using input parameters consistent with US locations.
MEEuP (ILCD)	I was developed to evaluate whether and to which extent various energy-using products (EuPs) fulfil certain criteria that make them eligible for CE labelling. The method also is intended to support eco-design in general.
EcoSense (ILCD)	It is an integrated atmospheric dispersion and exposure assessment model which implements the impact pathway approach. Additionally, it models impacts on man-made materials and resources.
Ecological footprint	The methodology is defined as the sum of time integrated direct land occupation and indirect land occupation, related to nuclear energy use and to CO2 emissions from fossil energy use, clinker production.
USEtox	It is an environmental model for characterization of human and ecotoxicological impacts in Life Cycle Impact Assessment (LCIA) and Comparative Risk Assessment (CRA).It is designed to describe the fate, exposure and effects of chemicals, and to improve understanding and management of chemicals in the global environment.
EPS 2000	The Environmental Priority Strategy in product design (EPS) is an environmental-accounting method, which describes impacts to the environment as impacts to specific safeguards subjects: diversity, production, human health, resources, and aesthetic values.
Cumulative energy demand	It indicates environmental hazards based on the energy consumption within the analyzed system, and states the entire demand, valued as primary energy, which arises in connection with the production, use and disposal of an economic good.
Cumulative exergy demand	It is introduced to depict total exergy removal from nature to provide a product, summing up the exergy of all resources required. It assesses the quality of energy demand and includes the exergy of energy carriers as well as of non-energetic materials.

Table 4 Life cycle impact assessment methods [78-79]

2.6 Life Cycle Costing

Cost is a crucial factor that contributes to the success of production and delivery of functional needs, especially within today's highly competitive market. To survive and thrive against competition, companies are increasingly required to improve their quality, flexibility, product variety and novelty, while consistently reducing the costs. In short, customers expect higher quality at an ever-decreasing cost. Companies that are unable to provide detailed and meaningful cost estimates at the early development phases have a significantly higher percentage of programs behind schedule and with higher development costs than those that can provide completed cost estimates [80].

Tougher statutory regulations (e.g. Directive on End-of-Life Vehicles and Directive on Waste Electrical and Electronic Equipment) and changing market requirements force companies to deal thoroughly with the recycling and disposal of their products. The directives and rules mentioned above aim at expanding the traditional role of the manufacturers and holding them responsible for the disposal of post-consumer products. This approach concerns the anticipated profit and cost of an organization as well as its assessment of risks and opportunities. Producers are to develop concepts for the design and manufacture of products which ensure a maximum life span and – at the end of a product's life cycle – allow employing the most efficient recycling or disposal method. Extending the producer responsibility raises questions of how to optimally allocate costs and revenues from development, manufacture, use and recycling [79].

The combination of inflation, cost growth, reduction in purchasing power, budget limitations, increased competition, and related factors has created an awareness and interest in the total cost of products, systems, and structures. Not only are the acquisition costs associated with new systems rising, but the costs of operating and maintaining systems already in use are also increasing. This is due primarily to a combination of inflation and cost growth factors traceable to the following [82]:

1. Unsatisfactory quality of products, systems, and structures in use
2. Engineering changes mandated during design and development
3. Changing suppliers in the procurement of system components
4. System production and/or construction changes
5. Changes in logistic support capability
6. Estimating and forecasting errors
7. Unforeseen events and problems

The current economic situation is further complicated by some additional problems related to the actual determination of system and/or product cost. Some of these are listed below [82].

Total system cost is not fully visible, particularly those costs associated with operation and support. The cost visibility problem is due to an “iceberg” effect, as is illustrated in Figure 19.

- Individual cost factors are often improperly applied. Costs are identified and frequently included in the wrong category: variable costs are treated as fixed (and vice versa), indirect costs are treated as direct costs, and so on.
- Existing accounting procedures do not always permit a realistic and timely assessment of total cost. In addition, it is often difficult (if not impossible) to determine costs on a functional basis.
- Budgeting practices are often inflexible regarding the shift in funds from one category to another, or from year to year, to facilitate cost improvements in system acquisition and utilization.

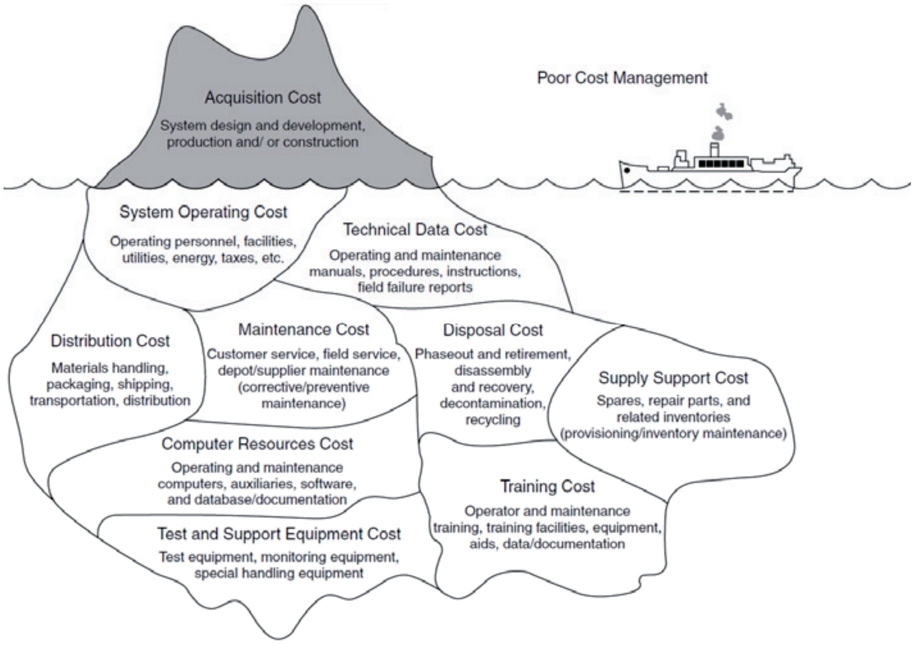


Figure 19 The problem of total cost visibility [82]

Life cycle costing’s most important use is in product analysis where costs expected over the asset's life are large relative to the purchase and installation costs. Factors of particular relevance are length of life and maintenance and operation costs. Initial cost will probably dominate for a short-lived asset while post-purchase costs will be more significant for long-lived assets. Where economies on maintenance and operation costs can be effected, LCC (life-cycle costing) can clearly demonstrate the savings [83].

The primary cause of the increased emphasis on life- cycle costing has been inflation, in particular, the escalation of energy prices. Expected rising costs of labor, materials, oil, and other operating and maintenance elements give greater weight to post-purchase cost estimates. The result is that life-cycle costing, which allows for both categories of costs, is becoming an essential evaluative technique.

The term life-cycle costing is not yet a part of the vocabulary of the average citizen, but as the concept becomes better understood it will have an enormous impact on the buying and selling of industrial goods and services. As buyers integrate factors such as operating and maintenance costs and length of service into their purchasing decisions through LCC analysis, suppliers will be forced to consider these factors in product development, pricing, and marketing decisions. Some firms are already fully aware of LCC and utilize it in planning, buying, and selling, but widespread use of it has yet to be realized. In a society that is becoming increasingly cost-conscious and intolerant of inflation , suppliers who choose to ignore life-cycle costing risk negative economic consequences [84].

Most businesses, if not all, live by buying something, adding some value to it, and then selling it for a higher price to someone. The organization cashes in the difference between the price charged and the costs incurred as a profit. Whereas the price is given in the marketplace and is ideally a function of supply and demand, the incurred costs are a result of a series of decisions throughout the organization that started long before the product was even conceived. This chain of decisions leads to costs being committed before they are incurred. Managing costs effectively and efficiently thus implies that costs must be eliminated in the commitment stage and not reduced in the incurring stage. Many organizations realize this, but is few practice it. The costing methods employed by most companies simply do not take such notions into account as they embark on cost cutting. This happens for many reasons, but it might simply be a matter of bad habits or because we dislike to learn new things unless the consequences of not learning are worse than those of learning. The points argued so far are illustrated in Figure 20. It shows that although about only 20 percent of the costs are actually incurred in the activities prior to production, these activities actually commit 80 percent of the costs. The production costs, however, incur about 80 percent of the costs, but production improvement efforts impact only about 20 percent of the cost commitment. This has been a well-known fact for many years. In fact, LCC came about in the early 1960s due to similar understanding concerning weapons systems procurement in the U.S. Department of Defense [85].

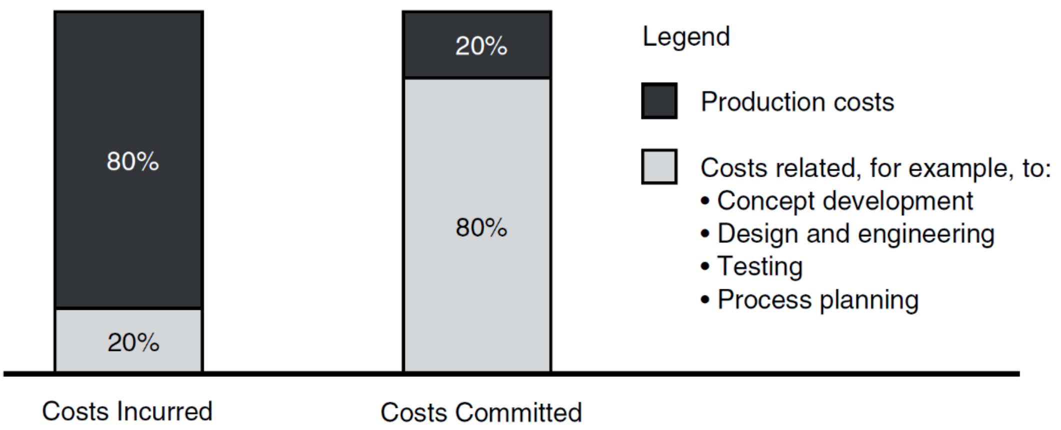


Figure 20 Cost committed versus costs incurred [85].

Value is defined as proportionate to the satisfaction of needs divided by the use of resources. In other words, value is proportionate to quality divided by costs. Value-driven organizations must therefore be both quality driven and cost conscious, something traditional management systems simply cannot deliver. On top of that, despite the fact that traditional cost management systems are partially designed to satisfy external needs for reporting, they have completely missed the concept of shareholder value and its measure of economic profit, or Economic Value Added (EVA). One such change in performance measures is to expand the horizon of the cost management efforts from the four walls of the company to the relevant parts of the life cycle where value is created and to employ foresight instead of hindsight. In this context, LCC can play a far greater role than traditionally thought [85].

The discipline of economics plays a key role in life cycle costing because, to calculate the life cycle cost of items, various types of economics-related information are required. Life cycle costing requires that all potential costs be calculated by taking into consideration the time value of money. In modern society, interest and inflation rates are utilized to take into consideration the time value of money. In life cycle costing, future costs, such as operation and maintenance costs associated with an item, have to be discounted to their present values before adding them to the item's acquisition or procurement cost. Over the years, many formulas have been developed in the area of economics for converting money from one point of time to another. Such formulas are considered indispensable in life cycle costing [86].

Life cycle costing (LCC) is concerned with optimizing the trade-off among all costs, which are attributable to a product from conception to those customers incur throughout the life of the product, including the costs of planning, design, testing, installation, production, marketing operation, support, maintenance and EOL treatment, to find the minimum lifecycle cost of the product. However excellent a product may be environmentally, it would not come into wide use in the economy to realize its environmental load reducing potential unless it is also economically affordable. LCC is a tool to assess the cost of a product over its entire life cycle, and can be regarded as an economic counterpart of Life Cycle Assessment (LCA). [87].

In general, costs over the life cycle fall into categories based on organizational activity needed to bring a system into being. These categories and their constituent elements constitute a cost breakdown structure (CBS), as illustrated in Figure 21. The main CBS categories are as follows:

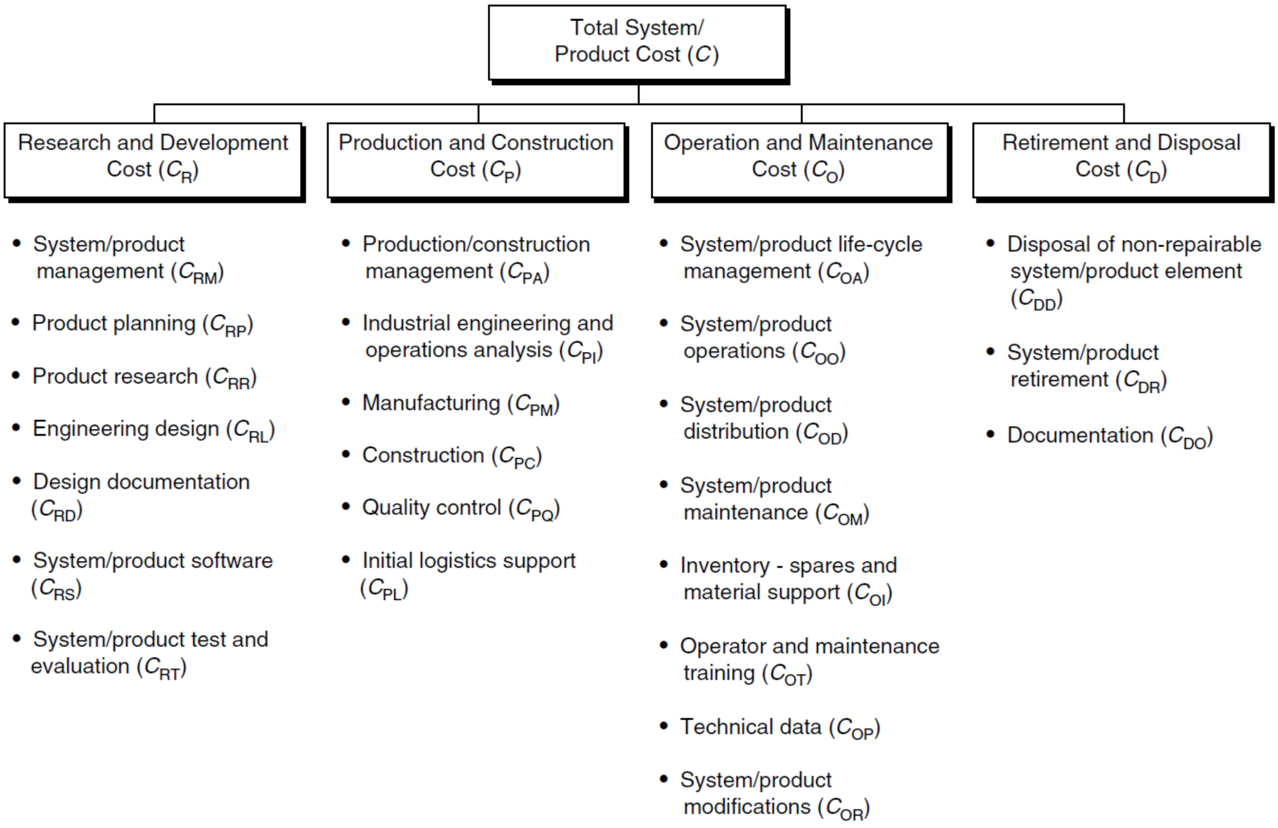


Figure 21 A general cost breakdown structure [68]

- Research and development cost. Initial planning, market analysis, feasibility studies, product research, requirements analysis, engineering design, design data and documentation, software, testing and evaluation of engineering models, and associated management functions.

- Production and construction cost. Industrial engineering and operations analysis, manufacturing (fabrication, assembly, and test), facility construction, process development, production operations, quality control, and initial logistic support requirements (e.g., initial customer support, the manufacture of spare parts, the production of test and support equipment, etc.).

- Operation and support cost. Customer or user operation of the system or product in the field, product distribution (marketing and sales, transportation, and traffic management), and sustaining maintenance and logistic support throughout the system or product life cycle (e.g., customer service, maintenance activities, supply support, test and support equipment, transportation and handling, technical data, facilities, system modifications, etc.).

- Retirement and disposal cost. Disposal of non-repairable items throughout the life cycle, system/ product retirement, material recycling, and applicable logistic support requirements.

The cost breakdown structure links objectives and activities with organizational resource requirements. It constitutes a logical subdivision of cost by functional activity area, major system elements, and/or one or more discrete classes of common or like items. The CBS provides a means for initial resource allocation, cost monitoring, and cost control [82].

Once the cost element and the structure is determined, cost estimation should be carried out for each cost element. Figure 22 shows the classification of cost estimation approaches. Niazi et al. classified cost estimation methods into qualitative and quantitative. Qualitative cost estimation techniques are primarily based on a comparison analysis of a new product with the products that have been manufactured previously in order to identify the similarities in the new one. Quantitative techniques, on the other hand, are based on a detailed analysis of a product design, its features, and corresponding manufacturing processes instead of simply relying on the past data or knowledge of an estimator [88].

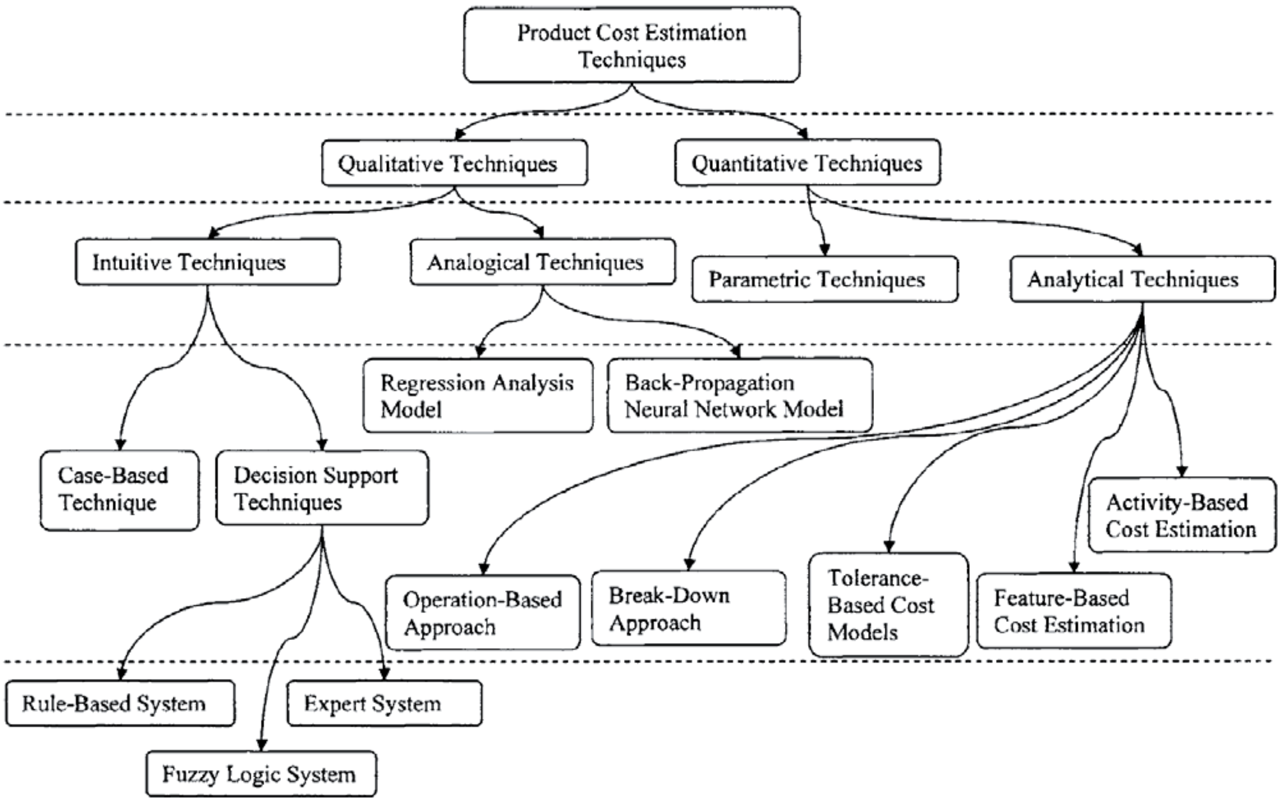


Figure 22 Classification of the product cost estimation techniques [82]

LCC is the total cost over a product's life cycle span, it includes design cost, manufacturing cost, operating cost and disposal cost. Other terminologies for LCC are WLC (whole life cost) and through-life cost. Nowadays, companies are more concerned to prepare LCC estimates of a product from its conception until the end of its life. This is emphasized by the shift in industrial business processes which have moved from delivering spares and parts to total care packages through the whole lifetime of a product [80]. LCC serves mainly three purposes today;

1. to be an effective engineering tool for use in design, procurement, and so on, which was the original intent,

2. to be applied proactively in cost accounting and management, and

3. to be a design and engineering tool for environmental purposes.

Nonetheless, the three purposes have a common denominator, which is the role of LCC to provide insight in future matters regarding all costs. Furthermore, since the future is always associated with uncertainty and risks, truly proactive cost management should also handle all sorts of risks that can incur losses to the organization. Such risks are commonly referred to as business risks and have become a new focal point of corporate governance. Knowing the life cycle costs and the trade-offs through the life cycle of the products decision makers may lower the risk of their actions [84].

Life cycle costing is increasingly being used in the industrial sector around the world to make various types of decisions that directly or indirectly concern engineering equipment and systems. There could be many reasons for this upward trend, such as, competition, increasing operation and maintenance costs, budget limitations, expensive products or systems (e.g., military systems, space systems, and aircraft), rising inflation; and increasing awareness of cost effectiveness among product, equipment, and system users [85].

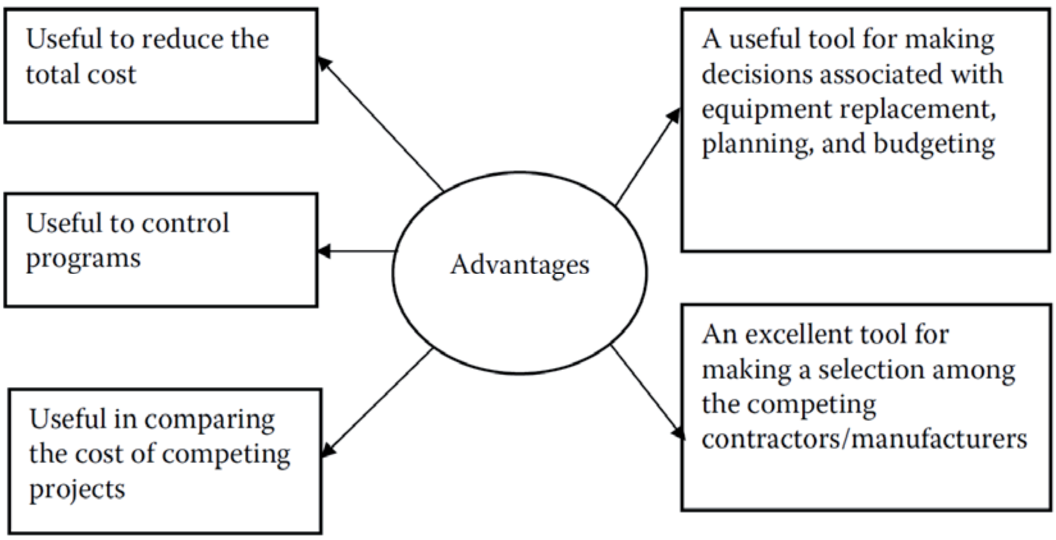


Figure 23 Life cycle costing advantages [89].

Over the years, various advantages and disadvantages of life cycle costing have been identified by various professionals. Some of the important advantages of life cycle costing are shown in Figure 23. In contrast, some of the main disadvantages of life cycle costing include that it is time consuming, costly, has doubtful data accuracy, and is a trying task when attempting to obtain data for analysis [89].

LCC concepts are resurging. LCC limitations are accepted as normal restrictions on every engineering tool. Usefulness has been demonstrated by passing the test of time with practitioners who have learned how to minimize LCC limitations. As with all cost techniques (and typical of all engineering tools) the limitations can result in substantial setbacks when judgment is not used. Here are some of the most often cited LCC limitations [90]:

- LCC is not an exact science, everyone gets different answers and the answers are neither wrong nor right - only reasonable or unreasonable. LCC experts do not exist because the subjects are too broad and too deep.
- LCC outputs are only estimates and can never be more accurate that the inputs and the intervals used for the estimates—this is particularly true for cost-risk analysis.
- LCC estimates lack accuracy. Errors in accuracy are difficult to measure as the variances obtained by statistical methods are often large.
- LCC models operate with limited cost databases and the cost of acquiring data in the operating and support areas is both difficult to obtain and expensive to acquire.
- LCC cost models must be calibrated to be highly useful.
- LCC models require volumes of data and often only a few handfuls of data exist—and most of the available data is suspect.
- LCC requires a scenario for: how the money expenditure model will be constructed for acquisition of equipment, how the model will age with use, how damage will occur, how learning curves for repairs and replacements will occur, how cost processors will function (design costs, labor costs, material costs, parts consumption, spare parts costs, shipping costs, scheduled and unscheduled maintenance costs) for each time period, how many years the model will survive, how many units will be produced/sold, and similar details required for building cost scenarios—most details require extensive extrapolations and obtaining facts is difficult.
- LCC models (by sellers) and cost-of-ownership (COO) models (by end-users) have credibility gaps caused by using different values in each model. Often credibility issues center on which is right and which is wrong (a win-lose issue) rather than harmonizing both models (for a win-win effort) using available data. · LCC results are not good budgeting tools. They're effective only as comparison/trade-off tools and producing good LCC results requires a project team approach because specialized expertise is needed.
- LCC should be an integral part of the design and support process to design for the lowest long term cost of ownership. End users can use LCC for affordability studies, source selection studies of competing systems, warranty pricing and cost effectiveness studies. Suppliers find LCC useful for identifying costs drivers and ranking the comparison of competing designs and support approaches.

Various types of information are required to perform life cycle costing studies. These include the acquisition cost of the item, the useful operational life of the item in years, the annual maintenance cost of the item, transportation (delivery) and installation costs of the item, discount and escalation rates, the annual operating cost of the item, taxes (e.g., tax benefits from depreciation, investment tax credit), and the salvage value or disposal cost of the item. Life cycle costing can be used in a large number of areas; selecting among competing bidders for a project, long-range planning and budgeting, controlling an ongoing project, comparing competing projects, deciding the replacement of aging equipment, and comparing logistics concepts. To be more specific LCC could be applied to ; determining cost drivers, forecasting future budget needs, selecting the most effective procurement strategy, improving comprehension of fundamental design-related parameters in equipment or system product design and development, formulating contractor incentives, making strategic decisions and design trade-offs, optimizing appropriate training needs, choosing among options, providing effective objectives for program control, assessing new technology application, and carrying out source selections [89].

2.7 Social Life Cycle Assessment

All over the world, companies make business decisions every day which affect people and environment, directly through their own operations, or indirectly through the value chain of their business. Increasingly, these companies are confronted with questions, e.g. from customers, consumer organisations and other NGOs, regarding their social performance. In several cases, which have reached the media, large multinational corporations have been held responsible for poor working conditions, not only in their own facilities, but also at their suppliers. Society's expectations to companies to assume a wider responsibility for the social impacts of their business activities is a challenge that has been accepted by companies that wish to conduct business in a more responsible way. Many companies, thus, see themselves in need of a tool which can help them make informed decisions about their social impacts throughout the life cycle of their products [91].

With increasing consumers’ awareness on consumers’ protection and rights, many companies (be it local or international) are often queried on the impacts the product has on people’s wellbeing within their own facilities or at the level of their suppliers (i.e. from cradle to grave). Companies failing to respond to these growing queries in the competitive market have often been tagged with ill images. These remarks have not only tarnished the image of the companies but have also resulted in considerable losses (Hauschild et al. 2008) in the corporate or companies’ turn over. Consequently, companies have recognized the urgency to conduct business in a socially responsible manner, where they undertake to care for the people affected by their business activities and at the same time be able to compete and make profit in order to survive in the marketplace [92].

In the last few decades, ethics in business activities has become part of the wider concept of corporate social responsibility (CSR), which is developing from a good idea to a critical part of business activity. CSR has become important in terms of consumers' perceptions, so it has become important for all consumer-oriented firms. CSR is a broader concept and not limited to supply chains, but to the companies' overall treatment of human beings and the environment. Although CSR is a well-established concept, there is no general consensus on the meaning of CSR in practice. This is a major problem considering companies' differences in size, products, profitability, resources, societal impacts, etc. Another factor contributing to the confusion about the nature of CSR is the large number of concepts used to describe largely the same phenomenon. Academics, consultants and corporate executives have provided various definitions to business's engagement in ethical issues. Among the concepts that have been used - apart from CSR - are sustainable development, corporate citizenship, sustainable entrepreneurship, the triple bottom line, and business ethics [93].

The technical system produces many effects (positive and negative) upon human well-being, which are experienced as social impacts by stakeholders (for instance, workers, consumers, local society, etc.) involved in the life cycle. Assigning these effects to one functional unit highlights the balance between the advantages (the units of service provided) and often the drawbacks (for example, quantities of health destroyed).Social impact refers to consequences caused by activities corresponding to various stakeholders. As far as social impacts are concerned, the consequences may be derived from three dimensions: behaviors (specific behavior/ decision) social-economic processes (the socio- economic decision e.g. investment decision) and capitals (human, social, cultural context) [94].

Social sustainability sees the development of society as a way of ensuring the participation of all members of society. This involves creating a balance between social forces with a view to achieving a livable society that is sustainable in the long term. As regards training, this means, for example, offering equal opportunities when it comes to accessing learning content irrespective of the geographical location of individual members of society. Manufacturing processes in mass production require workers who have an elementary education and need additional customized training programmes that are independent of specific manufacturers and products [95].

Social impacts are consequences of positive or negative pressures on social endpoints (i.e. well-being of stakeholders). Social impacts are understood by these Guidelines to be consequences of social relations (interactions) weaved in the context of an activity (production, consumption or disposal) and/or engendered by it and/or by preventive or reinforcing actions taken by stakeholders (ex. enforcing safety measures in a facility). When referring to the causes of social impacts, this generally implies three dimensions [96]:

- behaviors: social impacts are those caused by a specific behavior (decision). E.g. forbidding employees to form unions, allowing illegal child labor, and seizing employees' identity papers.
- socio-economic processes: social impacts are the downstream effect of socio-economic decisions. The question arises "What is chosen, both at the macro and micro level?" E.g. an investment decision in a sector to build infrastructure in a community.
- capitals: (human, social, cultural): social impacts relate to the original context (attributes possessed by an individual, a group, a society e.g., education level). They can either be positive or negative. For example the human capital might suffer from a high percentage of individuals being HIV positive. In this case a negative social impact may strike harder in this specific context or a positive may be of higher value.

Those three dimensions are not exclusive and have dynamic relationships: socio-economic processes have effects on behavior that may also be rooted in the attributes possessed by an individual or a group. For example, pressure for low prices (socio-economic processes) may draw suppliers to allow illegal child labor (behavior), a practice that may be accepted in a given society because of systemic poverty (capital) [96].

The methods available for working with social aspects in the supply chain include stand-alone tools as well as guidelines and standards. The difference between tools and standards are not clear-cut, and either or could be used as point of departure for improved social performance. The most established method is social impact assessment, but as the focus on social impacts within business (and within society at large) has increased over the last few years, so has the number of methods for assessing, reporting and improving performance with regard to these impacts. Below, the most important methods are presented in order of appearance [97].

1- *Social Impact Assessment*

Social Impact Assessment (SIA) was developed in the late 1970s along with environmental impact assessment (EIA). The two processes have a lot in common and the distinction between the two is not clear cut. Both are processes for identifying potential impacts of proposed actions, policies, programmes or projects. Not just identifying, but also monitoring and managing the impacts is often included in the process. For EIA the focus is on environmental impacts and for SIA on social impacts. SIA is an umbrella or overarching framework that encompasses all human impacts including aesthetic (landscape analysis), archaeological and heritage, community, cultural, demographic, development, economic and fiscal, gender, health, indigenous rights, infrastructure, institutional, political (human rights, governance, democratization etc.), poverty-related, psychological, resource issues (access and ownership of resources), the impacts of tourism and other impacts on societies. SIA is not limited to a narrow or restrictive understanding of the concept 'social'.

2- Social Accountability 8000 Standard

In 1997, the Social Accountability International (SAI) was formed as a non-governmental, multi- stakeholder organization with a mission to advance the human rights of workers around the world. The organization set up an international, expert, multi-stakeholder advisory board with which it cooperates continuously on standard development and revision, and other tasks within its field of operation. The International Standard Social Accountability 8000 (SA 8000) was first published in 1997 and revised in 2001 and 2008 (Social Accountability International 2008). The purpose of the SA8000 standard is to provide a standard based on international human rights norms and national labor laws that will protect and empower all personnel within a company's scope of control and influence, who produce products or provide services for that company, including personnel employed by the company itself, as well as by its suppliers/subcontractors, sub-suppliers, and home workers.

3- The Global Reporting Initiative

The possibly most widespread, or at least most visible, approach to corporate sustainability is sustainability reporting. The GRI Guidelines are very explicit on the recommendations of indicators and on how a sustainability report is constructed. Concerning exactly how information on the various indicators is to be retrieved, the guidelines are not very detailed, but give, for each category of indicators, ideas of potential information sources. For the social indictors these recommendations include documentation collected through quality management systems and from various departments of the reporting organization (e.g. customer relations, R&D departments, and legal, sales and marketing departments), local or central collective agreements, employee contracts, minutes of occupational health and safety committees, employee and attendance records, and results from external stakeholder forums and community programmes.

4- UN Global Compact

The UN Global Compact was launched in 2000 and was in 2009 the world's largest global corporate responsibility initiative, with more than 5.000 participants, including over 3.600 businesses in 100 countries. The UN Global Compact is a call to businesses around the world to align their strategies and operations with ten principles in the areas of human rights, labor, environment and anti-corruption, and to support the broader UN goals, like the Millennium Development Goals. It's an open and multi- stakeholder voluntary initiative. Signatories are monitored in order to avoid superficial commitment to the principles. The UN Global Compact model is a 6-step process; (1) commit, public leadership commitment; (2) assess, assessment of risks, opportunities and impacts across issue areas; (3) define, development of strategies, goals, metrics and policies; (4) implement, adjustment to core processes, education, capacity building, supply chain work; (5) measure, monitoring and analysis of performance metrics developed in earlier steps; (6) communicate, engagement with stakeholders.

5- Social Life Cycle Assessment of Products

In 2009, the UNEP/SETAC Life Cycle Initiative published their guidelines for social life cycle assessment (S-LCA) of products. Environmental lifecycle assessment (E-LCA) and LCC has been well developed and standardized in order to assess the environmental and economic aspects of the products. The new guidelines on S-LCA are meant to widen the scope of LCA so that the method becomes one of sustainability assessment, i.e. all three dimensions of sustainable development are captured, as in the triple bottom line concept. In the guidelines, S-LCA is described as distinct from social impact assessment (SIA) in two major ways. First, S-LCA, unlike both SIA and E-LCA, works with data at the enterprise management level per se. Labor practices are given as an example of such data. Secondly, the guidelines state that S- LCA is specifically adapted to life cycles of products, and therefore, unlike other tools and methods, takes the supply chain into consideration, rather than just the enterprise or facility. However, as shown in this report, also other tools and methods can be applied for supply chain work. S-LCA is systemic and systematic in its approach to assessing impacts, which makes it (theoretically) well apt for application on supply chains. The major differences between S-LCA and E- LCA are mainly a consequence of the different kind of data handled in the two methods; i.e. qualitative versus quantitative data.

6- ISO 26000: Guidance for social responsibility

In 2010 the International Organization for Standardization (ISO), published the voluntary international standard ISO 26000, Guidance on social responsibility. The aim of ISO 26000 is to assist public and private organizations in contributing to sustainable development and to encourage them to act proactively, i.e. to go beyond legal compliance. The standard leans on 7 principles of social responsibility; accountability, transparency, ethical behavior, respect for stakeholder interests, respect for the rule of law, respect for international norms of behavior, and respect for human rights. The standard is not meant to replace other assessment methods and initiatives, but to complement them. The standard guides the organization trough a number of steps towards (increased) social responsibility. The first step is to consider the characteristics of social responsibility and its relationship with sustainable development. The next step is for the organization to integrate social responsibility throughout its decisions and activities.

A social and socio-economic Life Cycle Assessment (S-LCA) is a social impact (and potential impact) assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle encompassing extraction and processing of raw materials; manufacturing; distribution; use; re-use; maintenance; recycling; and final disposal. S-LCA allows increasing knowledge, providing information for decision makers and promoting improvement of social conditions in product life cycles [96].

S-LCA does not have the goal nor pretends to provide information on the question of whether a product should be produced or not. S-LCA documents the product utility but does not have the ability nor the function to inform decision making at that level. It is correct that information on the social conditions of production, use and disposal may provide elements for thoughts on the topic, but will, in itself, seldom be a sufficient basis for decision. S-LCA is a technique that helps inform incremental improvements but does not in itself provide a breakthrough solution for sustainable consumption and sustainable living. Those topics go well beyond the scope of the tool. S-LCA provides information on social and socio-economic aspects for decision making, instigating dialogue on the social and socio-economic aspects of production and consumption, in the prospect to improve performance of organizations and ultimately the well-being of stakeholders [98].

One important feature to be emphasized is that social impact is not directly linked to the production chain process of a product, it is not determined by physical flows, unlike the E-LCA, but from the way it interacts with the stakeholders. Therefore, the identification of all stakeholders involved on the product/service life cycle is a fundamental issue when performing an S-LCA [94].

S-LCA is best used for increasing knowledge, informing choices, and promoting improvement of social conditions in product life cycles. S-LCA can be used to identify, learn about, communicate, and report social impacts; set up strategies and action plans; and inform management policies and purchasing practices. S-LCA documents the product utility but does not have the ability or the function to inform decision making at the level of whether or not a product should be produced.

Three types of indicators reported in the literature namely, quantitative, semi quantitative, and qualitative. In 'The Guidelines', qualitative indicators are defined as: "…nominative: they provide information on a particular issue using words. For instance text describing the measures taken by an enterprise to manage stress." Quantitative indicators are described as: "…a description of the issue assessed using numbers: for example number of accidents by unit process." Semi-quantitative indicators are described as: "…indicators that have results expressed into a yes/no form or a scale (scoring system): for example, presence of a stress management programme (yes/no). Qualitative and quantitative indicator results may be translated into semi-quantitative form" [89].

S-LCA follows the ISO 14044 framework, as environmental LCA, definition of the goal and scope, life cycle inventory analysis, life cycle impact assessment, and interpretation and reporting. Table 5 shows the differences between social and environmental LCA.

Phase of the study	Characteristics
Goal and scope	The product utility is required to be described in functional terms, both in E-LCA and S-LCA. S-LCA goes further by also requiring that practitioners consider the social impacts of the product use phase and function. Whereas E-LCA encourages involvement of stakeholders (beyond the commissioners) in the peer review of the study, S-LCA encourages that such "external" stakeholders be involved in providing input on impacts, within the assessment itself. In S-LCA, justification needs to be presented when a subcategory is not included in the study. In E-LCA this is not a requirement. The subcategories are classified both by stakeholder categories and by impact categories in S-LCA. In E-LCA they are classified only by impacts categories. Whereas both E-LCA and S-LCA impact assessment methods may be sensitive to location, no E-LCA LCIA methods are site-specific, and E-LCA methods often define and use categories of location types that depend on physical factors such as geography type or population density. S-LCA may require site-specific LCIA in some cases, and may also need information about "political" attributes, such as the country and its laws.
Life Cycle Inventory	The activity variables29 data is collected and used more often in S-LCA than in E-LCA (e.g. number of working hours for estimating the share of each unit process in the product system). In E-LCA, activity variables are used when data about impacts is not available. The subjective data is sometimes in S-LCA the most appropriate information to use. Bypassing subjective data in favor of more "objective" data would introduce greater uncertainty in the results, not less. The balance between quantitative, qualitative and semi-quantitative data will generally be different. The data sources will differ (coming from stakeholders). The data collection steps and methods vary (e.g. the irrelevance of mass balances).
Life Cycle Impact	The characterization models are different. The use of performance reference points is specific to S-LCA, e.g. thresholds. S-LCA encounters both positive and negative impacts of the product life cycle, beneficial impacts in E-LCA seldom occur.
Interpretation	The significant issues will differ. The addition of information on the level of engagement of stakeholders in S-LCA.

Table 5 Differences between S-LCA and E-LCA [92]

The most obvious difference between E-LCA and S-LCA is the focus. While the former is concerned with the evaluation of environmental impacts, the latter aims to assess social and socio-economic impacts. While, an E-LCA will mainly focus on collecting information on (mostly) physical quantities related to the product and its production/use and disposal, an S-LCA will collect additional information on organization related aspects along the chain. Figure 3 illustrates the specificities of the techniques.

Subcategories are the basis of an S-LCA assessment because they are the items on which justification of inclusion or exclusion needs to be provided. The subcategories are socially significant themes or attributes. Subcategories are classified according to stakeholder and impact categories and are assessed by the use of inventory indicators, measured by unit of measurement (or variable). Several inventory indicators and units of measurement/reporting types may be used to assess each of the subcategories. Inventory indicators and units of measurement may vary depending of the context of the study. Social/socio-economic subcategories may be first classified by stakeholder categories as this might assist with the operationalization. It can also ensure the comprehensiveness of the framework. The purpose of the classification into impact categories is to support the identification of stakeholders, to classify subcategory indicators within groups that have the same impacts, and to support further impact assessment and interpretation. The impact categories should preferably reflect internationally recognized categorizations/standards (like the UN declaration on economic, social and cultural rights - ECOSOC, standards for multinationals) and/or result from a multi-stakeholder process. The following figure illustrates the assessment reference framework.

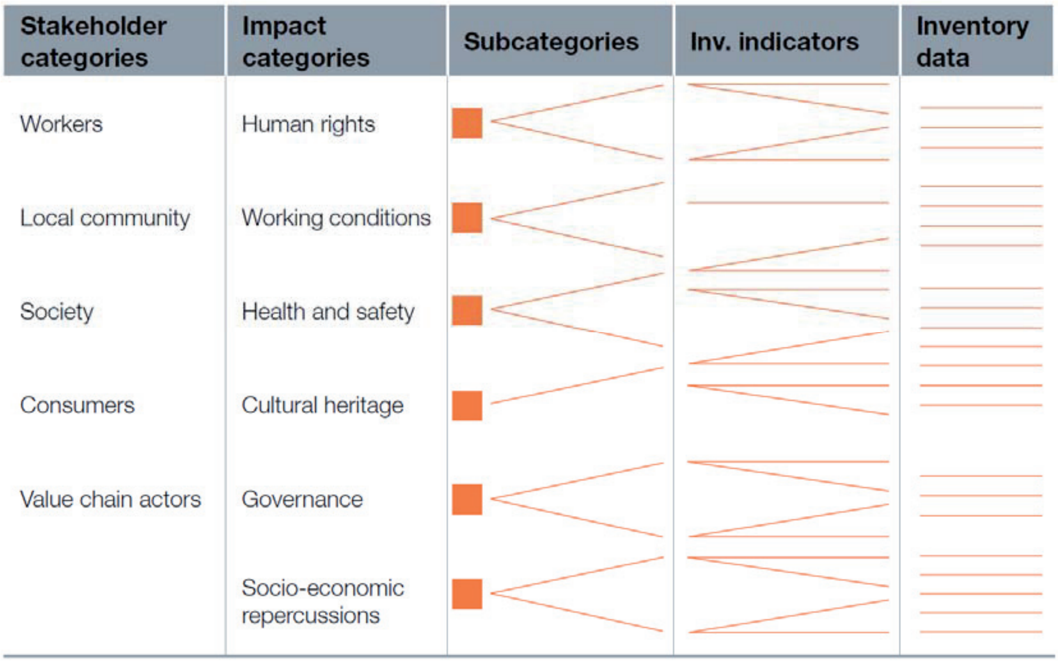


Figure 24 Assessment system from categories to unit of measurement [92]

The life cycle phases of a product (and their unit processes) can be associated with geographic locations, where one or more of these processes are carried out (mines, factories, roads, rails, harbors, shops, offices, recycling-firms, disposal-sites). At each of these geographic locations, social and socio-economic impacts may be observed in five main stakeholder categories;

- Workers/employees;
- Local community;
- Society (national and global);
- Consumers (covering end-consumers as well as the consumers who are part of each step of the supply chain) and
- Value chain actors

A stakeholder category is a cluster of stakeholders that are expected to have shared interests due to their similar relationship to the investigated product systems. The stakeholder categories provide a comprehensive basis for the articulation of the subcategories. The proposed stakeholder categories are deemed to be the main group categories potentially impacted by the life cycle of a product.

Stakeholder categories	Subcategories
Stakeholder “worker”	Freedom of association and collective bargaining Child labor Fair salary Working hours Forced labor Equal opportunities/discrimination Health and safety Social benefits/social security
Stakeholder “consumer”	Health & safety Feedback mechanism Consumer privacy Transparency End of life responsibility
Stakeholder “local community”	Access to material resources Access to immaterial resources Delocalization and migration Cultural heritage Safe & healthy living conditions Respect of indigenous rights Community engagement Local employment Secure living conditions
Stakeholder “society”	Public commitments to sustainability issues Contribution to economic development Prevention & mitigation of armed conflicts Technology development Corruption
Value chain actors* not including consumers	Fair competition Promoting social responsibility Supplier relationships Respect of intellectual property rights

Table 6 Stakeholder categories and subcategories [92]

With regard to the impacts and indicators it should be remembered that for good reasons there is also no definite list in LCIA. The main problems in SLCA seem to be the following:

- How to relate quantitatively the existing indicators to the functional unit of the system
- How to obtain specific data for the (necessarily) regionalized SLCA
- How to decide between many indicators (most of them qualitative) or a few ones that can be quantified, e.g. via the LCI labor hours per functional unit
- How to quantify all impacts properly and evaluate the results

The quantification of the indicators may be the most difficult problem and, indeed, the quantification of all environmental impacts in LCA has not been possible either [92].

Chapter 3 Holistic Life Cycle Approach

This chapter represents the holistic life cycle approach methodology, gives a general overview of the methodology and lists the requirements. The steps of the evaluation procedure are defined. And finally, performance characteristics and a conceptual Closed-loop Lifecycle Management system are explained in detail in this section.

3.1 Introduction

In spite the fact that technical issues and economics are the main driver in products design, it is also important to consider environmental and social attributes of the products for sustainability. Sustainability has often been thought as related only to the environmental impact of the product. As mentioned before, sustainability has three pillars, environmental, economic and social. Reducing the environmental impact of a product might also reduce the costs and improve the social well-being of the stakeholders. Unfortunately this might not be true in all cases, and should not be predicted unless an evaluation is made.

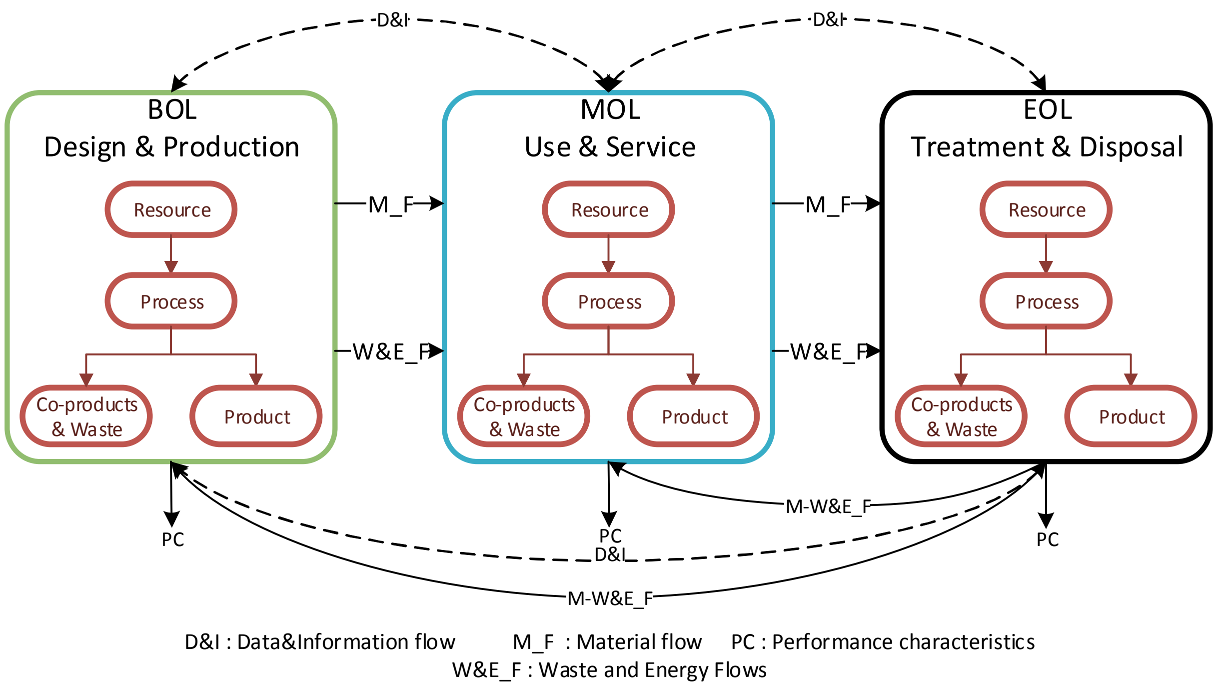


Figure 25 Holistic life cycle approach

Sustainability has been in the focus of the companies for some time. However, it is essential to note that companies which are into sustainable development or sustainability have to accommodate the concept in their decision making. Decision making involves risks. Decision support systems help decision makers make informed decision. DSSs o help to reduce the risks of decision making by providing information regarding a complex subject. In order to make decision based on sustainability, a DSS covering all aspects of sustainability (the whole life cycle and triple bottom line) is required.

Holistic life cycle approach (HLA), depicted in Figure 24, takes into account the whole life span of the product and provide a broader perspective to all activities of the product or processes through determining material, waste, energy, and data/information flows, and generating performance characteristics across all phases of the lifecycle. HLA requires collection of the life cycle data through the whole life cycle (BOL, MOL and EOL), generation and distribution of the performance characteristics (technical, environmental, economic and social) of the products. A Closed-loop Lifecycle Management system has all necessary components in order to collect life cycle data, transform it to performance characteristics and distribute them to related life cycle actors. HLA may be considered as a sustainability evaluation procedure which also provides information concerning the technical aspects of the product, processes and stakeholders.

3.2 Proposed Methodology

The proposed procedure for holistic life cycle approach is illustrated in Figure 26. It should be noted that the proposed approach is consistent with the life cycle assessment (LCA) framework, and it is extended to encompass life cycle costing (LCC) and social life cycle assessment (S-LCA). LCA, LCC and S-LCA methodologies combined in the evaluation procedure and technical performance characteristics are obtained from the life cycled actors. Combination of LCA, LCC and S-LCA has been proposed by Kloepfer as life cycle sustainability assessment [58]. However there is not a clear definition of the procedure and application of the methodology. In order to combine the mentioned assessment methodologies, the same life cycle inventory and same system boundaries is used. S-LCA is different than LCA and LCC, because S-LCA evaluates the performance of the life cycle actors, where LCA and LCC evaluates the performance of all processes and activities of life cycle actors. Secondly, the system boundaries of S-LCA is wider than LCA and LCC, where it is necessary to cover the actors of the value chain and the stakeholders (local community, NGOs, customers, and etc.) that are affected by the product.

The methodologies combined in HLA are better to compare alternative scenarios than making a descriptive assessment. Alternative scenarios are generated and compared in order to measure the distance between current and alternative situations. The evaluation is carried out based on the function of the product or process. The value chain of the products and the life cycle actors are determined in order to draw the system boundaries and specify the data sources for data collection. Life cycle inventory for evaluation is generated by defining the material and information flows. The inputs and outputs of the defined system, and the information necessary for the life cycle actors to accomplish their business activities and the feedback required for appraising their activities are defined in this step. The life cycle data is collected and DSS transforms the life cycle data into performance characteristics which is then transferred to the corresponding life cycle actor in order to inform them concerning their contribution to overall sustainability of the product. The proposed methodology benefits from the comprehensiveness of the life cycle thinking and integrates the tools for evaluation of all aspects of sustainability. The steps of holistic life cycle approach are defined below.

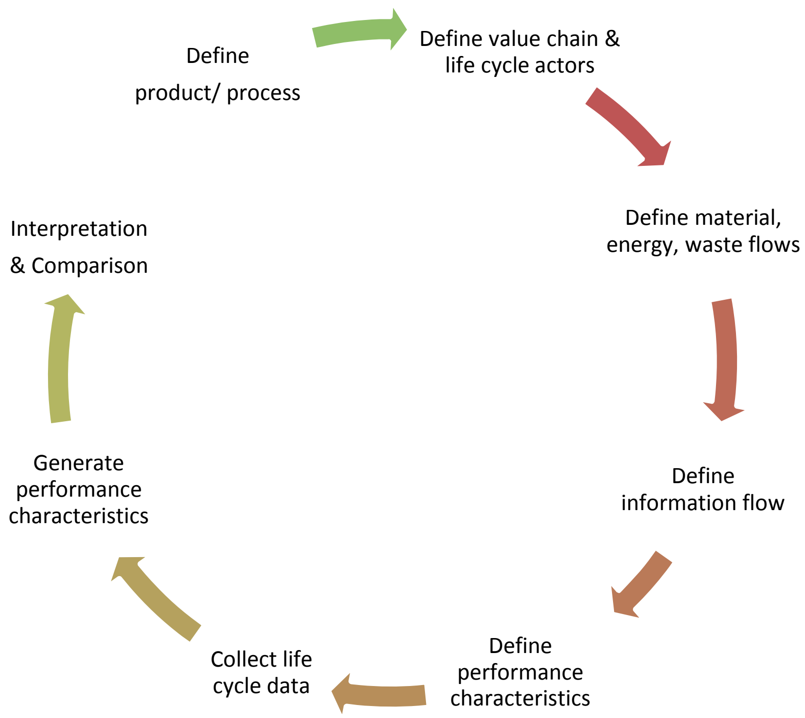


Figure 26 Holistic life cycle approach procedure

1st step: Determine the product/process

The evaluation is carried on based on the function of the product or process. The product and its function should be defined and specified in order to indicate essential technical characteristics and desired future alterations that will be made. However the outputs may vary, the function of the alternatives should be identical. This step is consistent with the goal and scope definition in life cycle assessment. The goal and scope definition of an LCA provides a description of the product system in terms of the system boundaries and a functional unit. Functional unit defines what precisely is being studied and quantifies the service delivered by the product system, providing a reference to which the inputs and outputs can be related. Further, the functional unit is an important basis that enables alternative goods, or services, to be compared and analysed [100]. The intended application of the evaluation is specified and clearly defined. A requirement analysis is performed in which most of the technical requirements (performance characteristics) are defined in this step.

2nd step: Define the value chain and all related stakeholders

It is necessary to distinguish value chain from supply chain. Supply chain concerns with collection of supplies for production and distribution of the product, on the other side value chain consists of series of activities that create and build value. Value is created in sequential steps by a set of distinct firms through the life cycle of the product. All the activities that develop competitive advantage, and life cycle actors related to these activities should be described in detail. The geographic location of the life cycle actors are also important. Additionally, all the stakeholders that are affected positively and negatively through the life cycle should be identified. The system boundaries for evaluation is defined in this step. The system boundaries help to determine the involved and excluded activities in the assessments. The system boundaries should be defined as large as possible in order to cover all important processes, and not too large, it is necessary not to go too deep that would not be possible to complete the assessment.

3rd step: Define material, energy and waste flows

A material flow analysis is performed in this step. Material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined in space and time. It connects the sources, the pathways, and the intermediate and final sinks of a material. An MFA delivers a complete and consistent set of information about all flows and stocks of a particular material within a system. Through balancing inputs and outputs, the flows of wastes and environmental loadings become visible, and their sources can be identified [101]. The material flow documents not only the materials and chemicals, but also energy used, and products, co-products, emissions and wastes produced in each stage of the life cycle of the product [102]. When material flow defined all important processes, production routes and the inputs and outputs should be documented.

The methodologies used in holistic life cycle approach are better and more meaningful to be used in comparison of alternative scenarios rather than calculating the performance of the product itself. A number of scenarios are defined in this step to make comparison. The model for LCA and LCC is defined according to the scenarios and the life cycle data necessary for the assessment is defined here.

4th step: Define information flows

In general, information is typically processed (or generated) in a certain sequence. This is referred to as the information flow [103]. Product lifecycle information has the following characteristics. Information flow;

- occurs when lifecycle information generated at the past period are changed or referred to by lifecycle actors,
- has closed-loops, and is horizontally and vertically closed,
- is accumulated and transformed, and
- is initiated by business drivers and used in appropriate information system [104].

Most of the information flow among the life cycle actors is transactional information flow which is necessary for the companies to retain their businesses. The information flow is the definition of source and content of information that will be used in evaluation and the feedback information that is necessary for the life cycle actors defined in the value chain. The feedback information that would be sent to the life cycle actors are the performance characteristics which indicate the success of the product or their contribution to the whole life cycle of the product.

5th step: Define performance characteristics

The performance characteristics indicate the success of the product, process or life cycle actor. The performance characteristics may differ depending on the purpose of the evaluation. This also determines the impact assessment methods to be chosen for the evaluation methodologies and the data to be gathered. Technical, environmental, economic and social performance characteristics are generated and compared in the proposed approach. More detailed information about performance characteristics is given in the next section.

6th step: Collect life cycle data

The most critical step is to collect life cycle data, which will be done through the closed loop PLM system and the PEIDs attached to the products. Ideally, a closed-loop PLM system is in charge of collecting life cycle information and providing feedback (performance characteristics) to involved partners. Most of the time generic or average data is used for assessment. Employing closed loop PLM system and the PEIDs might help to make a product based and real-time assessment of the product. The more detailed data is collected the more comprehensive the evaluation will be.

7th step: Generate the performance characteristics

The final step is to generate the performance characteristics and make the evaluation. Decision support system in the conceptual closed loop PLM system contains three separate (technical, environmental and economic and social evaluation) plugins for evaluation. These plugins enable to combine LCA, LCC and S-

LCA methodologies and additionally technical performance characteristics are obtained from the life cycled actors.

8th step: Interpretation and comparison

Finally, the results of the evaluation should be interpreted in order to validate the gathered data and find out if there are any irregularities. Additional or altered data set may be defined and collected if necessary. The results and performance characteristics are sent to decision makers in order to find out the most sustainable scenario and evaluate their situation. All the life cycle actors are informed about their contribution to the overall performance of the product and their success

3.3 Performance Characteristics

Holistic life cycle approach combines three methodologies so as to generate the sustainability performance characteristics. Performance characteristics (PC) are the key performance indicators that show the success of the product or process. PC enable to create value by transforming information to knowledge at all phases of the product lifecycle and thus product and service quality, efficiency and sustainability might be improved by considering these PCs. Holistic life cycle approach employs life cycle assessment (LCA) for evaluating environmental PC, life cycle costing (LCC) for evaluating economic PC and social life cycle assessment (S-LCA) for determining social PC. It is essential that the system boundaries for LCA, LCC and S-LCA should be identical and the life cycle inventory should contain all required input for the assessments. On top of the sustainability PC, technical PCs are also collected in HLA in order to ensure the functionality of the products and the success of the processes and actors of the value chain.

3.3.1 Technical Performance Characteristics

Technical PC stands for the ability of the product in order to accomplish the expected functions and user's expressed and unexpressed needs, as well as the capability of the value chain actors to perform their expected contribution on value creation. Technical PCs are related to material (mechanical properties, composition, etc.), production processes of the components (productivity, formability, castability, etc.) and performance of life cycle actors (production capacity, efficiency, quality, etc.). They are the properties of the product that are essential for the production of the product, to fulfill its function in a satisfactory way. Technical characteristics may be measured by predetermined test procedures, and some of them are going to be provided by the related life cycle actors.

3.3.2 Environmental Performance Characteristics

Environmental PCs indicate the environmental load occurred during the activities through the life cycle of the product. LCA will be used to generate the environmental PCs. The output of the LCA study (environmental PCs in this case) depend on the LCIA method chosen for the assessment. As stated before, LCIA methods aim to connect, as far as possible, each life cycle inventory (LCI) to its potential environmental damages, on the basis of impact pathways (impact pathways are composed of environmental processes like a product system consists of economic processes). LCIA methods were presented in the previous section. According to ISO, LCI results are classified in impact categories and the category indicator can be located at any place between the LCI-results (interventions) and the category endpoint. Based on this format, two main schools of methods developed [105]:

- Classical impact assessment methods (e.g. CML , EDIP) which stop quantitative modeling relatively early in the cause-effect chain to limit uncertainties and group LCI results in what we call here midpoint categories, according to common themes: i.e. common mechanisms (e.g. climate change-global warming) or commonly accepted grouping (ecotoxicity).
- Damage oriented methods such as Eco-indicator 99 or EPS, which try to enhance relevance by modeling (sometimes with high uncertainties) the cause-effect chain up to the endpoint or damage.

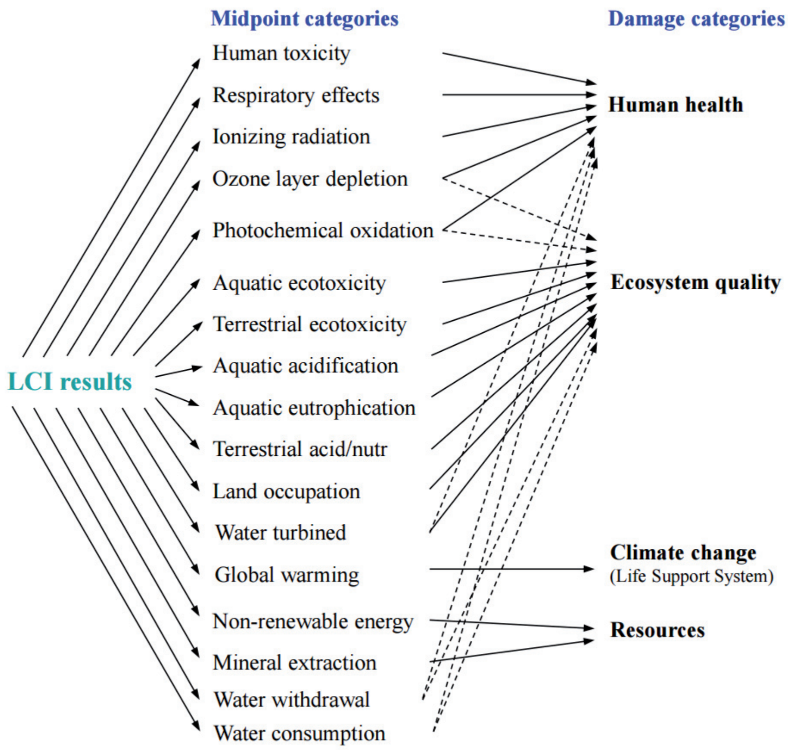


Figure 27 Overall scheme of the IMPACT 2002+ framework [105]

IMPACT 2002+ LCIA has been used in this thesis. The LCIA methodology IMPACT 2002+ vQ2.2 proposes a feasible implementation of the aforementioned combined midpoint/damage-oriented approach. Figure 4 shows the overall scheme of the IMPACT 2002+ vQ2.2 framework, linking all types of LCI results via several midpoint categories [human toxicity carcinogenic effects, human toxicity non-carcinogenic effects (these both categories are sometimes grouped in one category: human toxicity), respiratory effects (due to inorganics), ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity, aquatic acidification, aquatic eutrophication, terrestrial acidification/nutrification, land occupation, water turbined, global warming, non-renewable energy consumption, mineral extraction, water withdrawal, and water consumption] to four damage categories (human health, ecosystem quality, climate change, and resources) [106].

The environmental performance characteristics are calculated for each process along the life cycle of the product. The Quantis Suite 2.0 software, developed by Quantis, is used to assist the LCA system-modelling, link the reference flows with the life cycle inventory database and compute the complete life cycle inventory and potential impacts of the systems. Information on the production of commodities, energy and other processes are primarily based on the ecoinvent database (www.ecoinvent.ch). The environmental impact categories are given in Table 7.

Environmental impact category	Unit	Definition
Human health	DALY	Characterizes the disease severity caused by the processes
Ecosystem quality	PDF.m^2.y	Represents the fraction of species disappeared on 1m^2 of earth surface during 1 year.
Climate change	kg CO_2-eq	Expresses the amount of CO2 that equals the impact of the considered pollutant within the midpoint category studies.
Resources	MJ	Measures the amount of energy extracted or needed to extract the resource.
Water withdrawal	m^3	Includes the water use expressed in m^3 of water needed, whether it is evaporated, consumed or released again downstream,
Water turbined	m^3	Sum of the total quantity of water turbined to generate the electricity necessary during the life cycle processes

Table 7 The environmental impact categories [105]

3.3.3 Economic Performance Characteristics

Economic performance characteristics show the financial contribution of the value chain actors. The economic performance characteristics will define the costs of each process through the life cycle. The life cycle costs (material, energy, labour, transportation, overhead, etc.) of the product systems will be calculated. Since most of the LCA software's are capable of calculating the life cycle costs, The Quantis Suite 2.0 software is used to assist the LCC system-modelling and calculate the life cycle cost. The same model has been used for LCA and LCC so as to align the LCA and LCC results, which helps to obtain comprehensive understanding of the environmental and economic performance of the product. The cost breakdown structure for all the activities of the product is defined which is used to distinguish all cost elements for each process of each life cycle actor. These categories are also defined as the economic performance characteristics and shown in Table 8.

Economic performance characteristics	Definition
Overhead costs	Accounts for costs related to R&D, design and management activities, occupation of infrastructure and use of machinery, and maintenance activities
Acquisition costs	Accounts for the purchase of the auxiliary elements main elements for the product, virgin aluminum and aluminum scrap in this case study
Labour costs	Summation of direct labour cost accounted for the functional unit.
Process costs	Total of electricity, fuel, gas, water and all other process related costs.
Waste treatment costs	Total costs of waste treatment operations and taxes
Transportation cost	Stands for the costs occurred due to transportation of products materials and wastes.
Life cycle cost	Summation of all the costs occurred through the life cycle of the product

Table 8 Economic performance characteristics

3.3.4 Social Performance Characteristics

A number of social and ethical concerns have to be taken into account to evaluate sustainability of a product through its life cycle. Unfortunately, social and ethical concerns are not prior to technical and economic issues for many companies. Even if they are into social and ethical issues, they may not have the possibility to influence the actors they are related with. The important problem is that these issues are not quantitative and comparable to each other. Social and ethical performance of the component and life cycle actors will be evaluated through questionnaires. Social PCs indicate the social performance of the life cycle actors through the value chain. The involvement of a new life cycle actor in the value chain could be decided according to its social performance.

Social PCs are generated by Social LCA according to the guidelines of UNEP. The stakeholders concerning the product system are identified and the relevant social and ethical indicators are identified and prioritize determined by rapid risk ranking. To determine the social and ethical risk for various life cycle stages, an estimation of the frequency and the severity of each social and ethical indicator should be made. For each life cycle stage and each belonging indicator, a score is given based on overall social and ethical risk. Each social and ethical indicator is rated with high, moderate or low risk according to Table 9 [107].

Risk Level	Explanation
High risk = 1	High risk for bad or harmful conditions. Not acceptable – more specific information about the life cycle stage + issue should be gathered to get a better estimate of the risk.
Moderate risk = 2	Moderate risk for harmful conditions. The risk may be acceptable, but there are improvement possibilities, i.e. reducing the risk further. Possibilities for improvements should be sought.
Low risk = 3	Possible good conditions. The risk is low and further measures than monitoring status is not required.

Table 9 Risk classes of rapid risk ranking [107]

In the rapid risk ranking, the topics are classified qualitatively according to perceived risk for each topic. The topics to be evaluated are listed below. Example issues to look for in order to evaluate each topic are presented in the appendix.

1. Human rights
2. Health and Safety (HSE)
3. Labor and management relations
4. Fair employment and working conditions
5. Diversity and equal opportunity
6. Non-discrimination
7. Equal remuneration for women and men
8. Training and education
9. Freedom of association and collective bargaining
10. Forced and compulsory labor
11. Child labor
12. Disciplinary practices
13. Security practices
14. Investment and procurement practices
15. Bribery and corruption
16. Competition and pricing
17. Indigenous (native) rights
18. Community relations
19. Public policy
20. Political contributions
21. Customer health and safety
22. Customer privacy
23. Marketing communications

Performance characteristics		Required data	
PC_{seFS}	Fair salary	Salary of the workers Minimum living wage	$PC_{seFS} = \frac{Salary\ of\ workers}{Min.\ living\ wage}$
PC_{seWH}	Working hours	Weekly working hours Authorized working hours	$PC_{seWH} = \frac{Weekly\ working\ hours}{Auth.\ working\ hours}$
PC_{seOT}	Overtime	Overtime reported weekly	$PC_{seOT} = Weekly\ overtime\ reported$
PC_{seMH}	Man/hour Cost	Salary of the workers Weekly working hours	$PC_{seMH} = \frac{Salary\ of\ the\ workers}{Monthly\ working\ hours}$
PC_{seHS}	Health and safety	Number of incidents monthly Average number of incidents in the sector	$PC_{seHS} = \frac{Incidents\ reported\ monthly}{Average\ number\ of\ incidents}$

Table 10 Examples of social performance characteristics.

Once the relevant social and ethical indicators are determined, inventory data for these indicators will be collected accordingly. Examples of social performance characteristics and required data for generating them is given in Table 10. In is necessary to note that, S-LCA differs from LCA and LCC in the way the inventory data is collected. In S-LCA the inventory data is collected based on the life cycle actors, not based on the processes. If a life cycle actor is responsible for one process, in this case the LCI for all three assessment methods align in the same inventory.

3.4 Conceptual Closed-loop PLM System

The most important issue about the methodologies for evaluation the performance characteristics is that they are data intensive evaluation methods. It is necessary to collect life cycle data from the actors of the value chain. In other words, it is necessary to close the information loop through the value chain of the product. This makes having an information/knowledge management system, Closed-loop PLM system in this case, a prerequisite for such an evaluation. Without a Closed-loop PLM system the collection of life cyle data to form the life cycle inventory becomes very tricky. It is necessary to contact a number of stakeholders through the value chain and ask for information which is confidential most of the time. Furthermore such a data collection requires a serious effort and time. Closing product life cycle information loops also requires involvement of all actors of the value chain through the life cycle of the products and contributes to the overall objective of sustainability of product systems [109]. Closed-loop PLM system is capable of collecting and processing life cycle data; and transforming and transmitting the generated performance characteristics. A Closed-Loop Lifecycle Management system containing a DSS configured with the holistic life cycle approach will be an efficient tool to evaluate and improve the sustainability performance of products.

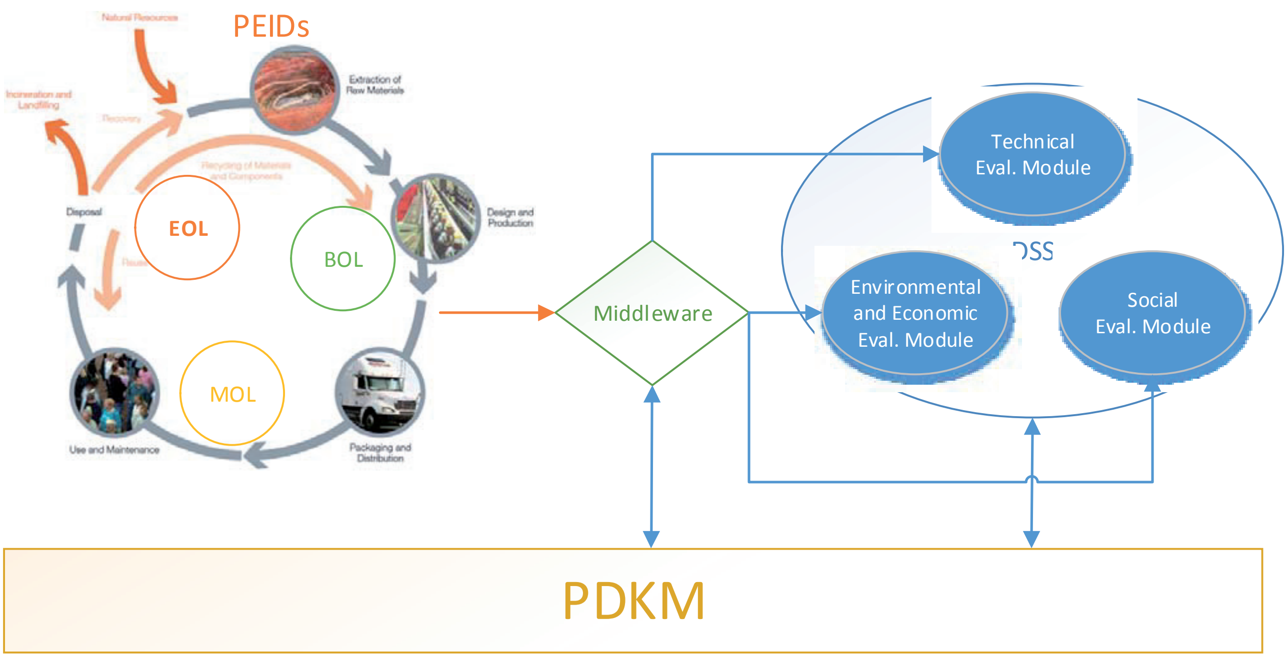


Figure 28 Closed-loop PLM concept with HLA

Figure 28 illustrates the concept of a closed loop PLM concept containing HLA as decision support system. Various types of PEIDs, RFID tags, on-board computers, and etc., are used to gather and manage product information through the life cycle for example. Both relevant and irrelevant data is collected from different life cycle actors. Collaboration of the life cycle actors is essential for setting up the data collection scheme. Middleware is the interface between life cycle actors and PDKM. It also determines the relevant data for evaluation and which data is transferred to which module.

Decision Support system consists of three modules that will generate the performance characteristics;

- technical evaluation module,
- environmental and economic evaluation module, and
- social evaluation module.

As noted before, in order to combine LCA, LCC and S-LCA, the system boundaries of the three assessments are required to be consistent. However, even the system boundaries are identical, LCA and LCC are process based and S-LCA is stakeholder based. The same life cycle inventory (LCI) may be used for LCA and LCC, but it is necessary to constitute a separate LCI for S-LCA.

The data required for LCA and LCC are;

- Geographical origin of the materials and the location of the life cycle actors
- Specific data about material production
- Specific data for energy, material use, emissions and residues for component production
- General data about the assembly process
- Energy consumption
- General data of maintenance operations
- Specific (or generic) data for energy and material use, emissions and residues related with EOL treatment processes
- Labor data for production, maintenance and EOL
- Cost data for material, production, maintenance and EOL, and etc.

The exemplary data required for S-LCA are;

- Working hours of the workers,
- Wage of workers,

- Child labour,
- Health and safety issues concerning the consumers,
- Community engagement and local employment,
- Contribution to economic development, corruption issues,
- Fair competition and respecting intellectual rights of the competitors, and etc.

The data required for LCA and LCC are quantitative, however the data required for S-LCA are both qualitative and quantitative which makes it difficult to aggregate. Having this in mind, environmental and economic evaluation may be combined in one module and social evaluation is made by another module. The outputs might be combined or used separately. On top of that, technical evaluation module is separate from the other modules.

Product data and management system PDKM manages information and knowledge generated during the product life cycle. The data collected by the PEIDs and aggregated by the Middleware and generated by the DSS are stored in PDKM. The confidentiality of the information collected and generated in the closed-loop PLM system is a major issue. PDKM also determines which performance characteristics can be accessed by which life cycle actor.

Chapter 4 Case Study 1- Front Lower Control Arm

The application of holistic life cycle approach on front lower control arm is presented in this section. The component is presented, actual and intended value chains, material and information flows are determined, alternative scenarios are defined and evaluated.

4.1 Introduction (Step 1)

Front lower control arm (FLCA), illustrated in Figure 29, one of the test case components of EU FP7 project called SuPLight (Sustainable and efficient Production of Light weight solutions). The aim of SuPLight is to enable closed loop recycling of lightweight components and increase use of recycled aluminum in production of high-end structural components [109]. FLCA is an important part of a vehicle's suspension system; it is a bar that is used to attach the suspension members to the vehicle's chassis. With the help of the pivots located at each end of the control arm, the part is capable of managing the motion of the wheels in order to ensure they remain in time with the body of the vehicle. Due to the nature of the part, every vehicle has several upper and lower control arms. In addition, because this part must endure continual movement, control arm bushings are put in place in order to reduce the amount of friction produced while also preventing the various vehicle parts from moving in multiple directions. FLCA consists of four components; body, ball joint, rubber bushing, and hydro bushing with aluminum housing. The body of the control arm is the focus of the study, the auxiliary parts are excluded from the assessment.

Figure 29 Front lower control arm (FLCA)

Mainly control arms are produced from steel by various production methods; forging, casting, forming and welding. In high segment vehicles the control arm is produced from aluminum alloys. The chosen control arm is produced from AA6082. AA 6xxx series alloys are low composition, medium-strength structural materials with silicon and magnesium as main alloying elements. Due to their specific characteristics (material of light weight, high strength, excellent corrosion resistance, good formability and weldability) these alloys are widely used in production of the most automotive structural components. The chemical composition of AA 6082 composition is given in Table 11.

		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others Each	Others Total
EN AW 6082	Min	0.70			0.40	0.60					
	Max	1.30	0.50	0.10	1.00	1.20	0.25	0.20	0.10	0.05	0.15

Table 11 Chemical composition of the standard AA 6082 alloy

The value of aluminum and necessity of aluminum recycling has already caught attention. However, wrought-to-wrought aluminum recycling still remains tricky due to their low alloy content. The wrought aluminum scrap is mixed with the cast aluminum scrap and recycled into cast aluminum alloys and may only be used for parts that are not dynamically loaded. The main objective of SuPLight project was to increase the use of secondary aluminum use in production of high-end structural components. Two options were indicated in order to accomplish this objective.

1- Closed loop recycling of control arm

2- Alternative aluminum scrap sources and new alloy formulation.

Category	Label	Default Value	Units
Mechanical Properties	Yield Strength	320	Mpa
	Tensile Strength	350	MPa
	Elongation	10	%
	Hardness	100	HV10
	Fatigue	140	MPa
	Corrosion resistivity	A	A, B, C, D
Structural Properties	Grain Size	90	µm
	Particle Size	5	µm
Physical Parameters	Density	2700	kg/m^3
	Young's Modulus	70000	MPa
	Strain rate	1	s^{-1}
	Specific Heat	1230	Joule/Kg °C
	Thermal Conductivity	230	W/m ·°C
	Emissivity	0,5	
	Poisson Ratio	0,3	

Table 12 Required properties for FLCA

Required properties for FLCA are listed in Table 12, and process related properties are listed in Table 13. The two tables present the first set of technical performance characteristics of FLCA.

Category	Label	Default Value	Units
Composition	Mass of product	1,572	kg
	Virgin aluminum input	3,373	kg
	Recycled Ratio	0	%
Process Related Properties	Extrusion Speed	4	m/min
	Extrusion temperature	470	°C
	Extrusion ratio	10	
	Extrusion pressure	6000	kN
	Extrusion efficiency		%
	Forging temperature	520	°C
	Forging load	15000	kN
	Forging efficiency		%
	Product Surface Quality	Y	
	Machinability	B	A, B, C, D
	Machining efficiency		%
	Solid solution temperature	530	°C
	Solid solution time	25	min
	Aging temperature	190	°C
	Aging time	120	min

Table 13 Process related properties

4.2 Value chain of FLCA (Step 2)

The actual value chain of FLCA, shown in Figure 30, is described in this section. Due to the regulations of the automotive industry every OEM should have at least two suppliers especially for the crucial materials. The alternative suppliers are not illustrated in the figure below. The suppliers are mainly chosen depending on the price and availability of the material. The approach described in this study may also involve environmental and social aspects in supplier selection process.

Virgin aluminum originates from Sweden or Austria, 30% and 70% respectively. Aluminum rod supplier (ARS) is located in Austria. ARS melts virgin aluminum, prepares the AA 6082 alloy and casts ingots for rod extrusion. The rods are extruded and transported to control arm manufacturer. ARS remelts its own aluminum scrap into wrought aluminum alloys. The control arm manufacturer which is also the designer of FLCA, and it is located in Norway. FLCA manufacturer is close contact with vehicle designers in order to fulfil the design requirements. Vehicle manufacturer assembles the suspension system and installs it on the vehicle.

MOL phase starts when the vehicle leaves the manufacturer and comes to distributer. Distributer is responsible for the marketing and sales of the vehicles. The owner uses the vehicle and takes the car to the service for maintenance. The control arm is designed to remain functional until EOL with no service, because fail of the control arm may lead to a serious accident. The control arm is inspected visually and changed if any critical error is observed. The common error related to the control arm is the wear off the bushings, and they are changed if necessary.

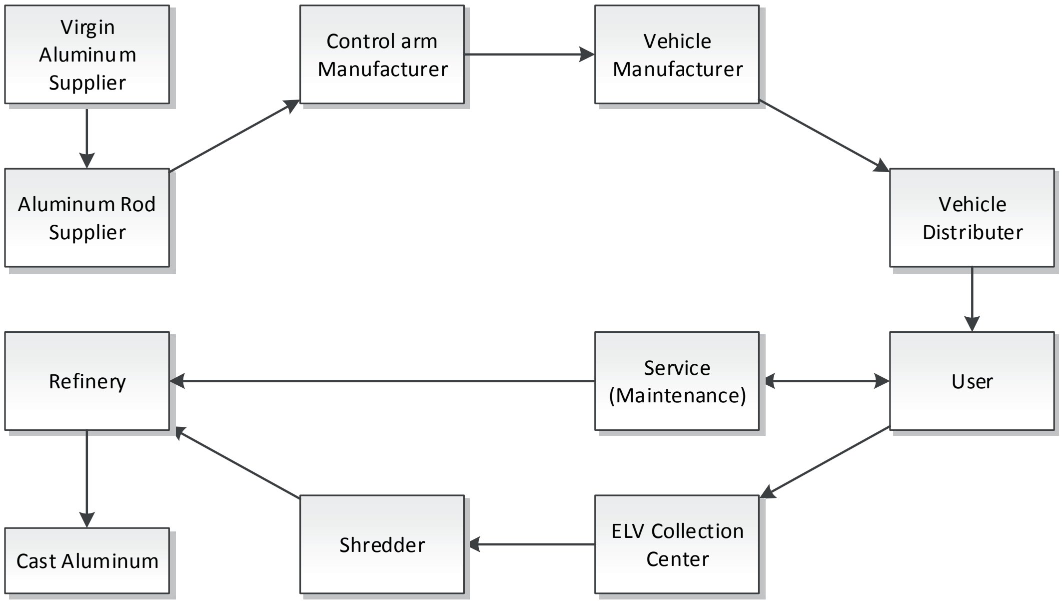


Figure 30 Actual value chain of FLCA

When the vehicles reach the EOL, they are collected in authorized collection center where they are deregistered, and the hazardous fluids and materials are extracted. The vehicles are then sent to the shredder where the vehicles are crashed into pieces and sorted according to the type of material; ferrous, non-ferrous, plastics, etc. All the aluminum sorted in the shredder is sent to the refinery for production of cast aluminum.

Global recycling rate of aluminum in transport is ~90% [110], which is driven by the high material value of aluminum scrap. In spite the fact that, the recycling rate of aluminum in transport is high, most of the aluminum scrap is recycled into cast products due to number of reasons. The intended value chain, shown in Figure 31, is formed according to the required actions in order to increase the recycled aluminum input.

Service station collects the worn control arms when they change it with the new one. ELV collection center disassembles the control arms. FLCAs are reused or remanufactured in order to replace the worn components depending on their conditions. If their condition is not reasonable, they are sent to scrap dealer. The aluminum scrap in the shredder is sorted in detail in order to separate cast and wrought scrap. Wrought scrap is sent to remelter. Scrap dealer collects control arms from service station, ELV collection center and wrought aluminum scrap shredder and sends them with predetermined aluminum scrap from various sources to the remelter. Remelter melts all the aluminum scrap and sends to aluminum rod supplier.

Currently, post-consumer aluminium scrap is in short supply and high demand, and secondary ingot sells near the price of much less alloyed prime wrought alloy. Consumption of necessary resources (labor, energy, transport etc.) for collection and reverse logistics of the wrought aluminum scrap should be taken into account. As long as this is the case, it is necessary to note that economy may not be the driving force for the objective.

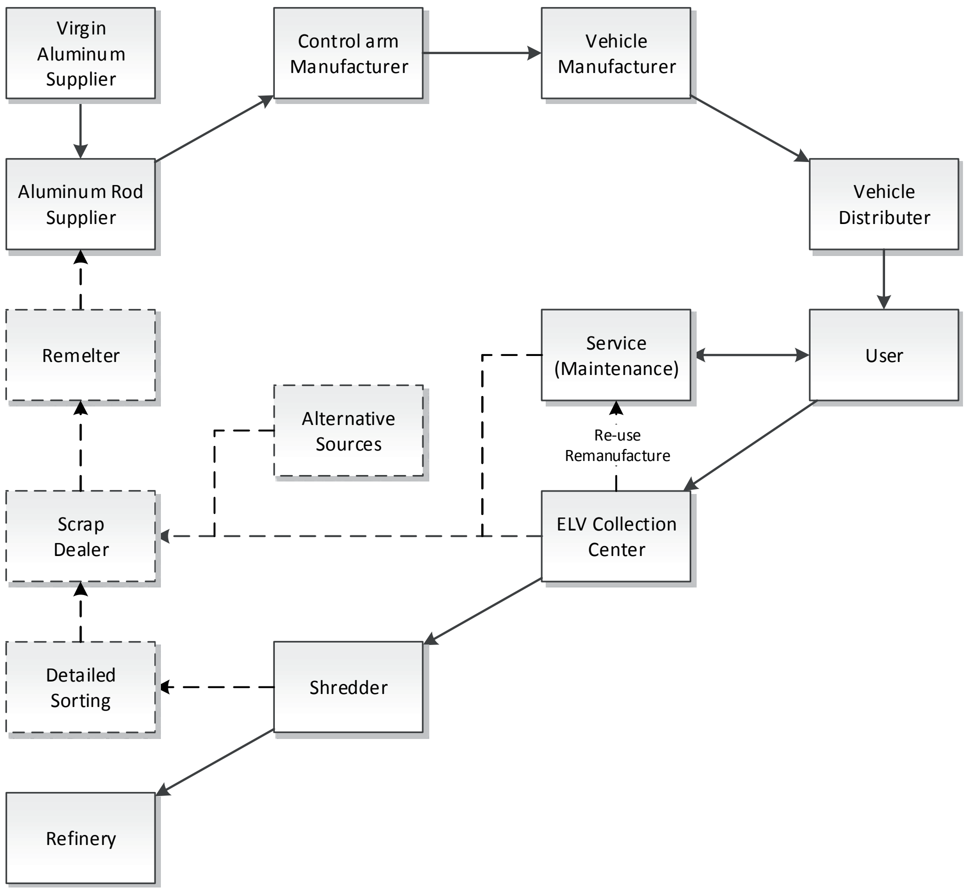
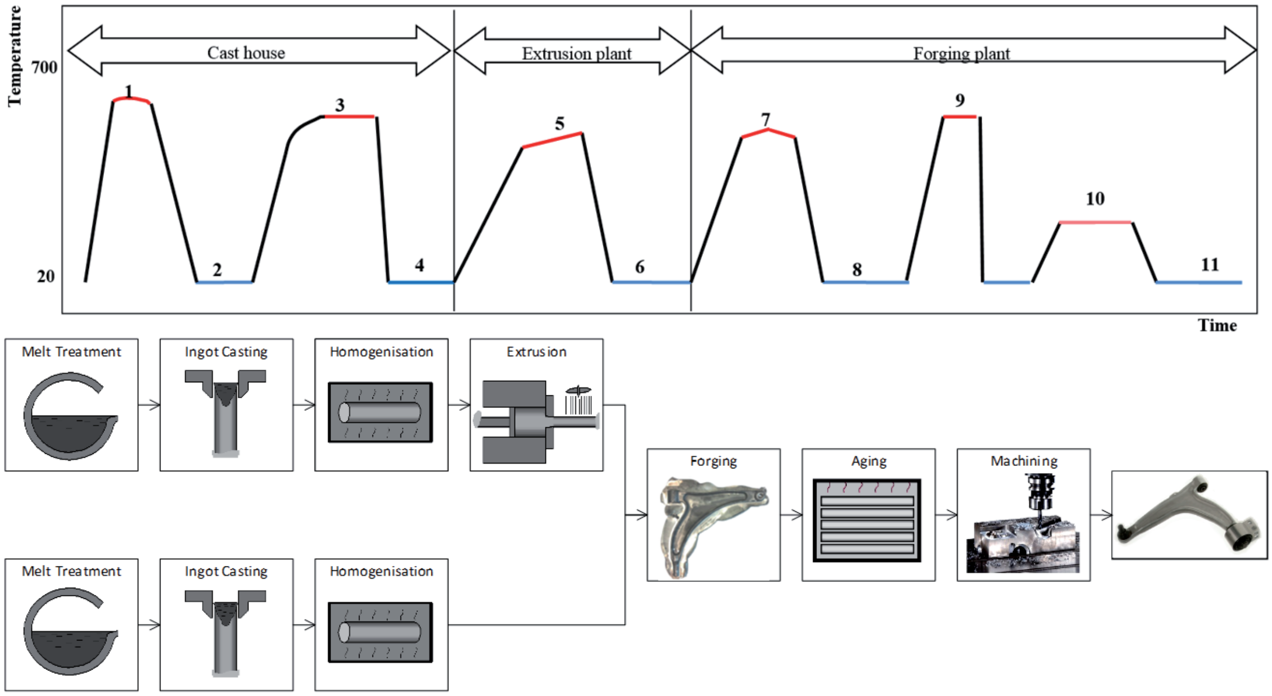


Figure 31 Intended value chain of FLCA

4.3 Material Flow of FLCA (Step 3)

Figure 32 illustrates the traditional production route of FLCA. It includes several basic manufacturing processes, direct chill (DC) casting of billets, rod extrusion, forging and machining. In order to obtain the necessary mechanical properties and process more easily, the material should be exposed to a number of heating and cooling cycles, shown in Figure 32 [111].

The main purpose behind using recycled aluminum is to decrease the environmental impact of the production phase. An alternative production route has been proposed which eliminates the extrusion step. This alternative production routes not only eliminates the environmental impact of extrusion but also reduces the virgin aluminum input and environmental impact of melt treatment and DC casting steps. The alternative production route is also depicted in Figure 32.



High temperature steps:
1- DC casting of billet
3- Homogenizing
5- Extrusion of rod
7- Forging
9- Solid solution heat treatment
10- Aging

Room temperature steps
2- Cutting
4- Scalp
6- Stretching / cutting
8- Flashing
11- Machining

Figure 32 Traditional and alternative production routes [111]

5 scenarios have been determined for evaluating the effect of using recycled aluminum and eliminating extrusion.

1- Traditional production route – 100% Virgin aluminum input (Reference)

2- Traditional production route – 75 % Recycled aluminum input

3- Alternative production route – 100% Virgin aluminum input

4- Alternative production route – 75 % Recycled aluminum input

5- Traditional production route – Steel (Assumption)

Figure 33 shows detailed material flow for the reference scenario. The material flow is used to generate the life cycle inventory. The material flows for each scenario are given in the appendix.

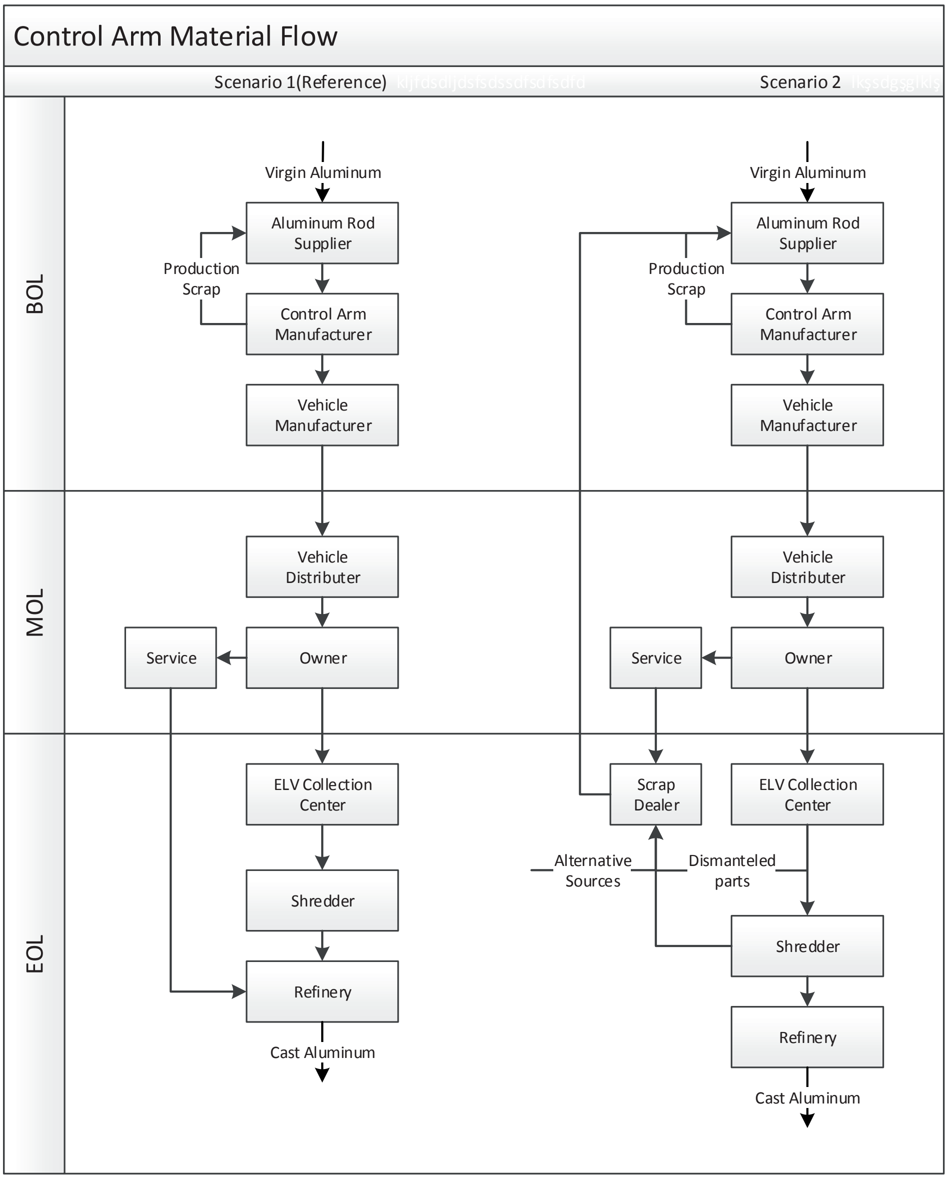


Figure 33 Reference scenario - Current Material Flow of FLCA

Some assumptions have been made in generation of the life cycle inventory. The main assumptions are shown below.

- The use of machinery and infrastructure are included as overhead.
- Waste flows are calculated for one control arm from the overall waste generation
- The fuel consumption of the vehicle, which is directly related to the environmental impact of the use phase, depends on the weight and aerodynamic resistance of the vehicle, 60% and 40% respectively. Since the control arm does not affect the aerodynamic resistance of the vehicle, FLCA accounts for/effects 60% of the total environmental impact of the use phase.
- The weight of the vehicle is 1000kg and life time is 200000 km.

The 5th scenario is proposed in order to compare the performance of aluminum over steel. The calculation setup for the steel FLCA is similar to that of the aluminium FLCA. As there are no data available for the steel scenario, the LCA model is structured based on the assumptions below:

1. The steel FLCA is produced by the same production route of aluminum case, and the process yields remain the same.
2. The most widely used steel alloy for high-end applications is 4130 chromium-molybdenum alloy steel. The mechanical properties and composition of this alloy are presented in Table 1 in the appendix, together with the aluminium alloy currently used in the FLCA.
3. It is necessary to redesign the part since a material with superior mechanical properties is used. The tips that other components are connected remain the same and the body is thought to be thinner according to the yield strength of the material.

4.4 Information Flow of FLCA [Step 4]

The tasks of the life cycle actors of FLCA are shown in Table 14. The tasks of the life cycle actors are related with the information they need and the information they may provide to the others to fulfil their activities.

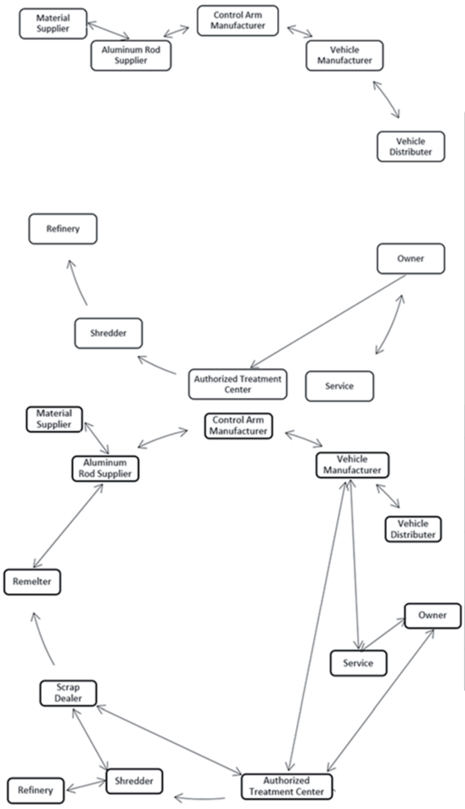
The main data to be transmitted between life cycle actors of control arm is shown in Figure 34. Most of the data between the life cycle actors are transactional data in order to retain their business. In BOL phase, the data is related with design, properties of material and supply and demand for production. DSS will provide information to related actors regarding the properties of the material and the control arm to adjust their production activities accordingly.

Life Cycle Phase	Life Cycle Actor	Tasks
BOL	Aluminum Rod Supplier	AA6082 ingot production Billet extrusion Define the acceptable scrap characteristics
	Control Arm Manufacturer	Define billet dimensions and properties Control arm design Control arm production Production scrap treatment Quality control
	Vehicle Manufacturer	Assembly of the vehicle Define design and quality requirements Provide disassembly information
MOL	Vehicle Distributor	Marketing Sales Provide sales forecast
	Owner	Use the vehicle
	Service	Maintenance Disassembly of worn components Collection detached components
EOL	Authorized Treatment Center	ELV collection ELV deregistration ELV depollution ELV storage
	Dismantler	Detachment of pre-determined components Detached component storage
	Shredder	ELV shredding Sorting shredded material
	Refinery	Treatment of aluminum scrap Cast aluminum production
	Scrap Dealer	Aluminum scrap collection Sorting collected scrap Storage of scrap

Table 14 Tasks of life cycle actors FLCA

In MOL, data is related with the use of the vehicle and the failure of the components if it happens. This data might be used to improve the design of the control arm, and appraise the performance of the material and reaction of the other parts attached to the control arm to the change of material. Sales forecasts are not directly related with SuPLight but with the vehicle and control arm production.

In EOL the data flow is necessary to enable the reverse logistics of the control arms back to BOL and collection of predetermined aluminum scrap from other sources.



Information Flow		Main data
Source	Destination	
Aluminum Rod Supplier	Control arm manufacturer	Mechanical properties of the billet Chemical composition of the billet Amount and source of recycled material in the billet
	Scrap Dealer	Characteristics of acceptable scrap
Control arm manufacturer	Aluminum Rod Supplier	Characteristics of acceptable billet
	Vehicle manufacturer	Quality control results of the control arm Related performance characteristics to be used for marketing
Vehicle manufacturer	Control arm manufacturer	Design requirements Amount of control arms needed for production
	Authorized treatment facility	Disassembly information
Vehicle Distributer	Vehicle manufacturer	Sales forecasts
Service	Vehicle & Control arm manufacturer	Reason of detachment
Authorized treatment facility	Shredder	Number ELV arriving List of parts to be disassembled
	Scrap Dealer	Amount and contents of dismantled components
Shredder	Scrap Dealer	Amount and contents of sorted material
	Refinery	Amount of material
Scrap dealer	Aluminum Rod Supplier	Amount and source of aluminum scrap

Figure 34 Main data to be transmitted between life cycle actors of FLCA

4.5 Performance Characteristics of FLCA (Step 5)

The list of technical performance characteristics of FLCA are given in Table 15. The technical performance characteristics for each scenario and compared in section 4.6.

Material Composition				**Mechanical Properties**	**Process Parameters**
Mass	FLCA			Yield strength	Ingot casting yield
	Virgin Aluminum			Tensile strength	Extrusion speed
	Secondary Aluminum			Hardness	Extrusion pressure
				Fatigue	Extrusion efficiency
Alloying elements		Mass	Ratio	Corrosion resistivity	Extrusion yield
	Si	**	**		Forging Load
	Fe	**	**		Forging yield
	Cu	**	**	Physical Parameters	Forging efficiency
	Mn	**	**	Density	Product surface quality
	Mg	**	**	Young's modulus	Machinability
	Cr	**	**	Strain rate	Machining efficiency
	Zn	**	**		Solid solution time
	Ti	**	**		Aging time

Table 15 Technical performance characteristics of FLCA

With what concerns the environmental, economic performance characteristics, as shown in Table 7 and Table 8 are computed for each process through the life cycle of the FLCA and compared in section 4.6.3 and 4.6.4 respectively. The rapid risk ranking of the social and ethical indicators and the performance characteristics for these indicators are given in section 4.6.

4.6 Comparison of the Scenarios (Step 6-7)

4.6.1 Technical Performance

The model alloy which is composed of virgin and recycled aluminum, contains more silicon and copper content than the original alloy. The composition of standard and model alloys are shown in Table 16.

		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others Each	Others Total
EN AW 6082	Min	0.70			0.40	0.60					
	Max	1.30	0.50	0.10	1.00	1.20	0.25	0.20	0.10	0.05	0.15
Model alloy		1.98	0.23	0	0.59	0.88	0.03	0	0.02	-	-

Table 16 Chemical composition of the standard AA 6082 and model alloy

The comparison of technical performance characteristics are given in Table 17. Generic test components were produced by the traditional and alternative production routes in order to test the materials and measure the properties of the two alloys.

Category	Label	Scenario1	Scenario2	Scenario3	Scenario4	Scenario5	Units
Composition	Mass of FLCA	1572	1572	1572	1572	3237,8	kg
	Virgin aluminum input	3373	843,25	2607	651,75	7245,4	kg
	Recycled aluminum input	0	2529,75	0	1955,25	0	
	Recycled ratio	0	75	0	75	0	%
Mechanical Properties	Yield strength	320	312	311	317	615	Mpa
	Tensile strength	350	341	340	344	415	MPa
	Hardness	100	98	97	106	175	HV10
	Fatigue	140	140	140	140	200	MPa
	Corrosion resistivity	A	A	A	A	-	A, B, C, D
Physical Parameters	Density	2700	2700	2700	2700	7850	kg/m^3
	Young's modulus	70000	70000	70000	70000		MPa
	Strain rate	1	1	1	1		s^{-1}
Process Related Properties	Ingot casting yield	98%	98%	75%	75%	-	%
	Extrusion speed	54	22	-	-	-	m/min
	Extrusion pressure	6000	6000	-	-	-	kN
	Extrusion yield	80%	80%	-	-	-	%
	Productivity of rod production	90%	36%	%95	%95	-	%
	Forging load	15000	15000	15850	15850	-	kN
	Forging yield	57%	57%	77%	77%	-	%
	Product surface quality	Y	Y	Y	Y	-	Y/N
	Machinability	B	B	B	B	-	A, B, C, D
	Machining yield	81%	81%	81%	81%	-	%
	Solid solution time	25	25	25	25	-	min
	Aging time	120	120	120	120	-	min
	Productivity of FLCA production	96%	96%	75%	75%	-	%

Table 17 Comparison of technical performance characteristics

The strength and hardness of the material reduces slightly if recycled material is used and the extrusion step is excluded. Both activities does not affect the fatigue and corrosion performance of the material.

Silicon, which is an inevitable addition of recycled aluminum alloys, has an important impact on alloy extrudability. An increase in silicon content may lead to a considerable reduction of the extrudability. This also reduces the productivity of the rod production facility marginally.

The shape and surface quality is determined by visual inspection. All generic test components, without regard to the chemistry and processing route, were found free of forging defects, hot cracks and with the same level of surface quality.

Both the standard and the model alloys, processed through the alternative production route have required higher force to be forged, but not more than 6% of the value measured for the reference scenario.

Changing neither the production route nor the material had significant impact on machining and heat treatment of the materials.

4.6.2 Environmental Performance

Figure 35 shows the comparison of environmental impacts of life cycle stages of the FLCA manufactured by the traditional production route (Scenario 1). This is the reference scenario for the other scenarios. The results are also given in numbers and percentages, in Table 18.

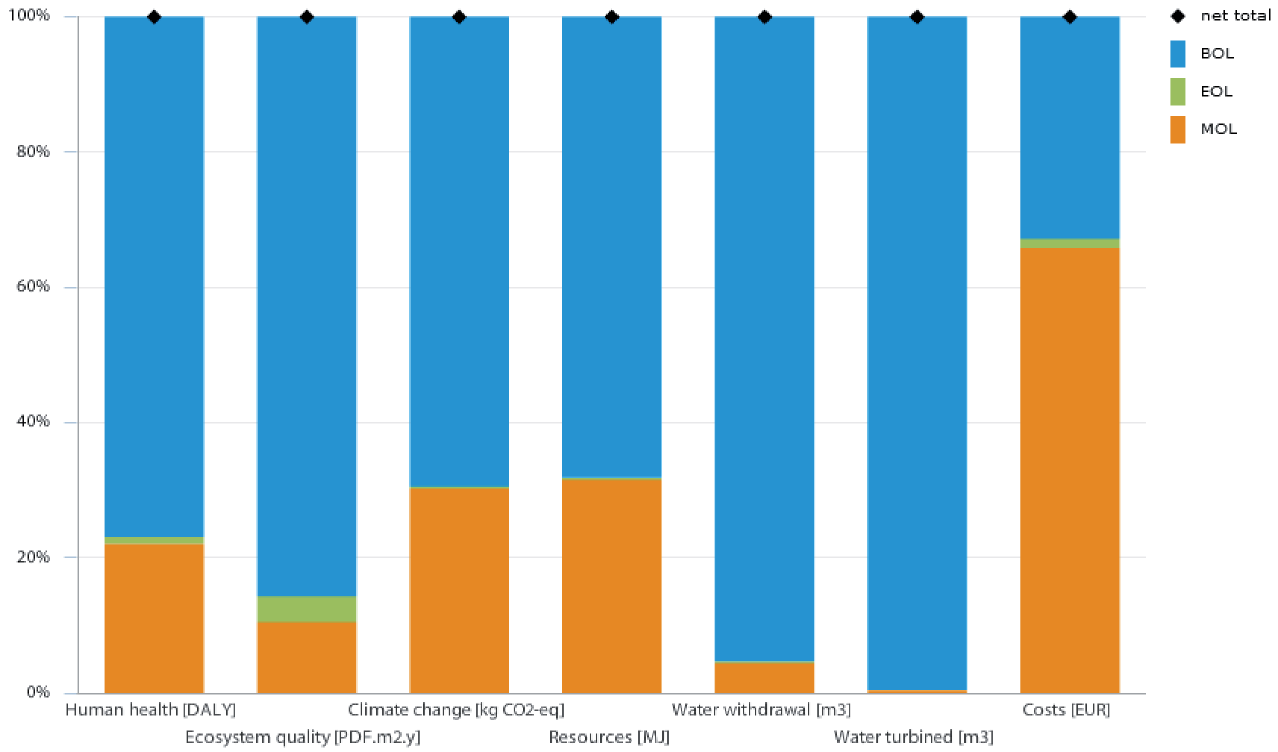


Figure 35 Life cycle environmental impacts and costs of FLCA

The EOL phase does not have a significant impact on the environment. However, in case of recycling, it reduces the environmental impact of BOL phase, and has a positive impact.

The BOL phase consists of activities concerning aluminium rod production and FLCA production. The MOL phase consists of vehicle use. The fuel consumption is allocated between the weight and aerodynamic resistance, which are 60% and 40%, respectively. Fuel consumption of the case vehicle is also taken from Eco invent database and was found to be 0.07 l/km. The EOL phase includes collection of end-of-life vehicles and transport to an end-of-life vehicle treatment site. Treatment of the scrap is not included, as the recycle content approach is applied.

For all impact categories, the BOL phase dominates the impacts over 60%, which is due to virgin aluminum used in production. Life cycle costs are dominated by the MOL phase.

Scenario 1	BOL		MOL		EOL		Total	Unit
Human health	4,175e-5	77,26%	1,175e-5	21,74%	5,409e-7	1,00%	5,337e-5	DALY
Ecosystem quality	28,89	85,7%	3,51	10,42%	1,3	3,86%	33,7	PDF.m2.y
Climate change	51,56	69,5%	22,42	30,22%	0,21	0,28%	74,19	kg CO2-eq
Resources	691,52	68,2%	319,92	31,54%	3,02	0,30%	1014,46	MJ
Water withdrawal	1,67	95,4%	0,0768	4,39%	4,068e-3	0,23%	1,75	m3
Water turbined	1200,37	99,6%	4,77	0,40%	0,316	0,03%	1205,46	m3
Costs	24,25	32,9%	,95	1,29%	48,58	65,84%	73,78	EUR

Table 18 Life cycle environmental impacts and costs of FLCA

For the BOL phase, virgin aluminium dominates the impacts, as one would expect. Figure 36 shows the environmental impacts of the BOL phase of the state-of-the-art production route. Detailed results of BOL phase are given in Table 19.

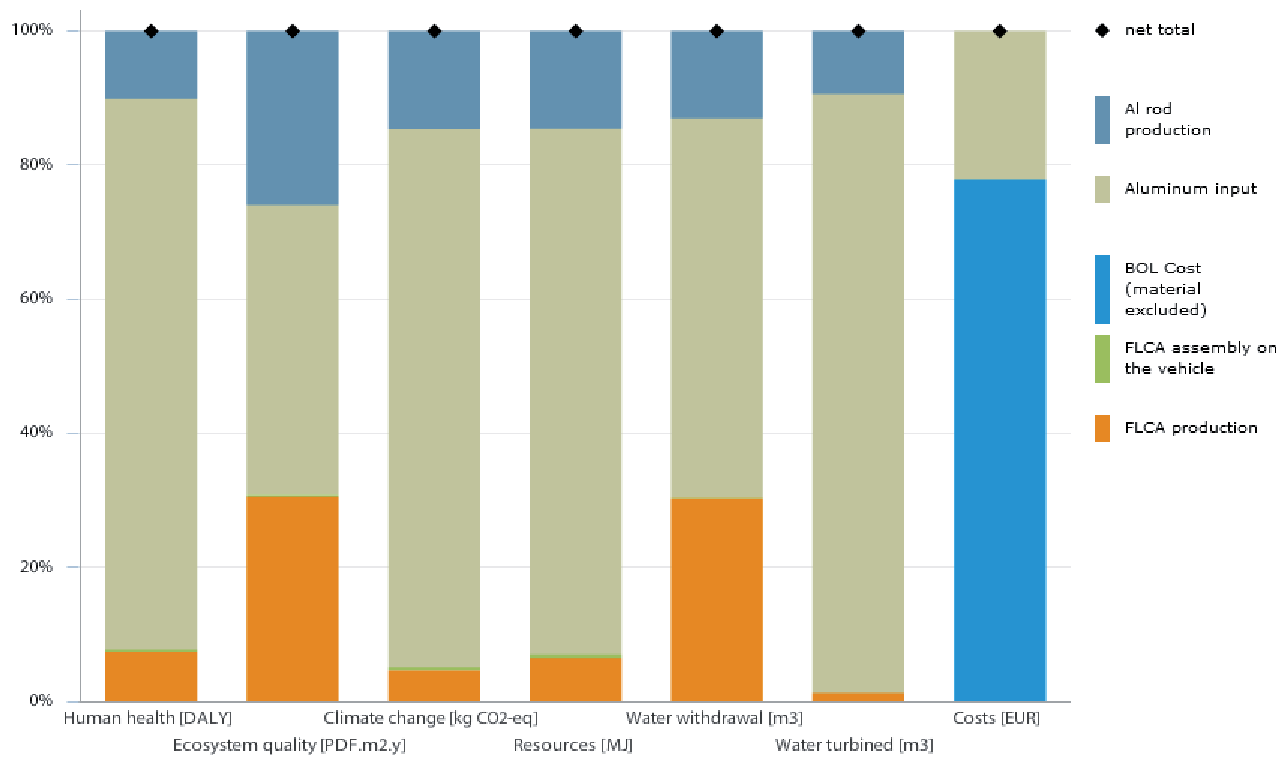


Figure 36 Environmental impacts and costs of BOL phase

The cumulative impact of production processes correspond to 15-20% of overall environmental impact of the FLCA for all the indicators. The production processes of most importance are; casting, extrusion, forging. Transport activities contains aluminium rod transportation to FLCA manufacturer, control arm transportation to vehicle manufacturer, aluminium scrap transportation to aluminum rod supplier, and waste transportation to the treatment facility. Transport activities contribute less than 3% to all impact categories.

Scenario 1 (BOL)	Aluminum Input	Al Rod Production	FLCA Production	FLCA Assembly	Total	Unit
Human health	3,373e-5	4,166e-6	3,032e-6	1,386e-7	4,107e-5	DALY
Ecosystem quality	12,48	7,51	8,82	0,0825	28,89	PDF.m2.y
Climate change	41,38	7,56	2,38	0,235	51,56	kg CO2-eq
Resources	541,92	101,07	44,57	3,96	691,52	MJ
Water withdrawal	0,943	0,218	0,506	2,324e-3	1,67	m3
Water turbined	1072,44	113,06	14,58	0,305	1200,37	m3
Costs	5,38	6,67	11,50	0,70	24,15	EUR

Table 19 Environmental impacts and costs of BOL phase

In comparison of the four scenarios, MOL phase remains the same, BOL and EOL phases differentiates due to changes in input material and production route. Figure 37 shows the comparison of the environmental impacts of BOL phase for the aforementioned scenarios. Because of the yield of the production processes, the material input of the alternative production route is less than the current production route.

Since contribution of primary aluminium to the overall environmental impact of the FLCA is overwhelming, the use of aluminium scrap decreases environmental impact of FLCA in all impact categories.

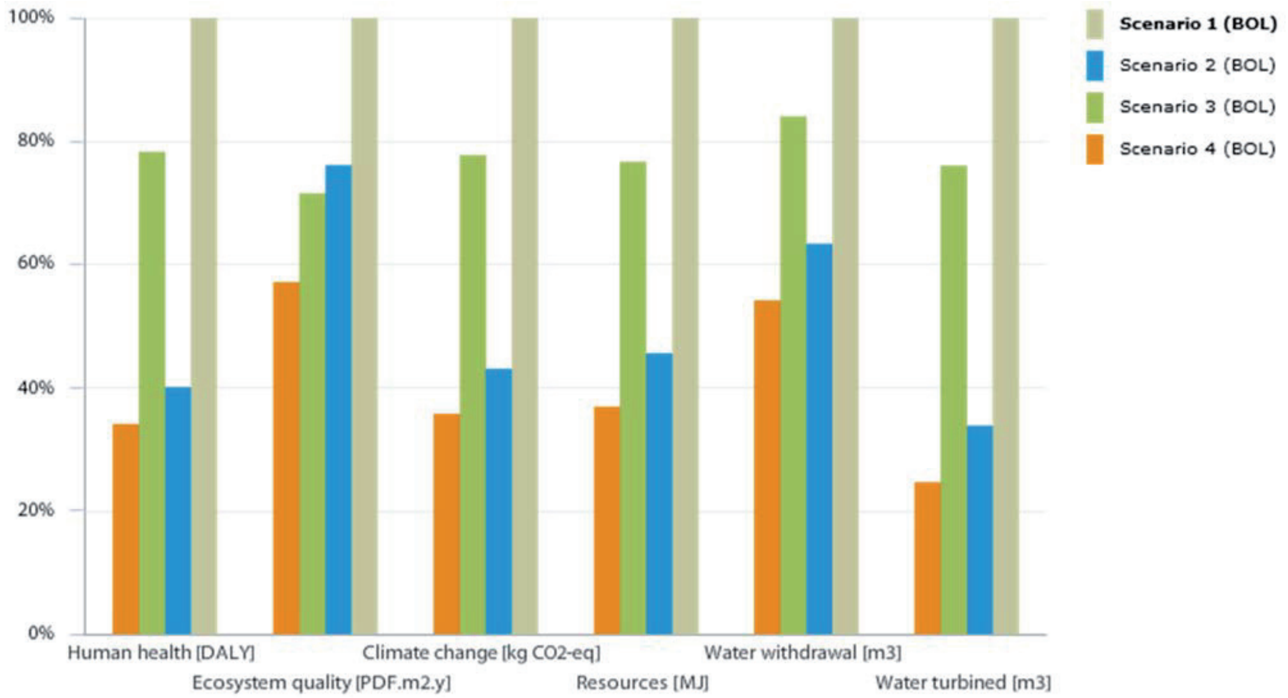


Figure 37 Comparison environmental impact of BOL phase of the four scenarios

Scenario 1 (BOL)	Scenario 1	Scenario 2		Scenario 3		Scenario 4		Unit
Human health	4,107e-5	1,650e-5	-59,8%	3,216e-5	-21,7%	1,404e-7	-65,8%	DALY
Ecosystem quality	28,89	22,01	-23,8%	20,69	-28,4%	16,49	-42,9%	PDF.m2.y
Climate change	51,56	22,26	-56,8%	40,13	-22,2%	18,48	-64,2%	kg CO2-eq
Resources	691,52	315,45	-54,4%	530,82	-23,2%	256,15	-63,0%	MJ
Water withdrawal	1,67	1,06	-36,7%	1,4	-16,0%	0,904	-45,8%	m3
Water turbined	1200,37	407,45	-66,1%	913,83	-23,9%	295,86	-75,4%	m3

Table 20 Comparison environmental impact of BOL phase of the four scenarios

The results of comparison of the four scenarios are given in Table 20. Since the aluminum has a substantial contribution to overall environmental impact of control arm, using recycled aluminum results in a significant reduction of environmental impact from about 50% to as 65%. The difference between traditional and alternative production route is the extrusion step in aluminium rod production. In the alternative production route, aluminium rods are produced by direct chill casting in the desired dimensions. An important energy intensive step is thus eliminated by switching to the alternative production route. On top of elimination of processing steps, the yield of the alternative production route is higher than the traditional production route. The higher yield results in reduced material consumption during production. The stated advantages of alternative production route results in reduction of environmental impact from 15% to 25%. Table 21 shows the comparison results of BOL phase in numbers and percentages. Scenario 4 combines the advantages of both scenario 2and 3 thus lead to higher reduction of environmental impact.

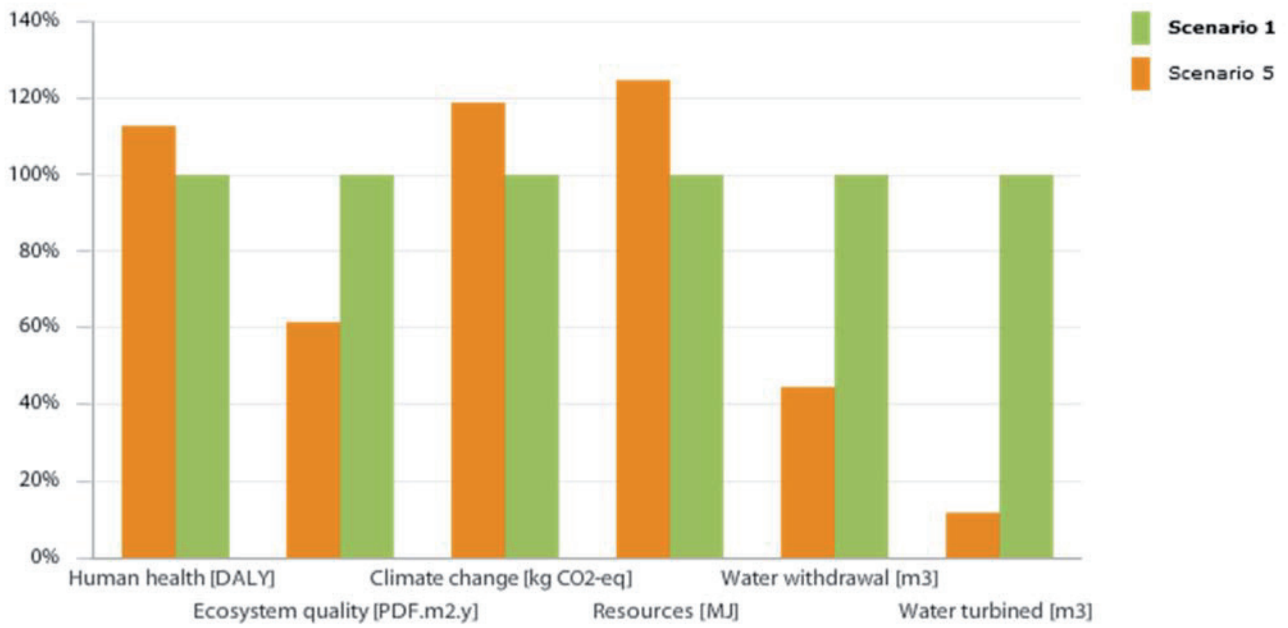


Figure 38 Comparison of environmental impacts of aluminum and steel control arms

The steel FLCA is assumed to be produced by the same production route as the aluminium FLCA and the process yields remain the same. The mass of the FLCA and the material used in production of the steel FLCA is calculated by these assumptions. The overall impacts on human health, climate change and resources of the steel FLCA is higher than aluminum FLCA from 10% to 25%. These impact categories are dominated by the MOL phase of scenario 5. On the other hand impacts on ecosystem quality, water withdrawal and water turbined are much less for steel FLCA.

Environmental impact categories	Scenario 1						Scenario5					
	BOL		MOL		EOL		BOL		MOL		EOL	
Human health	4,107E-05	63,1%	2,352E-05	36,1%	5,409E-07	0,8%	2,282E-05	31,1%	4,922E-05	67,1%	1,297E-06	1,8%
Ecosystem quality	28,89	77,6%	7,02	18,9%	1,30	3,5%	8,01	35,1%	14,69	64,3%	0,14	0,6%
Climate change	51,56	53,4%	44,83	46,4%	0,21	0,2%	20,51	17,9%	93,83	81,8%	0,32	0,3%
Resources	691,52	51,8%	639,84	48,0%	3,02	0,2%	318,61	19,2%	1339,16	80,5%	4,91	0,3%
Water withdrawal	1,67	91,4%	0,15	8,4%	0,00	0,2%	0,48	59,5%	0,32	39,7%	0,01	0,8%
Water turbined	1200,37	99,2%	9,53	0,8%	0,32	0,0%	120,98	85,6%	19,95	14,1%	0,44	0,3%

Table 21 Comparison of environmental impacts of aluminum and steel control arms

Similarly, the EOL phase does not have a significant effect in all impact categories, as shown in Table 21. Figure 39 shows the comparison of BOL and MOL phases for scenarios 1 and 5. As mentioned before BOL phase is the dominant phase for scenario 1. However, in case of steel FLCA the contribution of MOL phase is the higher for human health, ecosystem quality, climate change and resources indicators by 2-3 times of the BOL phase due to fuel consumption in this phase of the life cycle. The impacts on water withdrawal and water turbined of BOL phase is dominant for steel FLCA. However the impacts of aluminum FLCA is 3 to 5 times more than steel FLCA in these impact categories.

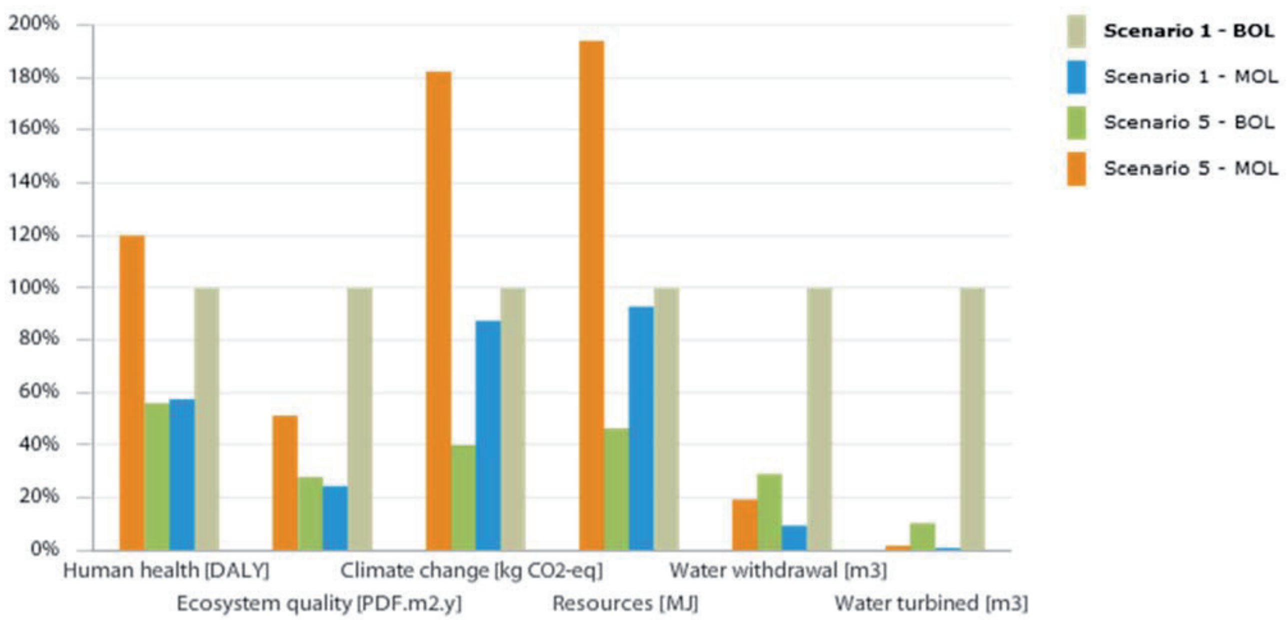


Figure 39 Comparison of BOL and MOL phases for scenario1 and scenario5

4.6.3 Economic Performance

Comparison of life cycle costs of the scenarios are shown in Figure 40 and Table 22. MOL phase is the dominant phase in all scenarios, ~65% for aluminum and ~85 for steel. Virgin aluminum cost constitutes the 22% of BOL costs and 7% of life cycle cost of FLCA. The cost of recycled aluminum is slightly less than virgin aluminum that’s why, using recycled aluminum does not have a significant effect on the life cycle cost of FLCA. Additionally, cost of EOL increases due to collection, treatment and transportation of aluminum scrap and processing of model alloy is slightly more costly than the standard alloy.

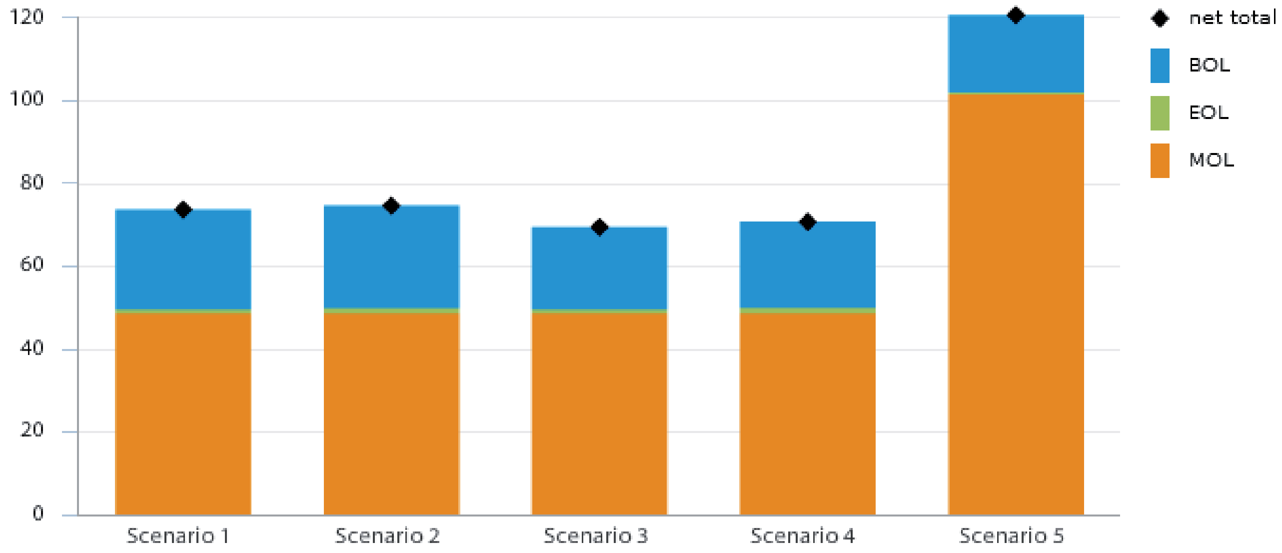


Figure 40 Life cycle cost [EUR] comparison of the scenarios

		Scenario1	Scenario2	Scenario3	Scenario4	Scenario5
Material Cost	Virgin	5,38	1,35	4,22	1,06	1,94
	Recycled		3,79		2,97	
BOL costs (material excl.)		18,87	19,72	15,75	16,80	16,83
MOL costs		48,58	48,58	48,58	48,58	101,47
EOL costs		0,95	1,25	0,95	1,35	0,48
Life cycle cost		73,77	74,67	69,50	70,76	120,72

Table 22 Life cycle cost comparison of 5 scenarios

Alternative production route decreases the BOL cost 12% due to less material usage and reduced processing cost (exclusion of extrusion). The material cost of steel is ~1/3 of aluminum, hence the processing costs are less than alternative production route. However, the MOL cost of scenario 5 is ~25% more than the life cycle cost of the most expensive scenario with aluminum input.

4.6.4 Social Performance

The rapid risk assessment of social and ethical indicators of FLCA is given in Table 23 and Figure 41. The social and ethical indicators taken into consideration in FLCA case study are; human rights, health and safety, labor and management relations, community relations, public policy, and political contributions. According to our assessment most of the indicators there is no risk and for the identified indicators there is a moderate risk which is acceptable. But it is required to monitor these indicators and search for improvement possibilities.

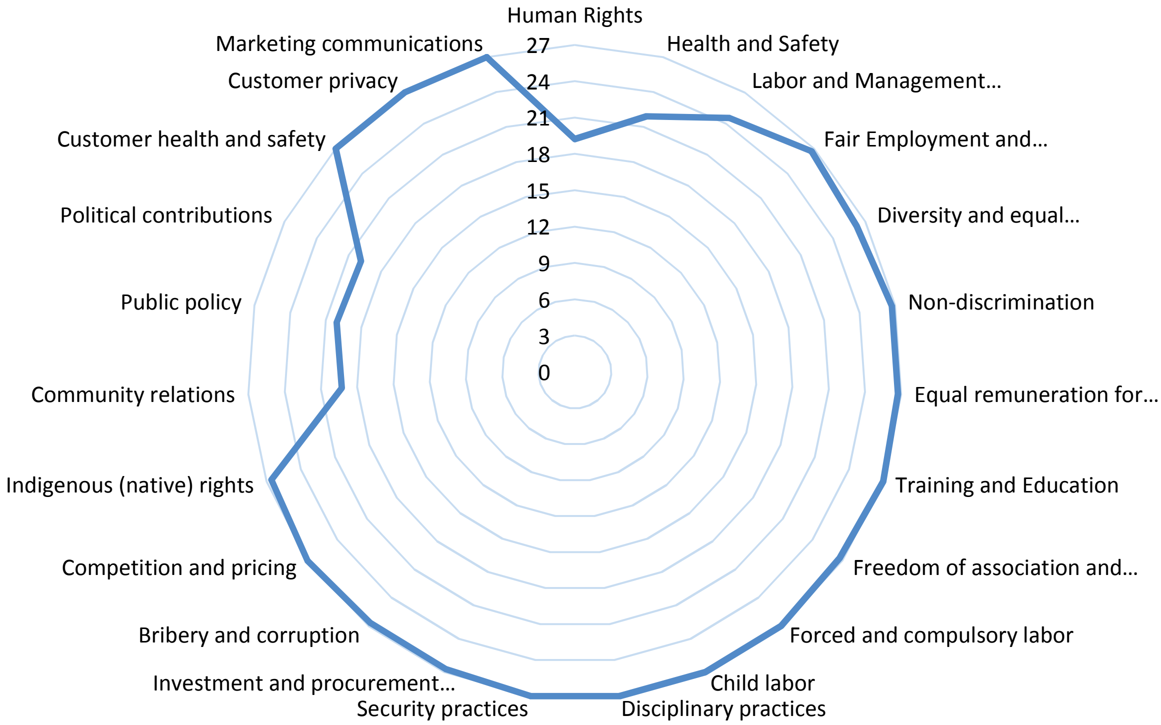


Figure 41 Rapid risk assessment of social and ethical indicators

However the most important risk indicator seems to be human rights, there is no significant violation of human rights by any value chain actor. The necessity to monitor the issue and make improvements by any means necessary remains intact. On the other hand, accept for the vehicle manufacturer, none of the life cycle actors have any procedure to follow or deal with the issues regarding human rights in business relations.

At the production sites of virgin aluminum production, there are reports describing and problems concerning land property and pollution issues, as well as poor relations with the local communities. That's why aluminum production stage should be kept in sight.

For the aluminum rod manufacturer and FLCA manufacturer, improvement possibilities are present when it comes to human rights issues in business relations, community relations, public policy and political contributions. These aspects are not concerned with high risk, but may be improved through more systematic and stronger emphasis internally and more information and transparency to the public.

Concerning other social and ethical aspects, the vehicle manufacturer is part of a global corporation which accounts for its sustainability practice. In addition, the automotive manufacturer has developed codes of conduct and development programs for communities, also available to the public. It is most frequently the focal firm in a supply chain which receives negative attention from media in the case of harmful social or ethical impacts to humans or the society. The vehicle manufacturer is the focal firm in its supply chain;

	Life cycle actors	Virgin Aluminum Producer	AA 6082 Rod Manufacturer	FLCA Manufacturer	Vehicle Manufacturer	Distributer	Owner	Authorized Collection Center	Shredder	Refinery/ Remelter	Total
1	Human Rights	2	2	2	3	2	2	2	2	2	19
2	Health and Safety	2	2	2	3	3	3	2	2	3	22
3	Labor and Management Relations	3	3	3	3	3	3	2	2	3	25
4	Fair Employment and Working Conditions	3	3	3	3	3	3	3	3	3	27
5	Diversity and equal opportunity	2	3	3	3	3	3	3	3	3	26
6	Non-discrimination	3	3	3	3	3	3	3	3	3	27
7	Equal remuneration for women and men	3	3	3	3	3	3	3	3	3	27
8	Training and Education	3	3	3	3	3	3	3	3	3	27
9	Freedom of association and collective bargaining	3	3	3	3	3	3	3	3	3	27
10	Forced and compulsory labor	3	3	3	3	3	3	3	3	3	27
11	Child labor	3	3	3	3	3	3	3	3	3	27
12	Disciplinary practices	3	3	3	3	3	3	3	3	3	27
13	Security practices	3	3	3	3	3	3	3	3	3	27
14	Investment and procurement practices	3	3	3	3	3	3	3	3	3	27
15	Bribery and corruption	3	3	3	3	3	3	3	3	3	27
16	Competition and pricing	3	3	3	3	3	3	3	3	3	27
17	Indigenous (native) rights	3	3	3	3	3	3	3	3	3	27
18	Community relations	2	2	2	3	3	2	2	2	2	19
19	Public policy	2	2	2	3	3	2	2	2	2	20
20	Political contributions	3	2	2	3	2	2	2	2	2	20
21	Customer health and safety	3	3	3	3	3	3	3	3	3	27
22	Customer privacy	3	3	3	3	3	3	3	3	3	27
23	Marketing communications	3	3	3	3	3	3	3	3	3	27

Table 23 Determination of social performance characteristics

therefore, it has worked continuously for many years to improve its overall sustainability conduct. As a consequence, only moderate risks concerned with HSE issues during manufacturing have been identified.

When it comes to sales, the vehicles are distributed and sold through brand stores, carrying one or more original brands. The FLCA itself has little influence over this stage in the product life cycle. The same is only partly true for the use and maintenance phase.

For the authorized treatment facility and shredder, there have been problems with the authorities concerning pollution. Moreover, issues as human rights in relation to the work space are not given a high priority within this company. Therefore, this company has been rated with moderate risk for some aspects.

Both refinery and remelter have the same aspects as moderate risk. Wrought-to-cast or wrought-to-wrought recycling does not have a substantial effect on the social performance of the control arm.

4.7 Discussion (Step 8)

The comparison of the defined scenarios for the defined performance characteristics is shown in Table 23. Using recycled material slightly reduces the mechanical properties, but does not have a significant effect on the technical performance. On the other hand, steel is superior to aluminum when it comes to mechanical properties, and the companies are more used to processing steel compared to aluminum. That’s why the technical performance of steel is better than aluminum.

Worse condition | Neutral condition | Better condition

Performance Characteristics	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Technical					
Environmental					
Economic					
Social					

Table 24 Comparison of the scenarios

It is necessary to note that, using recycled aluminum improves the environmental performance of FLCA significantly. Additionally, the alternative production reduces the amount of aluminum used in production thus have a positive impact on the environmental performance of FLCA. 4th scenario combines both 2nd and 3rd scenarios, has the best environmental performance. The most obvious using aluminum instead of aluminum is to reduce the emission on the use phase and improve environmental performance. The impact of MOL phase in 5th scenario is much more than reference scenario. Even BOL phase of 5th scenario has less impact on the environment, the environmental performance of 5th scenario is worse.

Since the price of the recycled material is close to virgin aluminum and the processing costs of the scenarios are not different than each other, and economic performance of FLCA is also not effected by using recycled material or changing the production route. The price and the processing costs of steel is less than aluminum, however the cost of use phase is 2 times more than reference scenario. That's why the economic performance of steel FLCA is worse than reference scenario.

The social performance of the life cycle actors, and the issues that needs to be monitored and improved. The main difference in the defined scenarios is the EOL actors and since they have similar social performance, there is no effect on the social performance of FLCA.

Chapter 5 Case study 2- Baggage Door Hinge

The application of holistic life cycle approach on baggage door hinge is presented in this section. The component is presented, actual and intended value chains, material and information flows are determined, alternative scenarios are defined and evaluated.

5.1 Introduction (Step 1)

Baggage door hinge, illustrated in Figure 42, of business jet aircraft Falcon 900 is the second test case component of SuPLight project. The component is located in the rear section of the aircraft and more precisely at the baggage compartment. It is assembled on the baggage door and its operation is to permit the rotation of the baggage door in a single axis line.

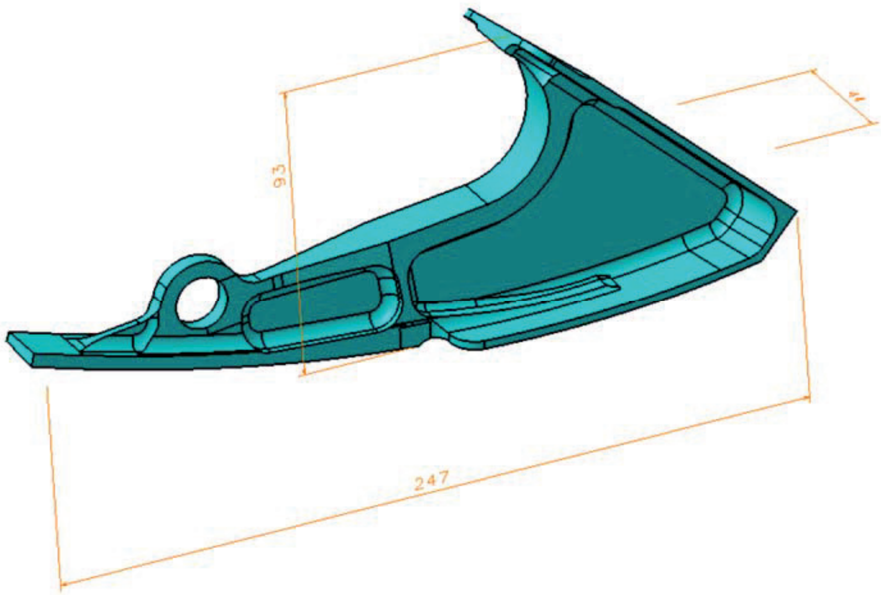


Figure 42 Baggage door hinge (BDH)

The hinge is machined from aluminum block by 5 axis milling machine. The material used for production is AA 7075-T7351, the chemical composition is given in Table 25. AA7075 is a very high strength material used for highly stressed structural parts and T7351 stands for the temper (heat treatment) which offers improved stress-corrosion cracking resistance. Mechanical and physical properties required from the material to produce BDH are listed in Table 26.

		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others Each	Others Total
AA 7075	Min			1.20		2.10	0.18	5.10			
	Max	0.40	0.50	2.00	0.3	2.90	0.28	6.10	0.20	0.05	0.15

Table 25 Chemical composition of the standard AA 7075 alloy

Category	Label	Default value	Units
Mechanical Properties	Yield Strength	503	Mpa
	Tensile Strength	572	MPa
	Elongation	11	%
	Hardness	155	HV10
	Fatigue	159	MPa
	Corrosion resistivity	B	A, B, C, D
Physical Parameters	Density	2.81	g/cc
	Young's Modulus	72	GPa
	Room temperature	23	°C
	Specific Heat	0,96	Joule/Kg °C
	Thermal Conductivity	155	W/m -k
	Emissivity	0,1	
	Poisson Ratio	0.33	

Table 26 Required properties for BDH

In this case study, the impact of using recycled aluminum and changing the production route of initial block for machining is investigated. More detailed information regarding the value chain, production routes and material flow are given in the previous sections.

5.2 Value Chain of BDH (Step 2)

The actual value chain of BDH, shown in Figure 43, is described in this section.

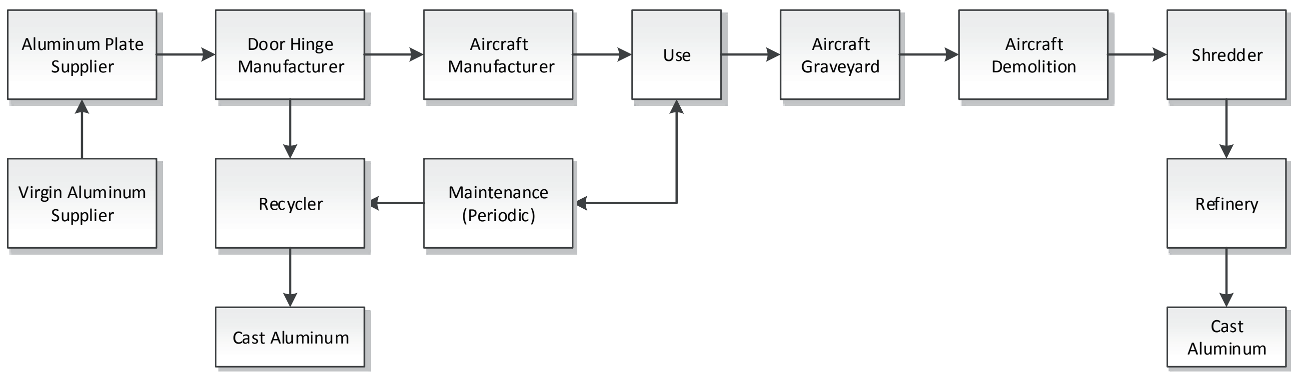


Figure 43 Actual value chain of BDH

The aluminum plate suppliers are situated in USA and UK. Aluminum plate supplier produces AA7075 from virgin aluminum and produces plates by hot rolling. The plates are heat treated in order to gain the designated temper and achieve necessary properties.

Door hinge manufacturer is situated in Greece, door hinge manufacturer receives the plates and cuts the plates in desired dimensions and the door hinge is machined by a 5-axis machining center. The aluminum plates are used not only to manufacture the door hinge but also other components for the aircraft. The door hinge is assembled to the baggage door and sent to the Aircraft manufacturer. Door hinge manufacturer uses various types of aluminum alloys for production of aircraft components. There is not a treatment procedure for the production scrap. Production scrap and detached components is collected and sent to the recycler which is located in France.

Aircraft manufacturer is situated in France. The door is assembled on the plane by the Aircraft manufacturer and sent to the customer. Door hinge manufacturer also provides on-site maintenance support to their customers. The components are inspected periodically and changed if there is any notice of failure. The components are also disassembled and changed with the new ones after a predetermined number of flight hours.

When aircrafts reach the EOL, they are mostly collected in airplane graveyards. Although most of an aircraft is made of aluminum, different aluminum alloys are used for different components. This makes the demolition of an airplane mode difficult and less profitable. When an airplane is demolished, aluminum components are separated from the others and sent to refinery for production of cast aluminum.

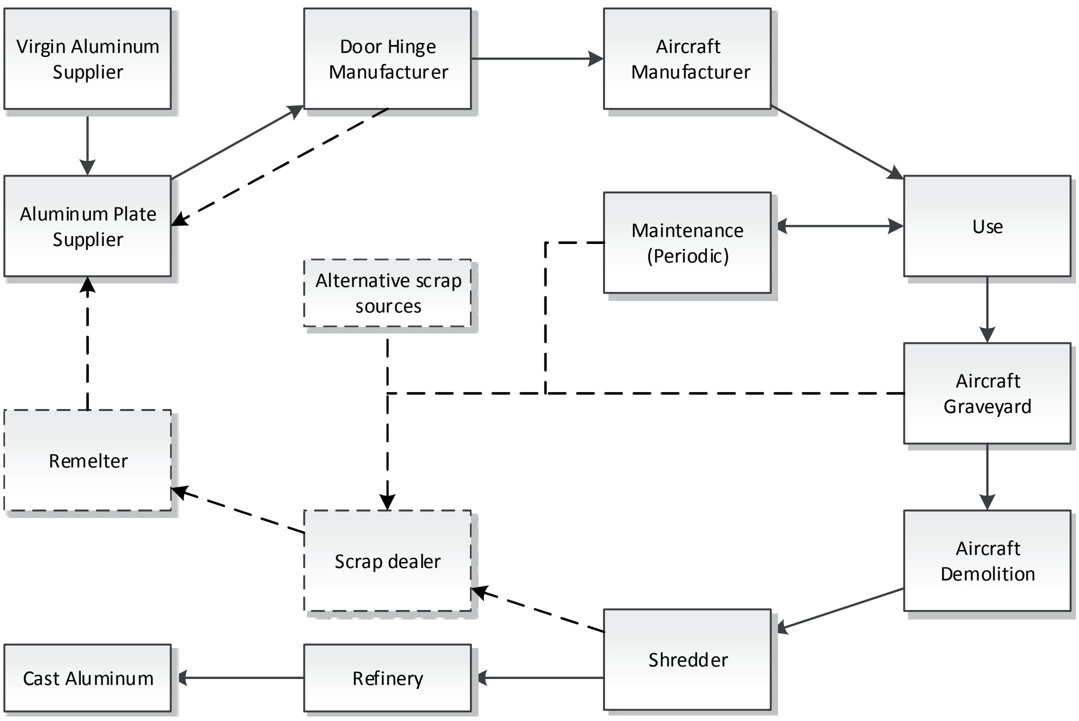


Figure 44 Intended value chain of BDH

The intended value chain of BDH is given in Figure 44. In order to achieve the aforementioned objectives the following actions should be taken. Door hinge manufacturer implement scrap treatment procedures and separates the aluminum scrap by alloy type. Production scrap containing the sawdust, machining chips and unqualified BDH are collected separately and sent to the aluminum plate supplier, where they are remelted in alloy treatment stage. Detached parts in maintenance, disassembled parts in the aircraft graveyard, detailed sorted aluminum scrap from shredder are sent scrap dealer. Scrap dealer collects the aluminum scrap from the life cycle actors and mix with aluminum scrap from alternative sources, to meet the demand and sends them to remelter. The remelter melts the aluminum scrap and prepares an aluminum alloy which is later alloyed to meet the desired composition.

5.3 Material Flow of BDH (Step 3)

The production stages of DBH is shown in Figure 45. Traditional production route includes, direct chill casting, hot rolling and machining. AA 7075 ingots are produced by direct chill casting, the ingots are homogenized and hot rolled to produce AA 7075 plates. The plates are then tempered to achieve desired mechanical properties. The blocks with desired dimensions are cut from the plates and the door hinge is machined from these blocks.

In the alternative production route, also shown in Figure 45, AA 6082 slabs are produced by the Aluminum Rod supplier of FLCA, by direct chill casting and extrusion. The alternative production route enables reduce initial block mass by 30%, since the dimensions of AA 6082 slab are designed for BDH production. The plate used in the traditional production route is has generic dimensions, and it is used to produce all kind of components for the aircraft.

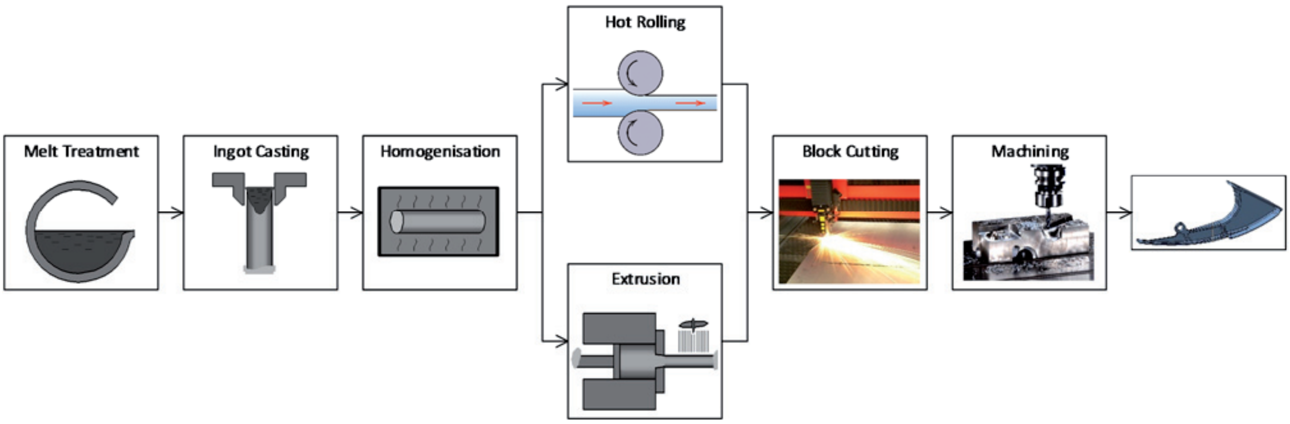


Figure 45 Traditional and alternative production routes for BDH

Taking into account the traditional and alternative production routes and substitution of recycled aluminum with virgin aluminum 4 scenarios have been determined for evaluation of BDH.

1- Traditional production route – 100% Virgin aluminum input (Reference)

2- Traditional production route – 75 % Recycled & 25% Virgin aluminum input

3- Alternative production route – 100% Virgin aluminum input

4- Alternative production route – 75 % Recycled & 25% Virgin aluminum input

The assumptions made to generate the life cycle inventory are as follows.

4. 75 % of the aluminum plates come from UK and 25% of them come from USA.

5. The use of machinery and infrastructure for each life cycle actor are included in the overhead. The overheads of door manufacturer and aircraft manufacturer is much higher than the life cycle actor of FLCA, since they produce fewer components and invest more to their operations.

6. Door hinge is checked after 6000 flight hours, and changed after 18000 flight hours, fuel consumption of Falcon 900 is 303 gallons/fhs, fuel price is 1.82 euro/gallons, and Weight of Falcon 900 is 10500 kg.

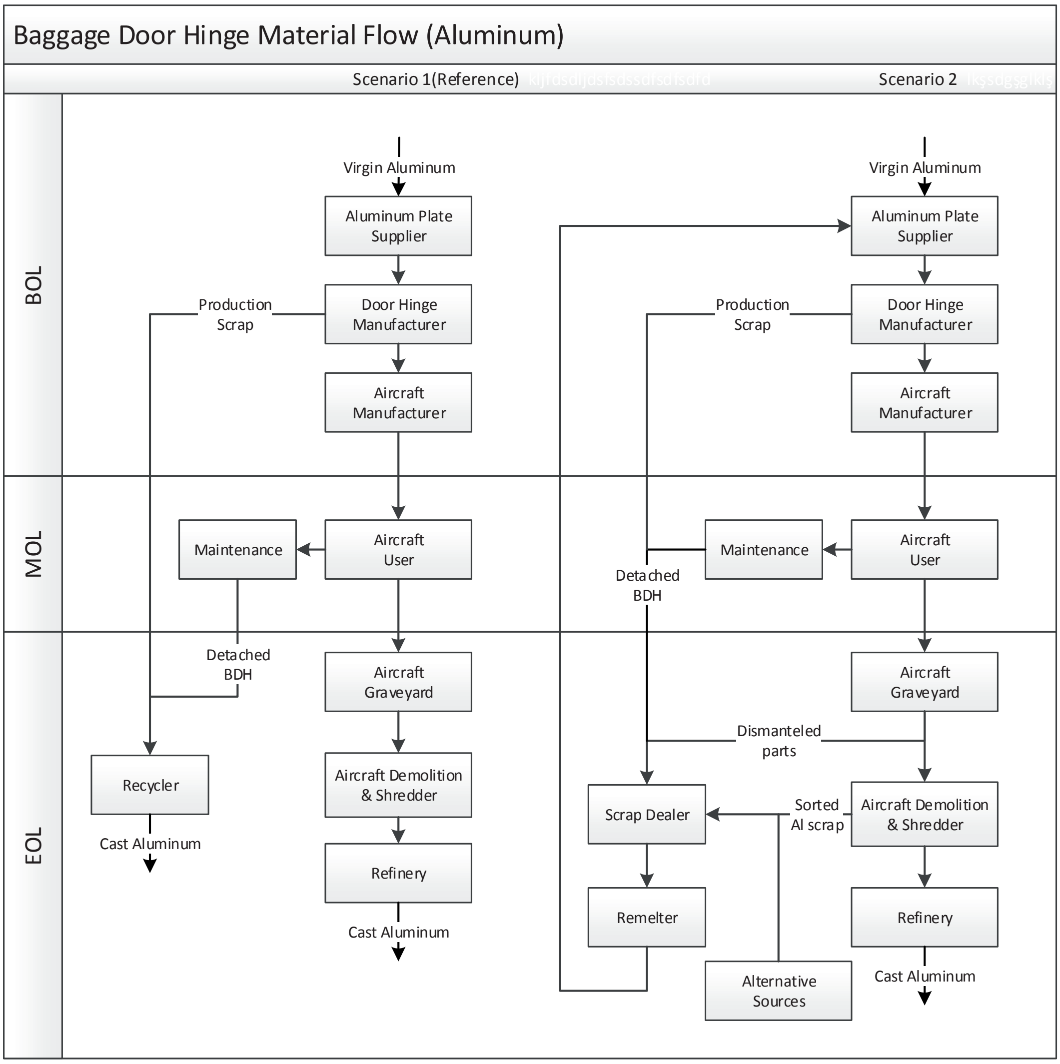


Figure 46 The aluminum flow in scenario 1&2

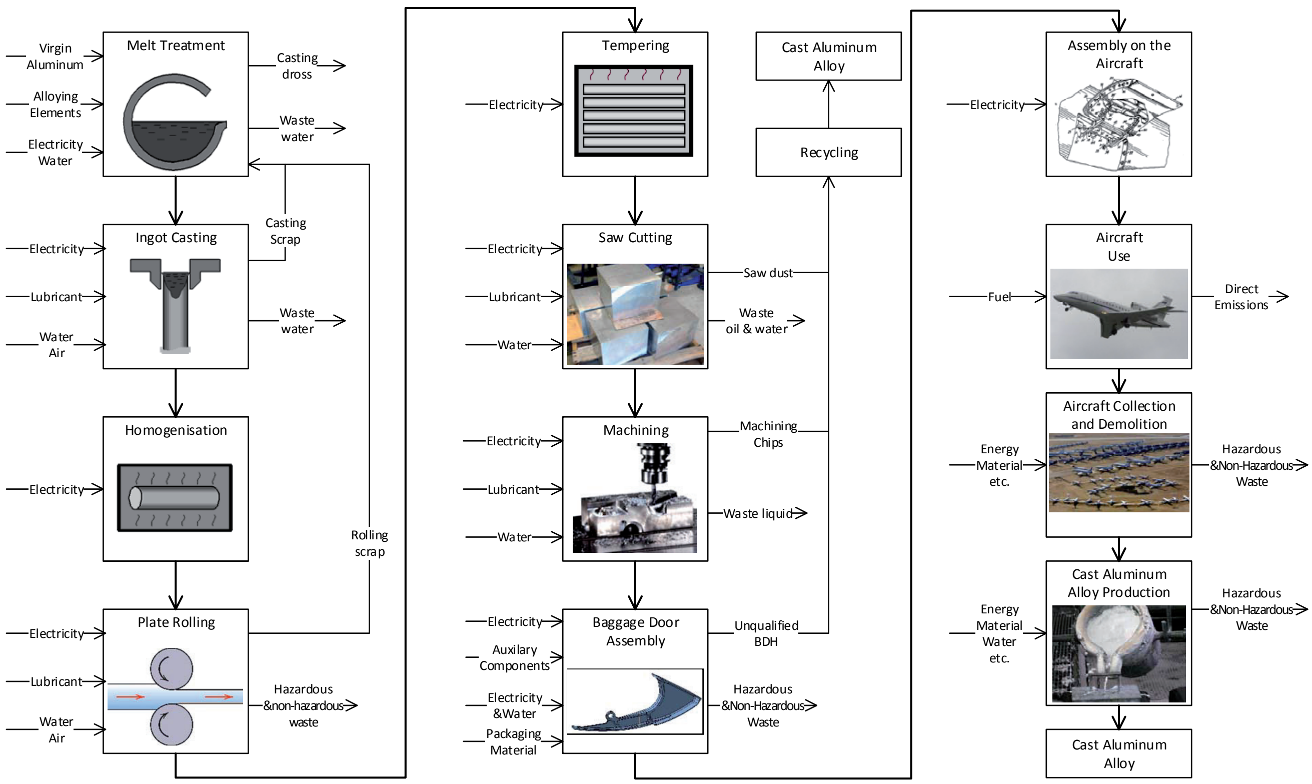


Figure 47 Detailed material flow of BDH

The aluminum flow of BDH for scenarios 1 and 2 are given in Figure 46. The life cycle inventory for BDH is generated taking in to account the detailed material flow which illustrated in Figure 47.

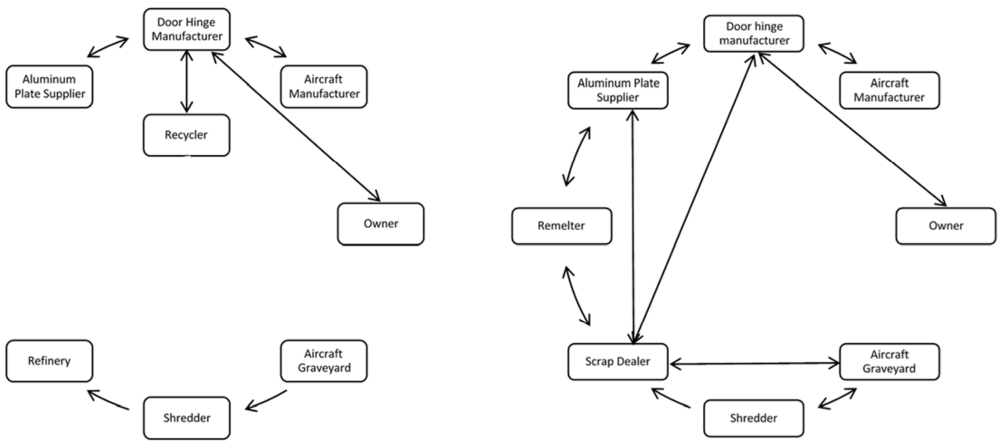
5.4 Information Flow of BDH (Step 4)

The related tasks of the life cycle actors of BDH are shown in Table 27. "*" indicates the tasks related with the alternative production route.

Life Cycle Phase	Life cycle actor	Tasks
BOL	Al Plate Supplier	AA7075 ingot and plate production (rolling) Plate heat treatment
	Aluminum Rod Supplier*	AA7075 ingot production Billet extrusion Heat treatment of billets Define the acceptable scrap characteristics
	Door Hinge Manufacturer	Define material properties Door hinge production Production scrap collection Quality control
	Aircraft Manufacturer	Door hinge design Define quality requirements
MOL	Door Hinge Manufacturer	Maintenance (periodic) Disassembly of worn components Collection detached components
EOL	Aircraft Graveyards	Aircraft collection and demolition Disassembly of designated components
	Shredder	Shredding scrap from aircraft demolition Sorting shredded aluminum scrap
	Refinery	Cast aluminum production
	Recycler	Aluminum scrap collection Wrought-to-cast aluminum recycling
	Scrap Dealer*	Aluminum scrap collection Sorting collected scrap Storage of scrap
	Remelter*	Wrought-to-wrought aluminum recycling

Table 27 Tasks of life cycle actors

The main data to be transmitted between life cycle actors of door hinge is shown in Figure 48. In BOL, information flow between aircraft manufacturer and baggage door hinge manufacturer is quite complete in order to design and product the door hinge. Due to the fact that, the amount of door hinges produced for the aircraft is not too much compared to mass-produced automotive components, and the maintenance of the components is carried out by the door hinge producer, the door hinge producer has full control over their product. It is even possible to track the each component, back to the aluminum plate received from supplier. The information flow in the EOL of the aircraft is Information flow in the current and alternative scenarios is different from each other. In the alternative scenario, it is required to there is a need for data concerning the EOL activities for gathering.



Information Flow		Main data
Source	Destination	
Aluminum Plate Supplier Aluminum Rod Supplier*	Door Hinge Manufacturer	Mechanical properties of the plate Chemical composition of the plate Amount and source of recycled material in the slab*
	Scrap dealer	Characteristics of acceptable scrap*
Door Hinge Manufacturer	Aluminum Plate Supplier Aluminum Rod Supplier*	Characteristics of acceptable plate/slab
	Aircraft manufacturer	Quality control results of the door hinge Reason of detachment (feedback to designers)
	Recycler	Amount of scrap (production scrap and detached components)
Aircraft manufacturer	Door Hinge Manufacturer	Design of door hinge Amount of door hinges needed for production Number of flight hours within the component can be operational
Aircraft Graveyard	Refinery	Amount of aluminum retrieved from demolition
Scrapyard*	Scrap dealer*	Amount and contents of aluminum scrap (BDH production ELV, EOL packaging and building demolition)*
Scrap dealer*	Aluminum Plate Supplier Aluminum Rod Supplier*	Amount and contents of aluminum scrap*

Figure 48 Main information flow between life cycle actors of BDH.

5.5 Performance characteristics of BDH (Step 5)

The list of technical performance characteristics of the door hinge is given in Table 28. The environmental, economic performance characteristics, shown in Tables 7&8, are computed for each process through the life cycle of BDH. Social and ethical indicator are specified by rapid risk ranking. However the social performance characteristics are not determined. The evaluation is made based on these indicators.

Material Composition				**Mechanical Properties**	**Process Parameters**
Mass	BDH			Yield strength	Ingot casting yield
	Virgin Aluminum			Tensile strength	Ingot casting electricity
	Secondary Aluminum			Hardness	Hot rolling yield
				Fatigue	Hot rolling electricity
Alloying elements		Mass	Ratio	Corrosion resistivity	Al plate supplier productivity
	Si	**	**		Extrusion yield
	Fe	**	**		Extrusion electricity
	Cu	**	**	Physical Parameters	Al rod supplier productivity
	Mn	**	**	Density	Initial block mass
	Mg	**	**	Young's modulus	Machinability
	Cr	**	**	Strain rate	Machining yield
	Zn	**	**		Machining electricity
	Ti	**	**		Product surface quality

Table 28 Technical performance characteristics of BDH

5.6 Comparison of the scenarios (Step 6-7)

5.6.1 Technical Performance

The composition of AA 7075 and AA6082 are given in Table 29. AA 7075 contains more Mg, Cu and Zn, which increases the strength of aluminum alloys significantly. Since the alloying elements in the AA7075 is higher, this also makes it easier to produce the alloy from aluminum scrap. However, the contamination of the aluminum scrap may be a problem, since high quality material is required for aeronautics applications.

		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others	
										Each	Total
AA 7075	Min			1.20		2.10	0.18	5.10			
	Max	0.40	0.50	2.00	0.3	2.90	0.28	6.10	0.20	0.05	0.15
AA 6082	Min	0.70			0.40	0.60					
	Max	1.30	0.50	0.10	1.00	1.20	0.25	0.20	0.10	0.05	0.15

Table 29 Chemical composition of the standard AA 7075 and AA 6082

Comparison of technical performance characteristics is shown in Table 30. Although, the strength of AA 6082 is less than AA 7075, it is sufficient for to pass the design requirements. It is obvious that using recycled material decreases the strength and hardness of the material, however the reduction is not significant. AA6061 has higher corrosion resistivity due to the fact that it is designed to be used in corrosive situations.

When the production routes are compared the yield and productivity of the processes are slightly higher in the alternative production route. The electricity consumption of alternative production route is also less not only because the processes are more efficient, but also because less material is used and processed for production of door hinge. Since, the last operation of the production route determines the surface quality of the product and both materials have the same machinability performance, BDH from all the scenarios have sufficient surface quality.

Category	Label	Scenario1	Scenario2	Scenario3	Scenario4	Units
Composition	Mass of BDH	205	205	205	205	gr
	Virgin aluminum mass	4860	1215	3321,6	830,4	gr
	Recycled aluminum mass	0	3645	0	2491,2	gr
	Recycled ratio	0	75	0	75	%
Mechanical Properties	Yield strength	503	490	320	312	Mpa
	Tensile strength	572	550	350	341	MPa
	Elongation	11	10	10	10	%
	Hardness	155	145	100	98	HV10
	Fatigue	159	155	140	140	MPa
	Corrosion resistivity	B	B	A	A	A, B, C, D
Physical Parameters	Density	2810	2810	2700	2700	kg/m^3
	Young's modulus	72000	72000	70000	70000	MPa
	Strain rate	-	-	1	1	s^{-1}
Process Related Properties	Ingot casting yield	95,0	92,0	98,0	98,0	%
	Ingot casting electricity	4,58	4,58	3,13	3,13	kWh
	Hot rolling yield	82,0	80,0	-	-	%
	Hot rolling electricity	0,27	0,27	-	-	kWh
	Al plate supplier productivity	77,9	73,6	-	-	%
	Extrusion yield	-	-	80,0	80,0	%
	Extrusion electricity	-	-	0,51	0,51	kWh
	Al rod supplier productivity	-	-	78,4	74,1	%
	Initial block mass	4185	4185	2790	2790	gr
	Machinability	B	B	B	B	A, B, C, D
	Machining yield	4,70	4,70	7,35	7,35	min
	Machining electricity	16	16	11	11	kWh
	Product surface quality	Y	Y	Y	Y	Y/N

Table 30 Comparison of technical performance characteristics

5.6.2 Environmental Performance

Lifecycle environmental impacts and costs of BDH by lifecycle phase are shown in Figure 49 and detailed results are given in Table 31. The environmental impact of EOL phase is very little compared to the other life cycle phases. When life cycle environmental impacts are examined, MOL phase dominates human health, climate change and resources indicators. MOL phase has over 80% contribution for these indicators. The main activity in MOL phase is fuel use in the flight of the plane. The flight of an aircraft has a significant impact on the environment, which may be reduced by decreasing the weight of the aircraft and/or its components.

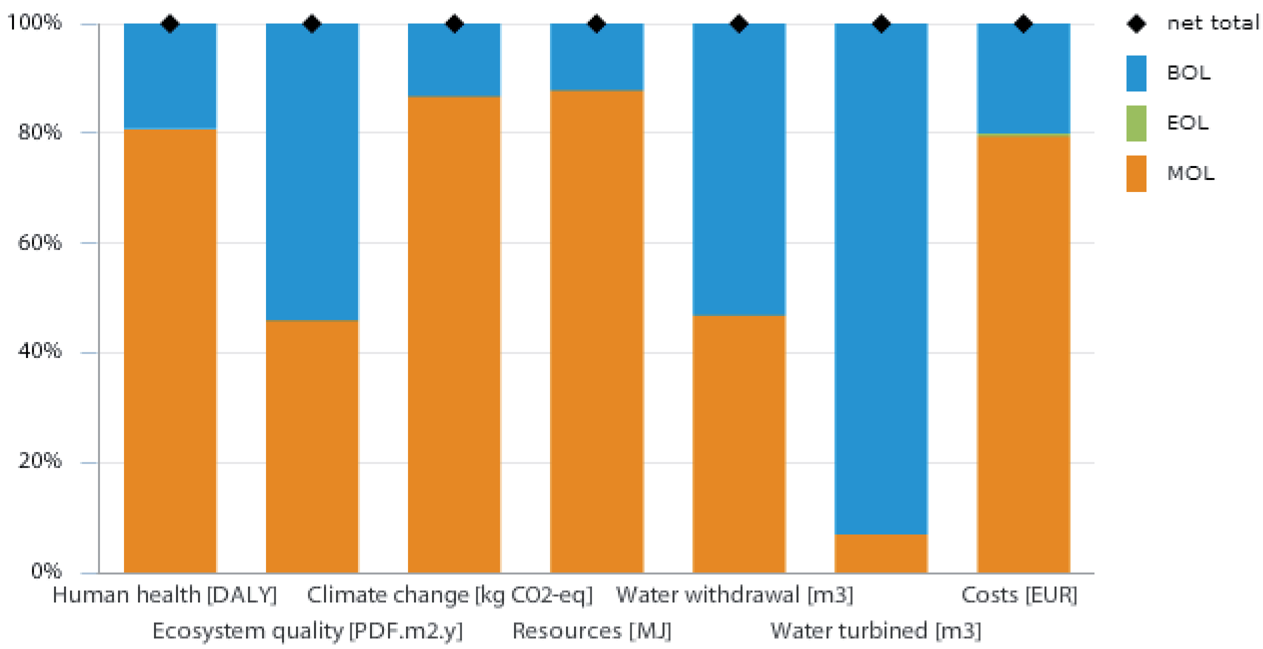


Figure 49 Lifecycle environmental impacts and costs of BDH

The impact of BOL and MOL phases are close for ecosystem quality, in which virgin aluminum used for production has a major contribution in BOL phase. The contribution of BOL phase for water turbined and water withdrawal indicators is significantly dominated by virgin aluminum production due to the electricity used for electrolysis.

Scenario 1	BOL		MOL		EOL		Total	Unit
Human health	8,89E-05	19,28%	3,72E-04	80,71%	5,91E-08	0,01%	4,61E-04	DALY
Ecosystem quality	87,91	54,06%	74,69	45,94%	2,83E-03	0,00%	162,60	PDF.m^2.y
Climate change	111,65	13,34%	725,47	86,66%	7,11E-03	0,00%	837,13	kg CO^2-eq
Resources	1491,21	12,24%	10694,48	87,76%	1,48E-01	0,00%	12185,84	MJ
Water withdrawal	2,89	53,20%	2,54	46,80%	3,36E-04	0,01%	5,43	m^3
Water turbined	1732,29	93,02%	129,93	6,98%	8,39E-03	0,00%	1862,23	m^3
Costs	61,87	20,08%	244,49	79,36%	1,70	0,55%	308,06	EUR

Table 31 Lifecycle environmental impacts and costs of BDH

When we compare the scenarios, it is obvious that using recycled aluminum and changing the production route has a positive impact on the environment (for human health, ecosystem quality, climate change, and resources indicators). Unfortunately this positive impact is not very much visible since BOL phase contributes less than 20% of life cycle environmental impacts of the door hinge. For water with drawal and water turbined indicators the impact of the alternative scenarios are more visible since these indicators are dominated by the electricity used and water consumed for aluminum production.

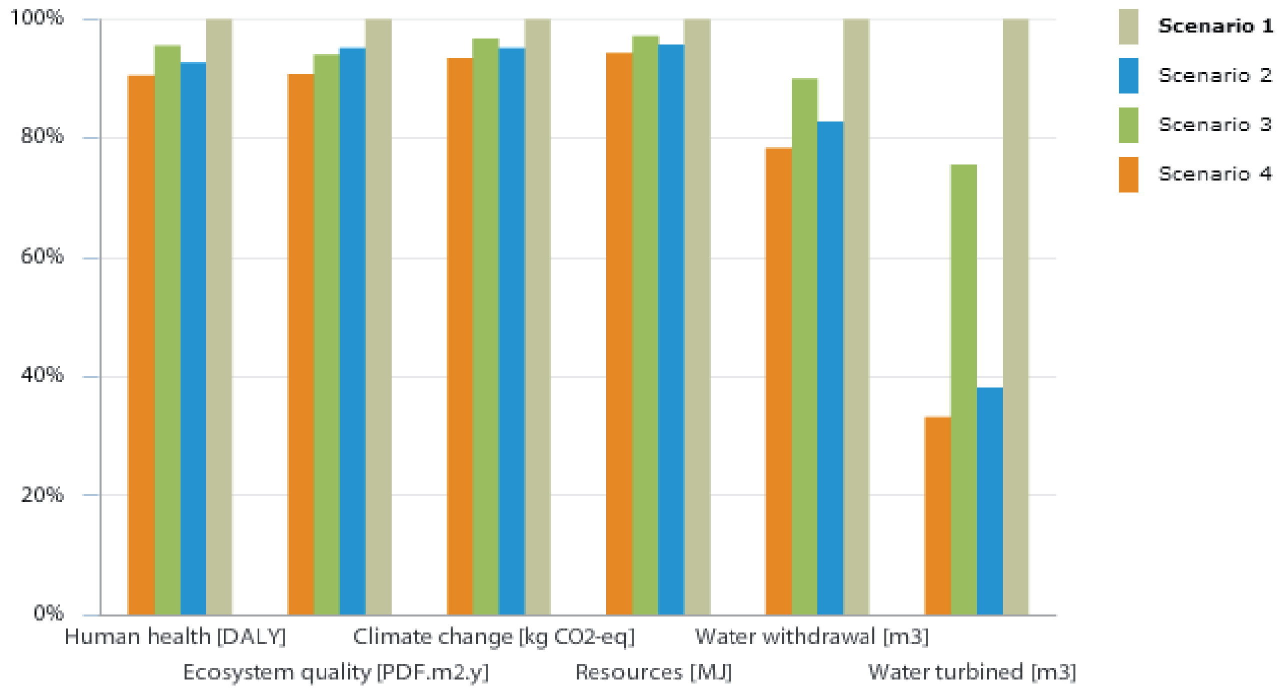


Figure 50 Comparison of the environmental impact of the scenarios

When we focus on the BOL phase the contribution of impact reduction activities become more visible. The comparison of environmental impacts of BOL phase is illustrated in Figure 51 and the results are given in Table 32. The impacts on human health, climate change, resources and water withdrawal may be reduced ~40% by using recycled aluminum. Since contribution BOL and MOL phases on the impacts on ecosystem quality is nearly equal, the reduction patter is similar to life cycle impacts in this indicator. As mentioned before contribution of virgin aluminum production is significant for water turbined indicator. The impact on this indicator may be reduced more than 60% by using recycled aluminum.

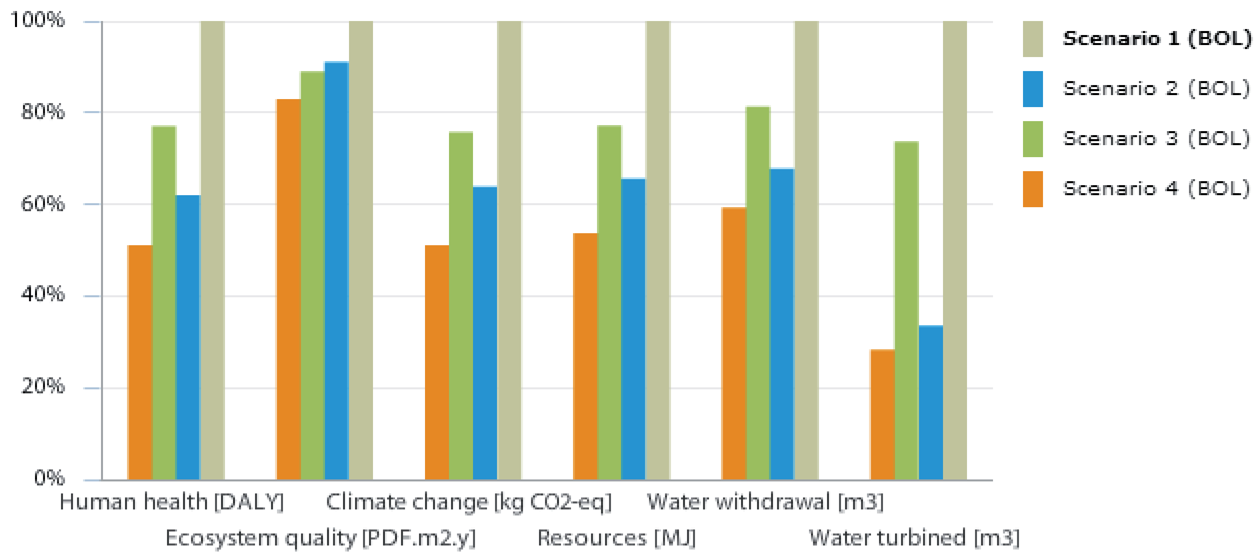


Figure 51 Comparison of BOL phases of the scenarios

Changing the production route also reduces the environmental impact on all the indicators by 10% to 25%. The main reason of the reduction is due to the fact that the amount of aluminum used for production is reduced.

	Scenario1 BOL	Scenario 2 (BOL)		Scenario 3 (BOL)		Scenario 4 (BOL)		Total	Unit
Human health	8,89E-05	5,51E-05	-38%	6,85E-05	-23%	4,54E-05	-49%	2,58E-04	DALY
Ecosystem quality	87,91	80,09	-9%	78,25	-11%	72,91	-17%	319,15	PDF.m^2.y
Climate change	111,65	71,28	-36%	84,60	-24%	57,01	-49%	324,54	kg CO^2-eq
Resources	1491,21	979,03	-34%	1150,41	-23%	800,38	-46%	4421,03	MJ
Water withdrawal	2,89	1,96	-32%	2,35	-19%	1,71	-41%	8,91	m^3
Water turbined	1732,29	580,01	-67%	1276,71	-26%	489,24	-72%	4078,25	m^3

Table 32 Comparison of BOL phases of the scenarios

The reduction on the all environmental impact indicators are maximized when both attempts are combined. It offers 40% to 50% reduction for all indicators, accept the reduction of the impact on ecosystem quality is 17%.

5.6.3 Economic Performance

The comparison of life cycle costs are shown in Figure 52 and results are given Table 33. More detailed results are given in the appendix. Similar to the environmental impacts, life cycle cost of the BDH is also dominated by MOL phase. 79% of the life cycle cost of BDH is caused by MOL phase. Contribution of EOL phase on the life cycle cost is around 1% even if the collection, separation and transportation efforts are included in the alternative scenarios.

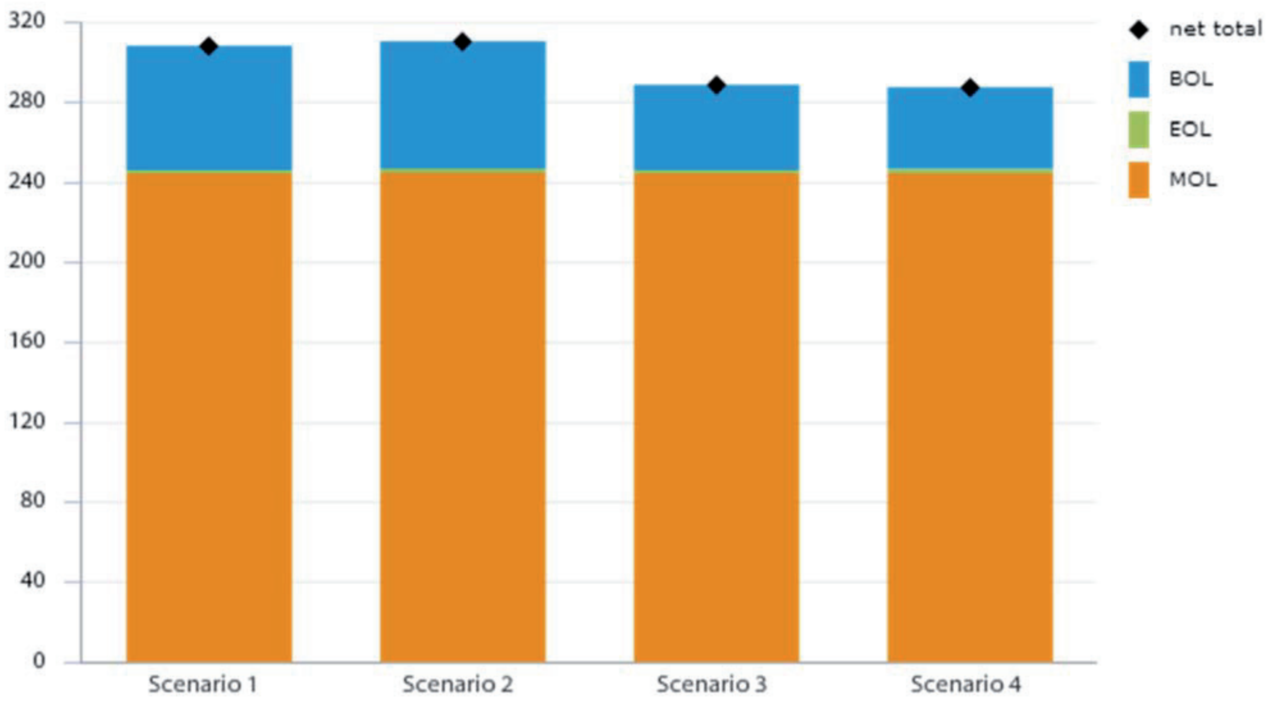


Figure 52 Lifecycle costs comparison of BDH scenarios (EUR)

Virgin aluminum cost constitutes 13% of BOL costs and 2.5% of life cycle costs. Since recycled aluminum cost is close to virgin aluminum, using recycled aluminum does not have significant impact, on contribution of aluminum on costs of BOL phase and life cycle cost of BDH. However, it raises Processing costs contributes 17.5% to life cycle costs. The overhead costs have a substantial contribution to BOL costs because of the fact that in aeronautics industry, the cost of infrastructure, machinery, management and engineering labor costs are high and in addition a small number of products are manufactured. The alternative production route reduces both aluminum and processing cost 32%. In scenario 4 contribution of BOL costs is 15% where in the reference scenario it is 20%.

		Scenario1	Scenario2	Scenario3	Scenario4
Material Cost	Virgin	7,87	1,97	5,38	1,35
	Recycled		5,54		3,79
BOL costs (material excl.)		54,00	55,80	36,85	37,95
MOL costs		244,99	244,99	244,99	244,49
EOL costs		1,70	2,30	1,70	2,30
Life cycle cost		308,56	310,60	288,92	289,87

Table 33 Life cycle cost comparison of BDH scenarios (EUR)

5.6.4 Social Performance

Rapid risk assessment results for the value chain actors of BDH are given in Table 34 and shown Figure 53. Related social and ethical indicators for the life cycle actors of door hinge are; health and safety, fair employment and working conditions, diversity and equal opportunities, training and education security practices, community relations, and public policy. There is moderate risk for these indicators, and it is acceptable. However, human rights seems to be the most significant issue for all the life cycle actor in Figure 53, there is not violation of human right bay any of the life cycle actors. This indicator is significant due to the fact that none of the life cycle actors have procedure concerning this indicator. All the life cycle actors should develop and exercise procedures and policies to monitor and improve their practices regarding human rights. Since the working conditions of the metal processing industry is hard, the number of women employed and employees that are older than a certain age are not hired which may also be considered as a diversity and discrimination issue. There are also issues regarding public policy and local community, due to the land occupation and pollution problems, in which there is moderate risk and improvement possibilities.

Virgin aluminum supplier has problems with the local authorities regarding pollution and land property which leads to poor relations with the local community. Due to number of accidents happened and the severity these accidents happened in the production site of the virgin aluminum supplier, there is a high risk of human health and safety and security practices. Although, the virgin aluminum supplier has procedures and policies. The working conditions of the workers should be improved and a monitoring system for employee satisfaction should be developed.

Figure 53 Rapid risk assessment of social and ethical indicators

There are improvement possibilities for health and safety, security practices, investment and procurement practices, and bribery and corruption concerning the social ant ethical aspects of aluminum plate supplier. The company promotes international labor standards and human rights among suppliers and business partners, and performs audits to their suppliers. However, it has not defined a minimum business partner standard regarding sustainability. The company does not have a code of conduct for bribery in the business relations. The company neither accept nor deny that the business transactions are performed with bribery. The most important improvement for this issue may be giving anti-corruption and information and training to all employees.

The social and ethical issues of aluminum rod supplier were discussed in section 4.6.4.

For what concerns the social and ethical performance of the BDH manufacturer, improvement possibilities are present when it comes to fair employment, and working conditions and competition in addition to the fore mentioned issues concerning all life cycle actors.

Concerning the social and ethical issues for aircraft manufacturer, there are improvement possibilities and requires monitoring on health and safety, fair employment and working conditions, diversity and equal opportunities and non-discrimination.

	Lifecycle actors	Virgin Aluminum Supplier	Al Plate Supplier	Al Rod Supplier	BDH Manufacturer	Aircraft Manufacturer	Owner	Aircraft Scrapyard	Shredder	Refinery	Recycler	Logistics Company	Scrap Dealer	Remelter	Total
1	Human Rights	2	2	2	2	2	2	2	2	2	2	2	2	2	26
2	Health and Safety	1	2	2	2	2	2	2	2	3	2	3	2	3	28
3	Labor and Management Relations	2	3	3	3	3	3	3	3	3	3	3	3	3	38
4	Fair Employment and Working Conditions	2	3	3	2	2	2	2	2	2	3	2	3	2	30
5	Diversity and equal opportunity	2	2	3	2	2	2	2	2	3	3	3	3	3	32
6	Non-discrimination	2	2	3	2	2	2	2	2	3	3	3	3	3	32
7	Equal remuneration for women and men	3	3	3	3	3	3	3	3	3	3	3	3	3	39
8	Training and Education	3	3	3	3	3	3	2	2	2	3	2	3	2	34
9	Freedom of association and collective bargaining	3	3	3	3	3	3	3	3	3	3	3	3	3	39
10	Forced and compulsory labor	3	3	3	3	3	3	3	3	3	3	3	3	3	39
11	Child labor	3	3	3	3	3	3	3	3	3	3	3	3	3	39
12	Disciplinary practices	3	3	3	3	3	3	3	3	3	3	3	3	3	39
13	Security practices	1	2	3	3	3	2	3	2	3	2	3	2	3	32
14	Investment and procurement practices	2	2	3	3	3	3	3	3	2	3	2	3	2	34
15	Bribery and corruption	2	2	3	3	2	3	3	3	3	2	3	2	3	34
16	Competition and pricing	3	3	3	2	3	3	3	3	3	3	3	3	3	38
17	Indigenous (native) rights	2	2	3	3	3	2	3	2	3	2	3	2	3	33
18	Community relations	2	2	2	2	2	2	2	2	3	3	3	3	3	31
19	Public policy	2	2	2	2	2	2	2	2	3	3	3	3	3	31
20	Political contributions	3	3	2	3	3	3	3	3	3	3	3	3	3	38
21	Customer health and safety	3	3	3	3	3	3	3	3	3	3	3	3	3	39
22	Customer privacy	3	3	3	3	3	3	3	3	3	3	3	3	3	39
23	Marketing communications	2	2	3	3	3	2	2	2	3	3	3	3	3	34

Table 34 Determination of social performance characteristics of BDH

When it comes to the use phase, the baggage door hinge has a very little effect on the social aspects of this phase.

All the EOL actors in the reference and alternative scenarios (aircraft scrapyard, shredder, recycler, scrap dealer, and remelter) have similar social and ethical issues. There are improvement possibilities on health and safety, fair employment and working conditions, training and education, security practices, and bribery and corruption. There is a moderate risk for these indicators, it is required to monitor these indicators and make improvements if possible.

Logistics company/ies have issues only regarding the working conditions, training and education and investment and procurement practices. For these indicators there is not any violation, the reason why these indicators have moderate risk, is due to lack of procedures and policies for dealing with any issues observed regarding them.

5.7 Discussion (Step 8)

The comparison of the scenarios for baggage door hinge is shown in Table 35. Recycling does not have a significant effect on the technical performance. Additionally, the mechanical properties of aluminum alloy in the alternative production route is sufficient for BDH but worse than the traditional alloy.

Worse condition | Neutral condition | Better condition

Performance Characteristics	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Technical				
Environmental				
Economic				
Social				

Table 35 Comparison of the BDH scenarios

Using recycled material reduces the environmental impact of the door hinge, and changing the production route improves the environmental performance by reducing the material input, and impacts due to material processing. Since both of the approaches are combined in the 4th scenario, the environmental performance is also improved.

~80% of life cycle cost of BDH occur during use phase. Recycling slightly increases the BOL phase but it is not essential. The alternative scenario reduces the material and processing costs thus have a better economic performance than reference scenario.

Recycling does not have a significant effect on the social performance but alternative production route involves companies with better social performance thus improves the social performance of the door hinge.

Chapter 6 Case study 3- Flexographic Ink Recycling

The application of holistic life cycle approach on flexographic printing ink recycling is presented in this section. Flexographic printing process and ink recycling is presented, actual and intended value chains, material and information flows of flexographic ink are determined, alternative scenarios are defined and evaluated.

6.1 Introduction (Step 1)

Flexography is a process used primarily for printing on paper, corrugated paperboard, and flexible plastic materials. Flexography uses a soft, flexible printing plate that is mounted on a rotary cylinder. Flexographic presses are equipped with anywhere from one to as many as twelve colour stations. Examples of items printed with flexography include comics, newspapers, appliance boxes, and many grocery store packages – including cereal boxes, shampoo and soda bottle labels, frozen food and bread bags, and milk cartons [1].

There are three primary flexographic ink systems, which are solvent-based, water- based and UV-cured ink systems. Solvent-based and water-based inks are dried using evaporation, whereas UV-cured inks are cured by chemical reactions. Solvent-based inks are widely used in many flexographic printing processes. They were the first printing inks to be available commercially. Historically they have been very popular because they dry quickly, perform well, and allow printers a wide choice of products. Solvent-based inks are generally considered to be the industry standard for ease of use and quality of printing. The solvents in these inks, however, are primarily volatile organic compounds (VOCs), which have caused concerns for health and safety, as they are usually very flammable and contribute to the formation of ground-level ozone, which is a component of smog and causes respiratory and other health problems. Partly because of these concerns, other types of inks were developed and markets for them began to develop [2].

After each printing job, flexographic printer are cleaned with solvents, and waste ink (containing both solvent and the excess ink) is collected and sent to incineration. On the other hand, waste ink may be recycled to generate secondary products (solvent, varnish and pigment), which enables closed-loop recycling of solvent and varnish and reuse of the pigment for newspaper production. Recycling waste ink is an alternative to the current costly (120 Euros/ton) mandatory incineration (hazardous waste). This case study belongs to ECO-INNOVERA SuWAS project aiming at the economic, social and environmental assessment of the deployment of waste ink recycling technology at EU scale [3].

6.2 Value Chain of Flexographic Ink (Step 2)

Figure 54 illustrates the actual value chain of flexographic ink. In this case study, all the value chain actors are located in Spain. Flexographic ink consists of solvent, resin and the pigments. Ink manufacturer collects these elements from their supplier and produces ink in the desired colour.

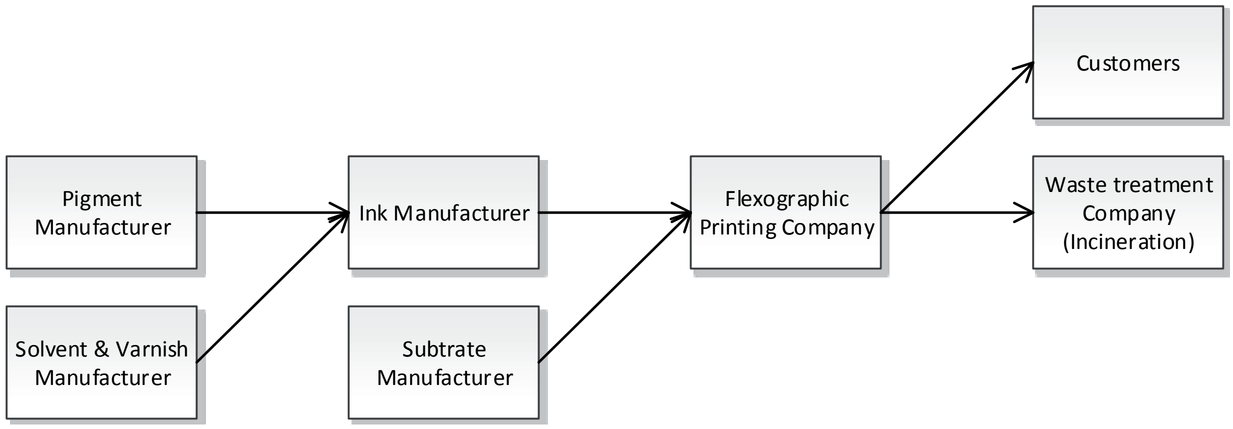


Figure 54 Actual value chain of flexographic ink

In flexographic printing is differentiates from paper printing by forming a layer on the flexible surface to generate the image. As mentioned before, all kinds of packaging material, brochures and books may be printed by flexographic printing. Flexographic printing company buys ink and substrate from their suppliers and prints the packaging media depending on the demands of the customer. After each printing job, the printing machines are cleaned and the waste ink is sent to Waste Treatment Company for incineration.

Waste Treatment Company deals with disposal of hazardous waste of all kinds. The company is responsible for safe treatment and incineration of the waste ink. Printing company may recover some of the solvent from the waste ink in order to reduce the amount of waste and reuse the solvent if they have required equipment. It is not possible to remove all the solvent because the resin is nitrocellulose, and it may explode if it is completely dry.

The intended value chain of flexographic ink is shown in Figure 55. In this scenario, the waste ink is recycled by waste treatment company, as depicted, or the printing company which is equipped with Olax22 recycling technology. Olax22 process enables to flocculate the pigments and remove them from the solution and produce a varnish which might be used in ink production. The waste ink contains all colours of pigments that’s why it is black, and it is low quality to be used for flexographic printing. The removed pigment might be used in newspaper printing.

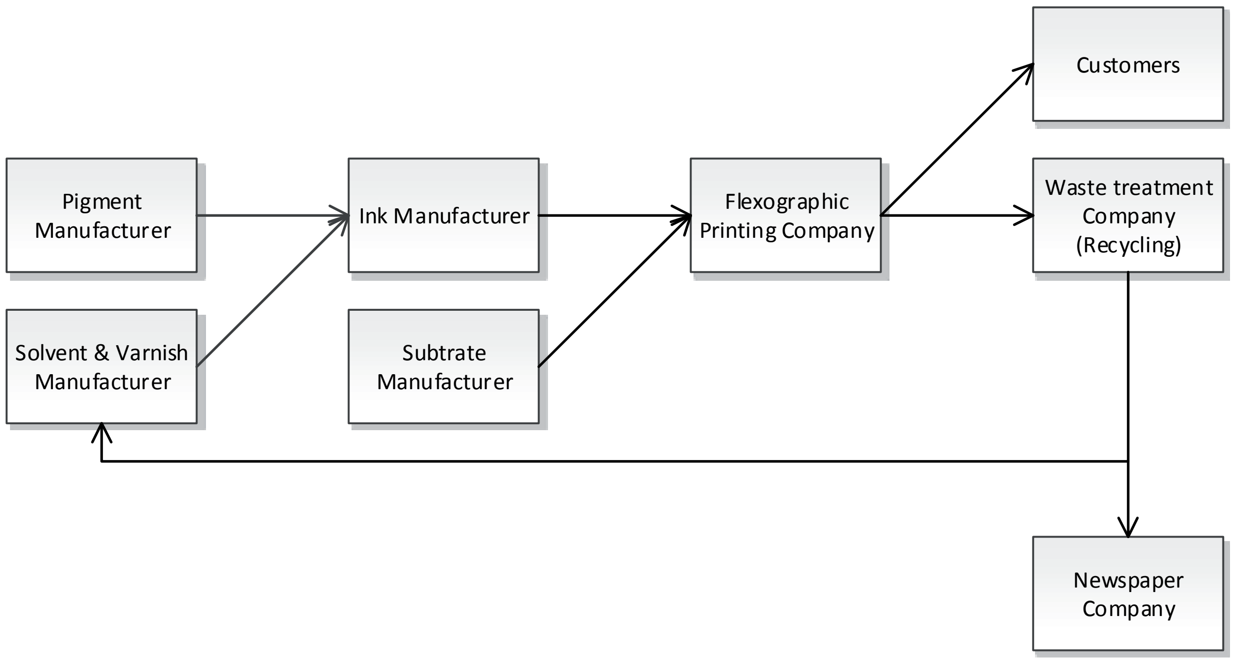


Figure 55 Intended value chain of flexographic ink

6.3 Material Flow of Flexographic Ink (Step 3)

Flexographic ink consists of three element, solvent, resin and pigment. The mixture of solvent and resin is called varnish. While printing 30% of the ink is laminated on the substrate, 55% of it evaporates as solvent when printed films are dried, and 15% becomes waste during cleaning. While cleaning additional solvent is included in the system.

The functional unit for this case study is determined to be one hour of LDPE (low density polyethylene film) flexographic printing. The main assumptions are;

1. The printing machine consumes 500000 btu/h heat and 31.6 KWh electricity.
2. 29.61 kg ink, 2.7 kg solvent, and 14.83 kg substrate (LDPE film) are used in one hour [2]
3. 0.67 kWh electricity is used for distilling 1kg of waste ink.
4. Waste ink consists of 70% solvent, 18.7% resin and 11.3% pigment [3].
5. The distance between ink and substrate suppliers, and printing company is assumed to be 200 km, and the distance between printing company and waste treatment company is assumed to be 50km.
6. The solvent is a mixture of ethanol and ethyl acetate.

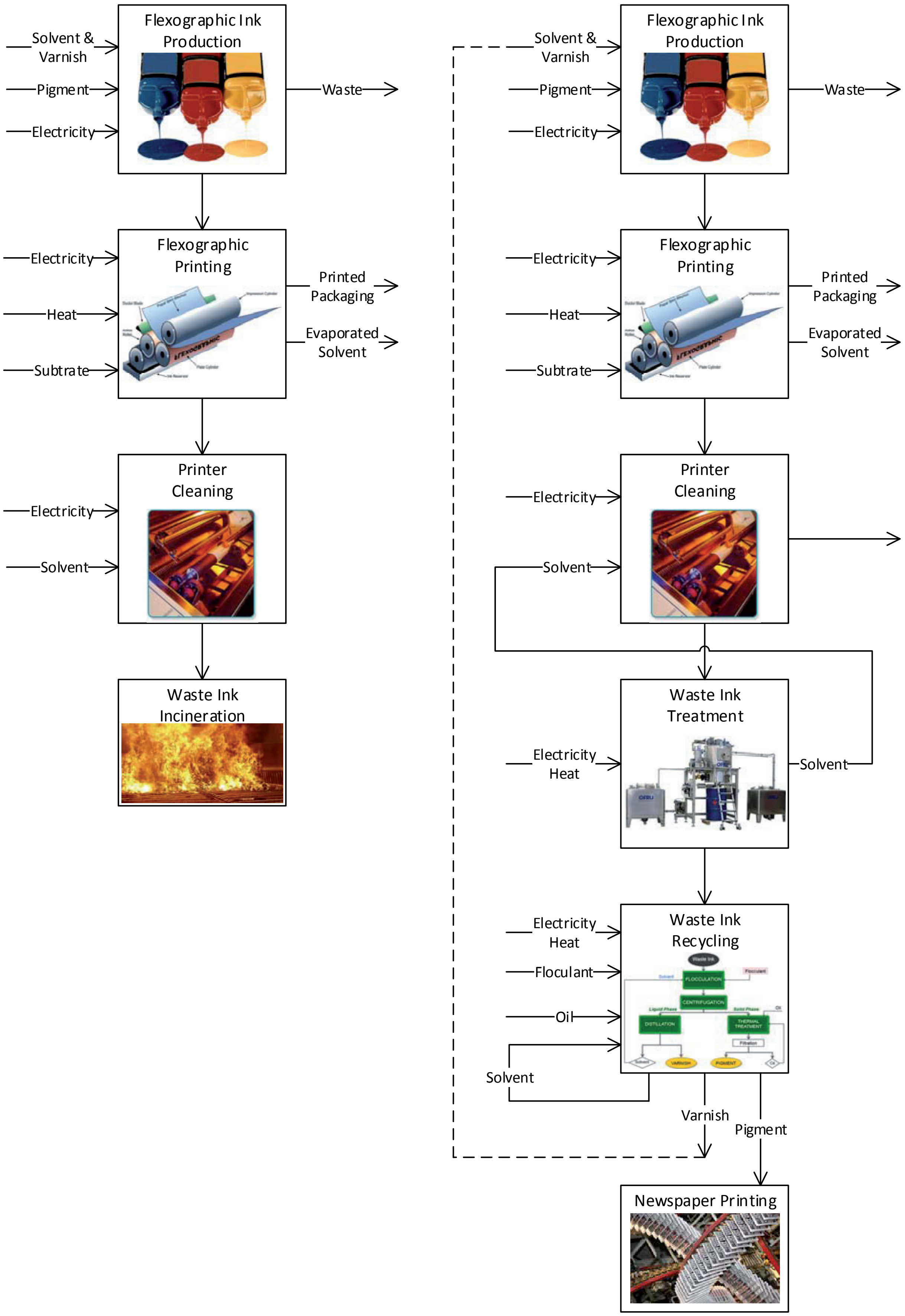


Figure 56 Detailed material flow of 2 scenarios

Figure 56 shows the detailed material flow of flexographic printing. The flow of energy, material and outputs are represented in this figure. The life cycle inventories prepared for the four scenarios presented below. Figure 57 shows the flow of flexographic ink in scenarios 1 and 4.

1. No solvent recovery – Waste ink is incinerated (Reference)

2. Solvent recovery on site and reused for cleaning – Waste ink incinerated

3. No solvent recovery – Waste ink recycled – Solvent is used for cleaning and varnish is used in ink production, recovered pigment is used as pigment for newspaper ink.

4. Solvent recovery on site and reused for cleaning – Waste ink recycled – Varnish is used for ink production, pigment is used as pigment for newspaper ink.

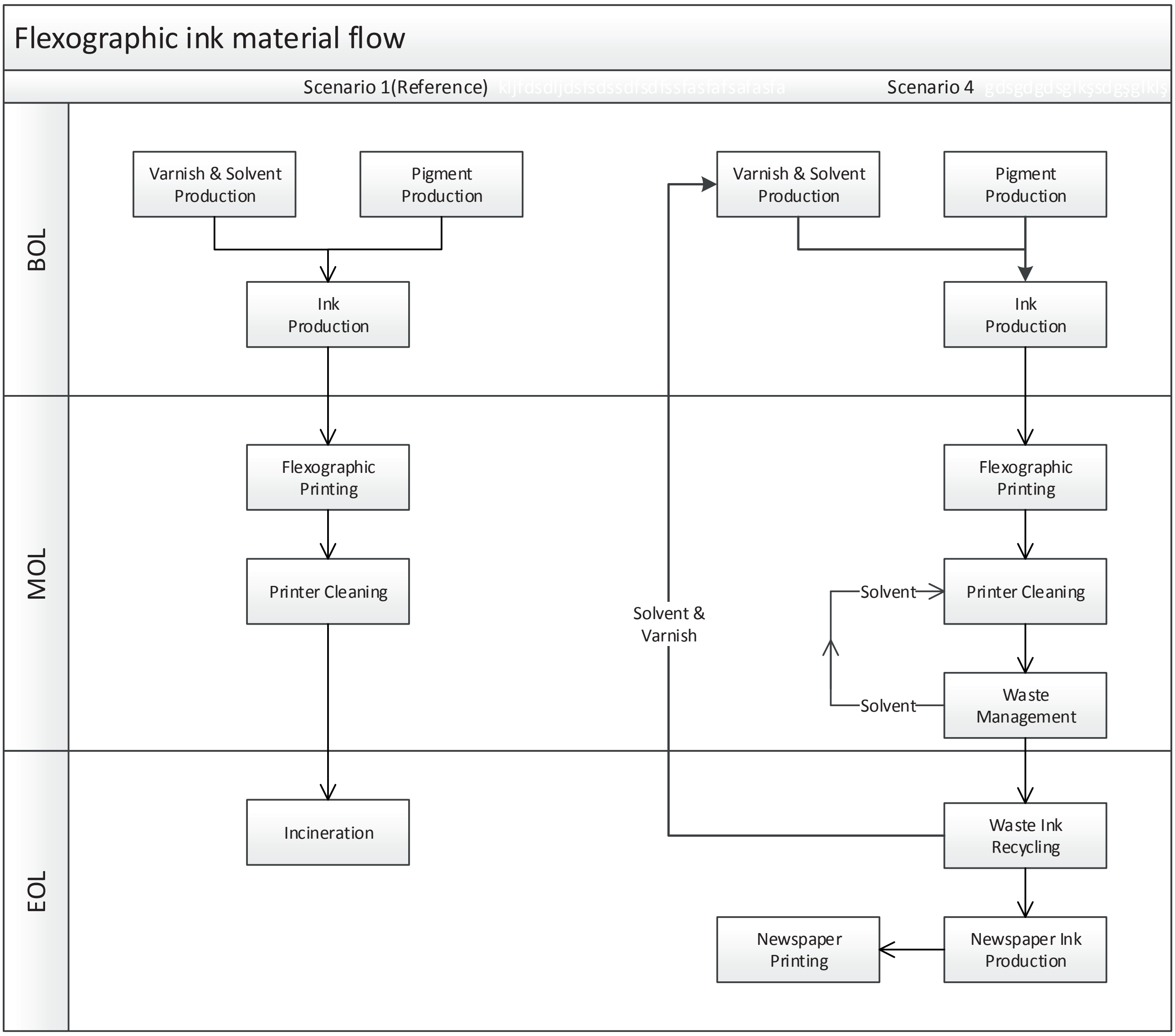
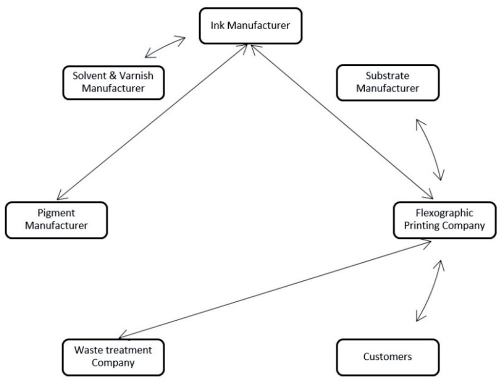
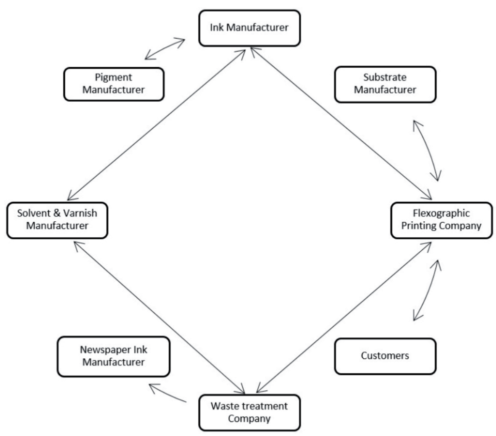


Figure 57 The material flow of flexographic ink for scenarios 1 and 4





Information Flow		Main data
Source	Destination	
Flexographic ink manufacturer	Solvent and varnish manufacturer	Characteristics (composition, viscosity, colour and etc.) and required amount of solvent, varnish, pigment. Feedback regarding solvent, varnish and pigment performance.
	Pigment manufacturer	
Flexographic printing company	Substrate manufacturer	Characteristics, and required amounts of substrate, solvent and ink. Feedback regarding ink and substrate performance.
	Flexographic ink manufacturer	
	Customers	Design of the packaging. Required amount of packaging.
	Waste management company	Weekly/monthly waste ink production.
Waste management company	Flexographic printing company	Waste/ink disposal capacity. Characteristics of the recovered solvent*
	Flexographic ink manufacturer	Characteristics and amount of recovered solvent and varnish.
	Solvent and varnish manufacturer	

Figure 58 The main data to be transmitted between life cycle actors of flexographic ink

6.4 Information Flow of Flexographic Ink (Step 4)

The tasks of life cycle actors of flexographic ink are shown in Table 36. The main data to be transmitted between life cycle actors of control arm is shown in Figure 58. As usual most of the data transmitted between the life cycle actors is transactional information. “*”indicates that the information flow is related to recovery of solvent and recycling of the waste ink.

Life Cycle Phase	Life Cycle Actor	Tasks
BOL	Solvent and varnish manufacturer	Resin and solvent production Define acceptable varnish properties
	Pigment manufacturer	Pigment production
	Flexographic ink manufacturer	Collection of varnish and pigment from their suppliers Ink production.
	Substrate manufacturer	Substrate production and distribution.
MOL	Flexographic printing company	Printing the packaging. Printing plate design and production. Waste ink collection. Waste ink distillation. *
	Customers	Packaging design for product manufacturers. Distribution of the packaging material.
EOL	Waste management company	Transport of waste ink. Waste ink distillation. Waste ink incineration. Determine the characteristics of the varnish.*

Table 36 Tasks of life cycle actors of flexographic ink

Ink manufacturer and flexographic printing company is in close cooperation in this case. Flexographic printing ink is not a mixture of some colours. They are coloured by the pigments included in the mixture. Different colours of inks also do not mix during printing process. Because of that, most of the time the inks are produced specific to the customers’ demands, the ink manufacturer should request the pigment producer to manufacture the specific colour of pigment.

The printing company is also in close contact with the customers in order to meet their demands and fulfil their quality requirements. The quality of the packaging is important as it represents the quality of the product inside it.

Waste Management Company is responsible for collection and disposal of the waste ink. In our case, the disposal option is incineration. In the scenarios, additional tasks, concentrating waste ink, and recycling, are also assigned to this life cycle actor. In the reference scenario waste treatment company has information flow only with the printing company.

6.5 Performance Characteristics of Flexographic Ink (Step 5)

Technical performance characteristics determined for this case study is given in Table 37.

Process	Parameter	Default Value	Unit
Flexographic ink	Viscosity	-	Centipoise
	Density	-	kg/m^3
	Percent area of coverage	60	%
	Solvent	50-70	%
	Resin	15-30	%
	Pigment	10-15	%
Flexographic printing	Printing Electricity	31.6	kWh
	Printing Heat (Natural gas)	500000	Btu
	Ink consumption	29.61	kg
	Solvent consumption	2.7	Kg
	Printing speed	120	m/min
	Cleaning electricity	5	kWh
	Cleaning solvent	5	kg
	Distillation electricity	2.96	kWh
	Recovered solvent	5	kg
	Waste ink	4.442	kg
	Waste ink/Ink input	0.150	-
Olax22	Electricity	0.590	kWh
	Additional solvent	0.485	kg per kg waste ink
	Floculant solution	0.009	kg per kg waste ink
	Recovered solvent	0.263	kg per kg waste ink
	Recovered pigment	0.122	kg per kg waste ink
	Recovered varnish	0.624	kg per kg waste ink
	Resin/Solvent	3/7	-
	Varnish colour	-	Yes/No

Table 37 Technical performance characteristics of flexographic ink

The environmental impact indicators, mentioned in section 3.3.2, and the economic performance characteristics, mentioned in section 3.3.3, are calculated for each process that was determined in the material flow. The rapid risk ranking of the social and ethical indicators, mentioned in 3.3.4, is done and the performance characteristics for the chosen indicators are generated for these indicators.

6.6 Comparison of the Scenarios (Step 6-7)

6.6.1 Technical Performance

The technical performance characteristics in this case study are used to generate the life cycle inventory for lifecycle assessment and life cycle costing. For all the scenarios it is assumed that the characteristics are the same. However, it is necessary to note that the performance of the ink produced with recycled varnish and solvent should be compared with the reference scenario.

6.6.2 Environmental Performance

The life cycle environmental impacts of flexographic ink, reference scenario, by life cycle phase is shown in Figure 59, and result are given in numbers and percentages in Table 38. For human health, ecosystem quality, resources and water withdrawal indicators, BOL phase accounts for over 60% of overall impact. Accept for impact on climate change, the contribution of EOL phase is not significant, less than 4%. The contribution of MOL phase (flexographic printing) on impact of climate change is 41%.

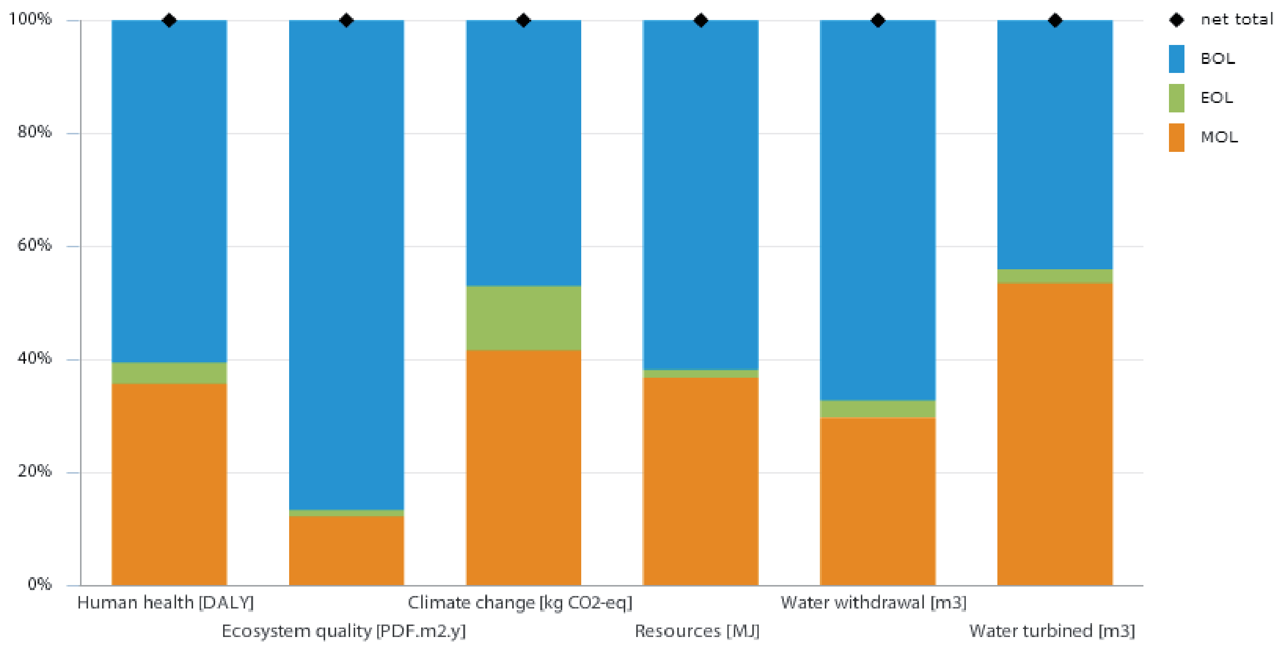


Figure 59 Life cycle environmental impacts of flexographic printing ink by life cycle phase

Scenario 1	BOL		MOL		EOL		Total	Unit
Human health	4,92E-05	60,60%	2,89E-05	35,67%	3,02E-06	3,73%	8,11E-05	DALY
Ecosystem quality	39,23	86,71%	5,51	12,19%	0,50	1,11%	45,24	PDF.m2.y
Climate change	80,99	47,08%	71,46	41,53%	19,60	11,39%	172,05	kg CO2-eq
Resources	2501,83	61,83%	1483,34	36,66%	61,08	1,51%	4046,24	MJ
Water withdrawal	2,84	67,37%	1,25	29,68%	0,12	2,95%	4,22	m3
Water turbined	135,08	44,10%	163,75	53,46%	7,45	2,43%	306,28	m3

Table 38 Life cycle environmental impacts and costs of flexographic printing

As shown in Figure 60, flexographic ink itself has a major contribution to all impact categories, and additionally, printing is the 2nd major contributor to environmental impact. So the efficiency of flexographic ink production has an important role on the environmental impact life cycle of the ink. The impact of waste ink incineration is more visible in climate change category. The transportation activities contribute less than 2% in all categories. When it comes to flexographic printing, the energy consumption, electricity and natural gas, has ~90% contribution to all impact categories.

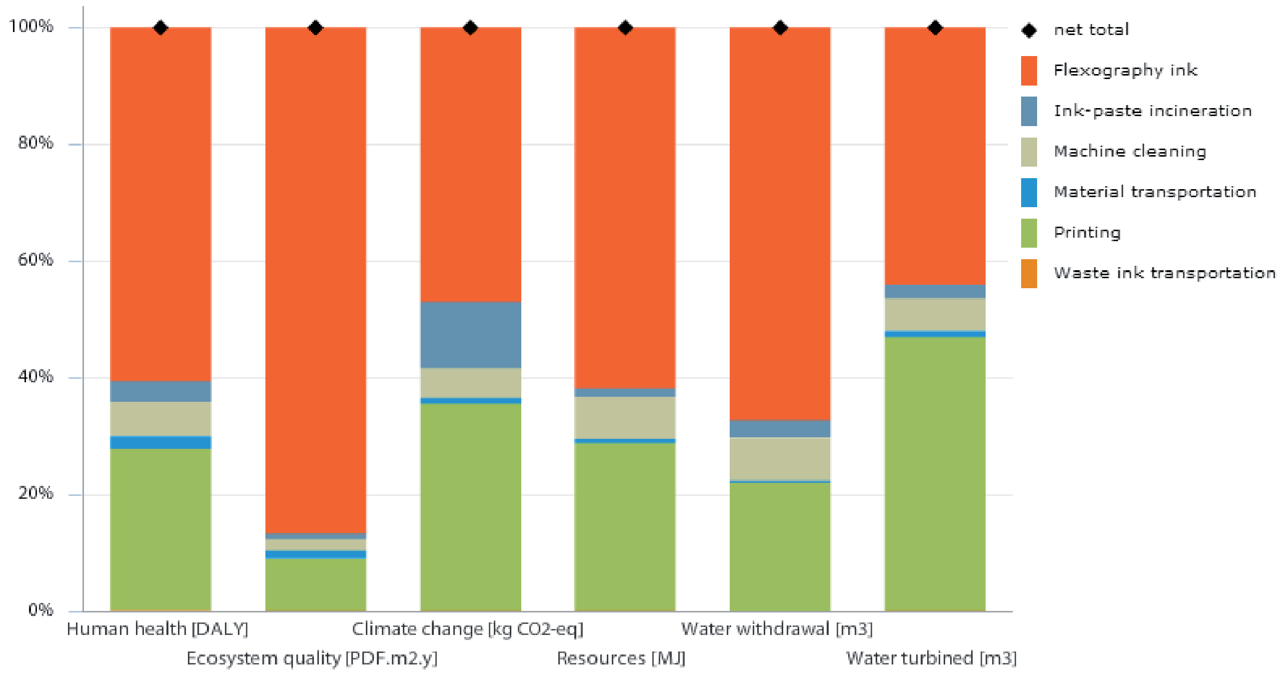


Figure 60 Life cycle environmental impacts of flexographic printing ink by process

Figure 61 illustrates the comparison environmental impacts of the scenarios that are mentioned in section 6.3, and the results are given in Table 39. In all the scenarios, the impact on water turbined increases, due to the increased need for electricity for distillation and recycling in MOL and EOL phases. For the impacts on ecosystem quality distillation have a very small impact, but recycling process increases the impact on this category. In scenario 2, distillation and reuse of the solvent reduces the environmental impact of MOL and EOL phases for all impact categories by 5 to 10%.

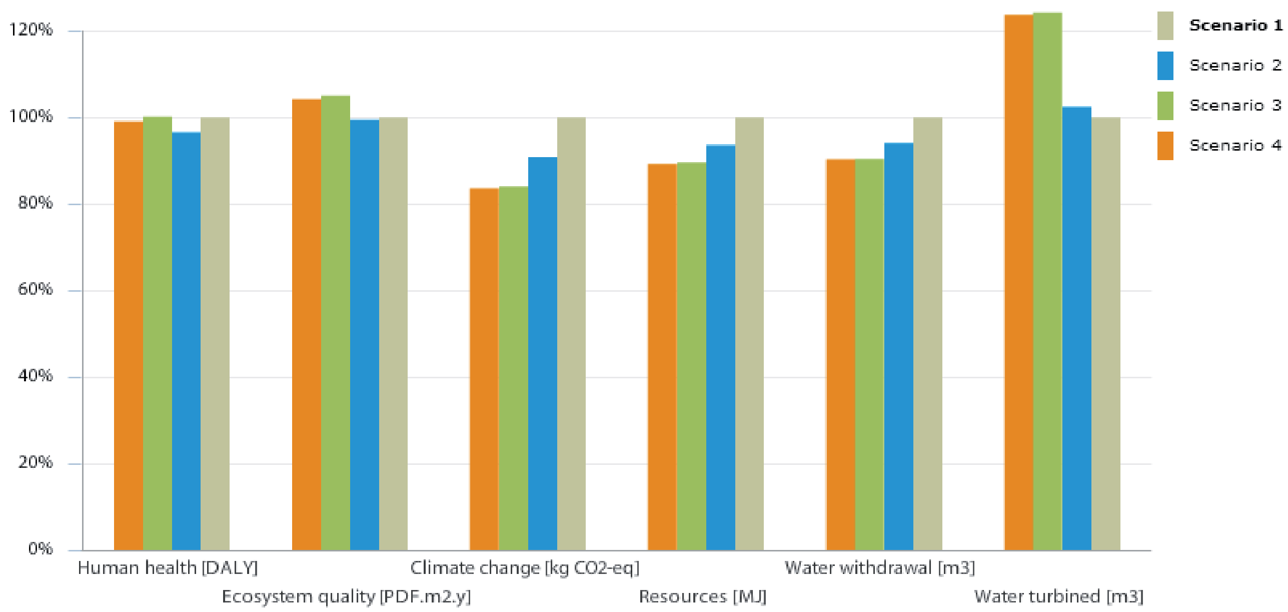


Figure 61 Comparison of scenarios for flexographic ink recycling

Impact Categories	Scenario 1			Scenario 2			Scenario 3			Scenario 4			Unit
	BOL	MOL	EOL	BOL	MOL	EOL	BOL	MOL	EOL	BOL	MOL	EOL	
Human health	4,92E-05	2,89E-05	3,02E-06	4,92E-05	2,74E-05	1,72E-06	4,30E-05	2,89E-05	8,45E-06	4,30E-05	2,74E-05	1,02E-05	DALY
Ecosystem quality	39,23	5,51	0,50	39,23	5,45	0,32	38,03	5,51	3,63	38,03	5,45	3,77	PDF.m2.y
Climate change	80,99	71,46	19,60	80,99	65,56	9,61	69,07	71,46	3,26	69,07	65,56	9,34	kg CO2-eq
Resources	2501,83	1483,34	61,08	2501,83	1244,37	41,56	2133,63	1483,34	-4,33	2133,63	1244,37	237,93	MJ
Water withdrawal	2,84	1,25	0,12	2,84	1,06	0,07	2,51	1,25	0,05	2,51	1,06	0,25	m3
Water turbined	135,08	163,75	7,45	135,08	174,13	4,66	119,20	163,75	96,05	119,20	174,13	86,04	m3

Table 39 Comparison of scenarios for flexographic ink recycling

Scenario 3 shows the impact of Olax 22 recycling process on the environmental impact of flexographic ink. Required energy and material in this scenario increases the environmental impact of EOL phase, 3 times more than the impact on human heath, 7 times more than the impact on ecosystem quality and 12 times more than the impact of water turbined. The impact on resources is negative in the EOL phase, due to solvent recovery by distillation. All the solvent and varnish sent to BOL phase and used as input for ink production, which reduces the impact in all the categories 3% to 15%. Recycling process reduces the impact of BOL phase on human health, climate change, resources and water withdrawal, on the other side increases the impact on ecosystem quality and water turbined.

In scenario 4, the solvent for cleaning is distilled in printing company, and varnish from waste ink recycling is used in ink production. The environmental gain in scenario 3 and scenario 4 is same, but it is distributed to BOL and MOL, and recycling process puts extra load on the environment, due to electricity and solvent consumption.

6.6.3 Economic Performance

The life cycle cost represents total cost of one hour flexographic printing of LDPE packaging. The life cycle cost comparison of the scenarios presented in section 6.3 are shown in Figure 62 and results are given in Table 40.

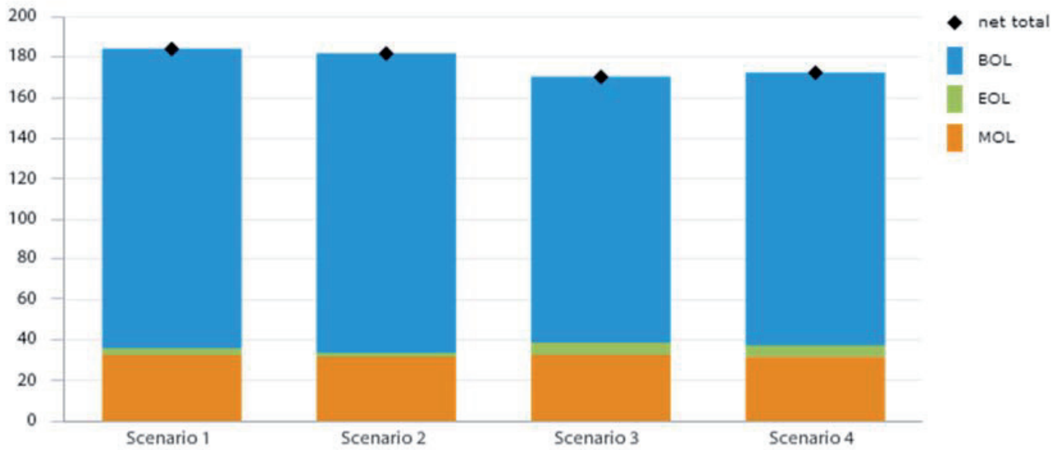


Figure 62 Life cycle costs comparison of flexographic ink

Life cycle costs		Scenario 1	Scenario 2	Scenario 3	Scenario 4
BOL	Cost	148,05	148,05	148,28	148,28
	Revenue	0	0	16,43	13,18
	Total	148,05	148,05	131,87	135,11
MOL	Cost	32,57	35,00	32,57	35,00
	Revenue	0	3,25	0	3,25
	Total	32,57	31,75	32,57	31,75
EOL	Cost	3,50	2,06	5,89	5,55
	Revenue	0	0	0	
	Total	3,50	2,06	5,89	5,55
	Total	184,12	181,86	170,32	172,40

Table 40 Life cycle cost comparison of flexographic ink

The costs represent summation of expenses of each processes, and revenues are exclusion of cost due to reuse of recovered materials for the life cycle phases. The unit costs and cost breakdown for each scenario is given in the appendix.

Flexographic ink has the major contribution to LCC by 80%, additionally MOL and BOL contribute 17.7% and 1.9% respectively. In scenario 2, some extra costs occur due to distillation, however the value of recovered solvent is more than these cost. MOL cost of scenario 2 is less than scenario 1, additionally EOL cost is also reduced because less material is incinerated. In scenario 3, MOL cost does not change since same cost occur like scenario 1. Due to labor, material and energy costs arise in Olax 22 recycling process, the EOL cost of scenario 3 increase ~70%. However, when the recovered solvent and varnish is used in BOL phase, the BOL cost decreases 11%, and life cycle cost decreases 7.5%.

In scenario 4, the waste ink is distilled on printing company which reduced MOL cost, and additionally the recovered solvent and varnish in the EOL phase is reused in ink production that reduced the BOL cost. However in this case the gain is not as much as scenario 3.

6.6.4 Social Performance

The rapid risk assessment of social and ethical indicators of flexographic ink is given in Table 41 and Figure 63. As shown in the Table 41, accept health and safety issues and community relations of waste treatment company, there is a moderate risk and improvement possibilities for labor and management relations, fair employment and working conditions, security practices, customer health and safety, marketing communications and training and education.

As for the other case studies in this thesis, the companies do not have any issues regarding human right in business relations, but they also do not have any procedures or policies if any issues come out. Additionally for all the companies there are improvement possibilities regarding health and safety. There is always a risk of exposure to accidents and hazardous substances. Since these companies have strict standards to follow and audited regularly. They have to monitor issues regarding this indicator.

	Life cycle actors	Pigment Manufacturer	Solvent& Varnish Manufacturer	Subtrate Manufacturer	Ink Manufacturer	Flexographic Printing Company	Waste Treatment Company	Waste-ink Recycling Company	Total
1	Human Rights	2	2	2	2	2	2	2	14
2	Health and Safety	2	2	2	2	2	1	2	13
3	Labor and Management Relations	2	2	2	3	3	2	3	17
4	Fair Employment and Working Conditions	2	2	2	3	2	3	3	17
5	Diversity and equal opportunity	3	3	3	3	3	3	3	21
6	Non-discrimination	3	3	3	3	3	3	3	21
7	Equal remuneration for women and men	3	3	3	3	3	3	3	21
8	Training and Education	3	3	3	3	3	2	2	19
9	Freedom of association and collective bargai	3	3	3	3	3	3	3	21
10	Forced and compulsory labor	3	3	3	3	3	3	3	21
11	Child labor	3	3	3	3	3	3	3	21
12	Disciplinary practices	3	3	3	3	3	3	3	21
13	Security practices	3	2	3	2	3	2	2	17
14	Investment and procurement practices	3	3	3	3	3	3	3	21
15	Bribery and corruption	3	3	3	3	3	3	3	21
16	Competition and pricing	3	3	3	3	3	3	3	21
17	Indigenous (native) rights	3	3	3	3	3	3	3	21
18	Community relations	3	3	3	3	2	1	2	17
19	Public policy	3	3	3	3	3	3	3	21
20	Political contributions	3	3	3	3	3	3	3	21
21	Customer health and safety	2	2	2	3	3	3	3	18
22	Customer privacy	3	3	3	3	3	3	3	21
23	Marketing communications	3	2	3	2	2	3	3	18

Table 41 Rapid risk ranking of social performance characteristics

The pigment manufacturer, solvent and varnish manufacturer, and substrate manufacturer have poor relations with their employees due to chintzy working conditions of their sites. These companies need to implement procedures and policies for handling work related complaints, and monitor and increase employee satisfaction.

Solvent and varnish manufacturer, ink manufacturer and flexographic printing company have to monitor and improve their marketing communications. Although using recycled material is often thought as a way of heading towards sustainability and innovation, because of the lack of confidence on the quality of the recycled materials in this industry, the companies do not want to declare that they use recycled material. Declaring the improvement of their environmental performance, and stability of their technical performance, these companies may improve their marketing communications.

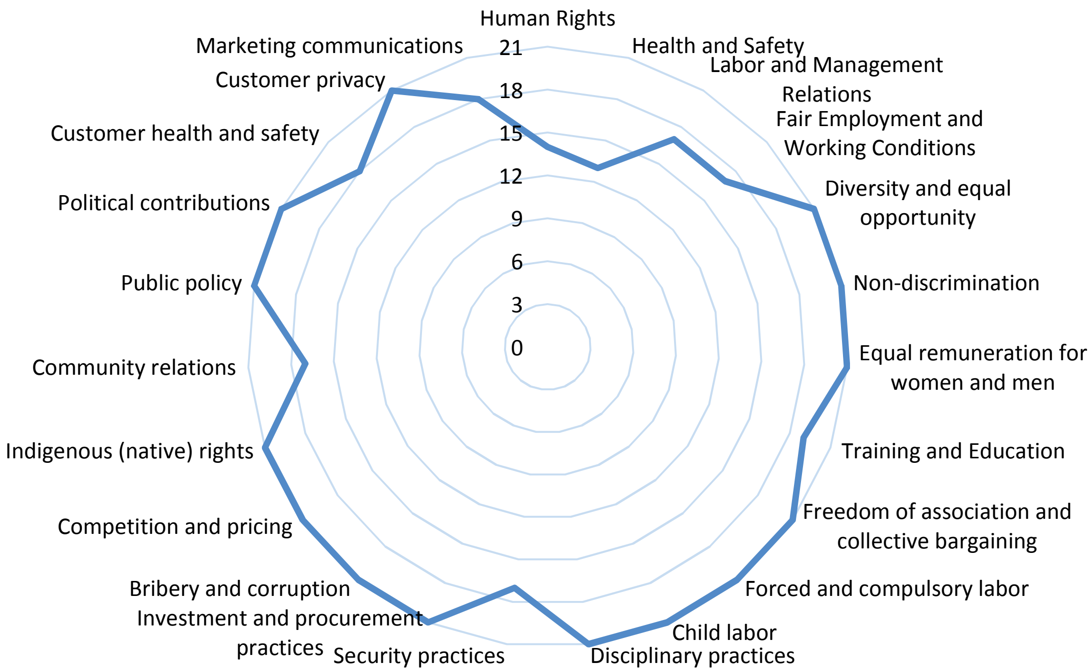


Figure 63 Rapid risk assessment of social and ethical indicators

The waste treatment company has issues with the local community and authorities due to pollution issues and health and safety. The HSE conditions of the company is not good, the site is lacking incident handling system, and there is possibility to exposure accidents and hazardous chemicals. There high risk for this indicator and the condition is not acceptable.

6.7 Discussion (Step 8)

The comparison of the scenarios for waste ink recycling is shown in Table 42.

Worse condition		Neutral condition		Better condition	

Performance Characteristics	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Technical				
Environmental				
Economic				
Social				

Table 42 Comparison of the waste ink recycling scenarios

The technical and social performance of flexographic ink is not affected whether the waste ink is incinerated or recycled.

The environmental performance of flexographic ink is improved by distillation and recycling due to use of recovered material in printing and ink production. In house distillation does not improve the economic performance since processing cost and gain through recovered solvent in in-house distillation are close and there is not a significant improvement. Even solvent is recovered in-house or in recycling facility, it results reduction of MOL and BOL costs and improvement of economic performance.

Chapter 7 Conclusion

This dissertation proposes a methodology for holistic life cycle approach for evaluation for products in the context of sustainability. This chapter describes the conclusions of the current work, the necessary elements of the proposed approach and achieved results from the case studies for validation. Furthermore, the possible future directions of this work are briefly presented.

7.1 Achieved Results

This dissertation proposes a methodology for holistic life cycle approach for evaluation for products. It may also be used to evaluate processes, companies, projects. The proposed methodology intends to generate technical, environmental, economic and social performance characteristics in order to be used for evaluation. These characteristics represent the three pillars of sustainability.

Sustainability has environmental, economic and social dimension, and all the processes, activities from material extraction and production to use and disposal should be taken into account. So when it comes to evaluation of sustainability it is required to combine a number of methodologies with life cycle perspective. The proposed methodology combines life cycle assessment (environmental performance), life cycle costing (economic performance) and social life cycle assessment (social performance). Due to the fact that these methodologies are data intensive and require collaboration of all the life cycle actors related with the assessment. Even more, social life cycle assessment requires collaboration of all the stakeholders that are influenced by the product. Closed-loop life cycle management offers unique capabilities to track product and collect life cycle data through the life cycle of a product, which is required for the fore mentioned methodologies. A closed-loop PLM system also employs decision support system, which transforms the collected life cycle data into performance characteristics for evaluation. The evaluation is carried-out by defining scenarios and comparing the performance of each scenario with the reference scenario.

The amount of material, chemicals and energy used for production, the amount of waste produced and the way it is treated, and direct emissions due to may be used as indicators of environmental impact. However, the load imposed directly and indirectly on the environmental by these activities have to be determined. Life cycle assessment consolidates the material, energy and waste flows and generates environmental impact indicators based on the determined life cycle impact assessment methodology. These indicators help to make more comprehensive environmental assessment. In life cycle costing, in addition to acquisition costs; processing, labour, transportation, use and waste treatment costs are aggregated to calculate the cost of each phase of the life cycle and life cycle cost. When it comes to social life cycle assessment, rapid risk assessment of social and ethical indicators is apprehended for all the companies in the actual and intended value chain.

The proposed methodology is applied to three case studies in order to be validation. In front lower control arm case study impact of using recycled aluminum on the performance automotive components is investigated. Additionally, an alternative production route, which eliminates an energy intensive stage of production, is proposed and investigated as well. Steel is commonly used in production of automotive components. The components manufacturers are more used to processing steel, rely on steel rather than other materials. Former studies show that MOL phase, the use of the vehicle, dominates the lifecycle environmental impacts and costs. Since lightweighting reduces fuel consumption and emissions to the air, it has a positive impact on MOL phase. Aluminum has low density, sufficient mechanical properties and good corrosion resistivity. Aluminum offers a good opportunity to reduce the weight of the components. However production of aluminum is electricity intensive and a huge amount of land is disturbed during bauxite mining. Using recycled material reduces the environmental impact of aluminum production considerably. The key finding of this case study are as follows.

- The technical performance of the FLCA is not affected by using recycled aluminum or the alternative production route. On the other hand steel has superior technical performance to aluminum, which offers additional design
- BOL phase dominates the environmental impact of FLCA made of virgin aluminum. Using recycled aluminum reduces life cycle environmental impacts and contribution of BOL phase significantly proportional to the amount of recycled aluminum used in production, and does not have considerable positive impact on the economic performance, because the price of recycled aluminum is close to virgin aluminum, additionally EOL costs rise due to sorting, collection and treatment of aluminum scrap, similarly it does also not affect the lifecycle cost significantly.
- The alternative production route has a higher yield than traditional production route, because of that less virgin and recycled aluminum is used in production, which also reduces the need for energy and material and wastes generation and improves the environmental performance and reduces material and processing costs, but does not affect the MOL costs due to the fact that the weight of the product, and eventually the fuel consumption does not change is the same, alternative production route does not affect the MOL costs. Taking all into account we can say that the economic performance increase visibly.

- When recycled aluminum is used in alternative production route both the environmental and economic performance are improved considerably.

- MOL phase dominates the environmental impact of FLCA made of steel. Due to the higher weight of steel control arm, the fuel consumption and the emissions to air is more than aluminum FLCA. Environmental impact of BOL phase is less than the reference scenario, however the material (steel) processed is much higher in this case. The life cycle cost of steel FLCA is also dominated by MOL phase, and is much higher than reference. Thus the economic performance is worse than the reference scenario.

- The social and ethical indicators taken into consideration in FLCA case study are; human rights, health and safety, labor and management relations, community relations, public policy, and political contributions. According to our assessment most of the indicators there is no risk and for the identified indicators there is a moderate risk which is acceptable. But it is required to monitor these indicators and search for improvement possibilities.

In baggage door hinge case study impact of using recycled aluminum and changing the production route on the performance aeronautics components is investigated. Lightweight materials, like aluminum, titanium and composites, are used on aircrafts. Due to high quality requirements of these materials, and lack of trust for recycled materials, virgin aluminum is used for production of aircraft components. The key findings of this case study are as follows.

- The material in all the scenarios have sufficient material properties and quality for production. It is necessary to note that the yield of machining is very low, which is not a problem because number of door hinges produced for the aircrafts is not too much. However, in case of mass production, the production route of the door hinge should be re-designed.

- MOL phase dominates both environmental impacts and life cycle costs. Using recycled aluminum and changing the production route reduces the environmental impact of BOL phase but does not affect the dominant MOL phase. Using recycled aluminum do not have a significant impact on the economic performance. Alternative production route requires less material, and because of that the environmental and economic performance of 3rd and 4th scenarios are better than reference scenario.

- Related social and ethical indicators for the life cycle actors of door hinge are; health and safety, fair employment and working conditions, diversity and equal opportunities, training and education security practices, community relations, and public policy. There is moderate risk for these indicators, and it is acceptable. However, human rights seems to be the most significant issue for all the life cycle actor, there is not violation of human right by any of the life cycle actors. This indicator is significant due to the fact that none of the life cycle actors have procedure concerning this indicator. All the life cycle actors should develop and exercise procedures and policies to monitor and improve their practices regarding human rights.

In flexographic waste ink case study the impact of recycling over incineration is investigated. After each printing job, the printing machines are cleaned with solvent and the excess ink and solvent mixture is sent to waste treatment company for incineration. The printing company may concentrate the waste ink in order to recover solvent and reduce the amount of waste and incineration cost.

- The technical performance of the waste ink is assumed to be the same in all the scenarios and the life cycle inventory is defined accordingly.
- The impact of incineration in the EOL phase on the environmental impact is not too much. Distillation and recycling of the waste ink improve the environmental and economic performance flexographic printing. The use of recovered solvent and varnish in ink production improve the environmental performance of BOL and offer economic benefits.
- Accept health and safety issues and community relations of waste treatment company, there is a moderate risk and improvement possibilities for labor and management relations, fair employment and working conditions, security practices, customer health and safety, marketing communications and training and education.

7.2 Future Development

The proposed methodology presented in this dissertation could be further extended in order to provide additional functionalities. The methodology is recommended to be used as a decision support system for a closed-loop lifecycle management system. A conceptual closed-loop lifecycle management system has been proposed. But it has not been applied to a closed-loop lifecycle management system. It helps to obtain an overview of overall performance of the products, it could provide more detailed information than presented in this dissertation if it was applied to a closed loop PLM system.

Social performance evaluation is done by rapid risk assessment. The indicators with high and moderate risk are determined. However due to lack of data social performance characteristics for these indicators are not well covered. The approach gives an overview over the social performance, but it does not help to monitor the progress of improvements.

Finally, concerning the steel FLCA scenario, this scenario requires a more thorough observation and verification of the assumptions. If this scenario could be studies more deeply, comparison of this scenario with the reference might be a valuable contribution to the literature.

Appendix

Social Life Cycle Assessment

Main Topic	Example of issues to look for:
Human rights	Does the company respects human rights in general? Procedures and policies and monitoring systems? Mitigates impacts due to business, product or service?
Health and Safety (HSE)	Are the overall HSE conditions good? Exposure to accidents, hazardous substances, noise, vibrations, poor lighting, extreme temperatures, ventilation, fire? HSE system, procedures and responsibilities defined? Access to PPE? Training? Risk information? Incident handling system? Emergency systems and contingency plans? HSE committees? Clean and maintained workplace and machinery? Safe drinking water? Precautions for disabled employees, pregnant women or other vulnerable groups? Internal audits?
Labor and management relations	Are the overall relations and cooperation between employees and management good? Employee satisfaction? Involvement in decision making? Monitoring of employees? Informed and described in procedures? Privacy respect? Access to personal data recorded? Transparency in decision making? Employees may speak freely without reciprocation? Procedures for handling work related complaints? Warnings without fear of retribution? Freedom of speech and open information?
Fair employment and working conditions	Are the overall working conditions good and fair? International labor standards? Limited weekly work hours (< 48h)? Overtime? Work hour monitoring? Work contract with salary? Rest and breaks? Living wage? Holidays? Sick leave? Maternity leave? System or procedures for handling complaints? Without retribution? Sanitary work facilities? Short term contracts to avoid fulfilling labor and social security regulations? Wage deductions for disciplinary measures?
Diversity and equal opportunity	Are employees given equal opportunities for hiring and growth? Objective criteria for hiring, promotion, work hours, holidays, job assignments, social security and services, training, retirement, discipline, termination etc? Job descriptions including qualifications? Advertisements for employees do not discriminate? Non-discrimination training for hiring managers? Incident handling system?
Non-discrimination	Do employees suffer from discrimination of any kind? Physical, sexual, verbal harassment or abuse? Threating or exploitative manners? Procedures and training to handle complaints and instances without retributions? Non-discrimination training?
Equal remuneration for women and men	Are employees given equal remuneration for similar/equal jobs? Objective criteria wages? Salary level to each job category?
Training and education	Are employees given training and education according to work risk? On the job training? Training for hazardous work tasks? Human rights and labor standards training for management and procurement staff? Anti-corruption and ethical training? Fair competition and pricing? Overall sustainability awareness training? Opportunities for lifelong learning
Freedom of association and collective bargaining	Are employees freely given the opportunity to join or form a trade union? Recognition of collective bargaining? Employee gatherings during normal work hours allowed? Discrimination from participation in lawful trade unions? Cooperation meetings between management and employee representatives?
Forced and compulsory labor	No employees are part of bonded or forced labor? Contracts prior to start of work are transparent and understood? Employees are free to leave company premises after work hours or during breaks? Identity cards, passports, salaries are not withheld? Voluntary work? Recruitment fees or lodging deposits paid? Human trafficking?
Child labor	Are minimum age standards followed (13 years light work, 15 years full time, 18 years hazardous work)? Procedure to check age? Work interferes with basic education? Apprenticeships are according to law? Young workers work time (<8h day)? Health and safety issues concerned with young workers?

Disciplinary practices	Are performed in a fair and fact based way? Dignified and respectful treatment? System or procedures for fair handling disciplinary issues? With participation of employee elected representatives? Committee?
Security practices	Are there security risk issues associated with company operation in the area? Security risk assessment? Security arrangements according to risk in the area? Procedures? Security arrangements effect on human rights? Procurement of security services according to good standards? Evaluation and complaints handling from security issues.
Investment and procurement practices	Are the overall procurement practices in the company according to standards? Promotes international labor standards and human rights among suppliers and business partners? Audits? Has defined minimum business partner standard? Procedures for such? Collaboration with suppliers that support oppressive regimes? Supply chain risk assessment? Collaboration with suppliers to improve labor standards? (Limited weekly work hours (< 48h)? Overtime? Work hour monitoring? Work contract with salary? Rest and breaks? Living wage? Holidays? Sick leave? Maternity leave? System or procedures for handling complaints? Without retribution? Sanitary work facilities? Short term contracts to avoid fulfilling labor and social security regulations? Wage deductions for disciplinary measures?)? Anti-corruption practices? Employee satisfaction? Employee involvement in decision making?
Bribery and corruption	Are business activities ethical and performed without bribery and corruption? Code of conduct for business activities? Procedures and responsibilities defined? Anti-corruption statements from management? Public anti-corruption commitment? Corruption risk assessment for business activities? Action plan? Anti-corruption information and training to all employees? Disciplinary actions from corruption? Hotline for reporting of suspicions? Handling of gifts? Internal audits? All contracts and agreements are written and signed? Only bank transfer of money? Use of intermediates?
Competition and pricing	Is the company committed to fair competition and pricing? Court decisions regarding anti-trust or monopoly regulations? Fix prices? Output restrictions? Divide markets?
Indigenous (native) rights	Impacts on native population and native rights? Land ownership properly assessed? Culture heritage? Ethical and spiritual values? Contribution to internal population shifts? Demographic change? Religious change? Recreation and aesthetic values?
Community relations	Are the overall environmental and social impacts on the local community positive? Groups or individual affected (tenants, settlers, minorities)? Involvement of affected groups/individuals? Community participation? Plans to improve social/environmental impacts from company practices? Fair compensation? Complaint handling? Employment effects? Wealth distribution? Traffic and transport systems? Other infrastructure? Philanthropy activities? Sponsorship programs? Development programs?
Public policy	Does the company provide open information to the community and public? Corporate social performance? Corporate social responsibility? Communication on sustainable benchmark results? Transparency concerning investments and owners? Communication on standards adherence? Motivational activities to promote reuse and recycling?
Political contributions	Procedures for political lobbying and monetary contributions? Transparency? Open information?
Customer health and safety	The product does not lock customers into unsustainable practices? Human risk from product use, maintenance, EOL? The company provides information and warnings for product and packaging, including EOL instructions? Unintended use? Monitors human and safety effects from use of product? Requirements for PPE? Social and ethical labeling (fair trade labels)? Adverse health/safety impacts on community from use?
Customer privacy	Does the company collect, store and use customer information in an ethical manner? According to laws?
Marketing communications	Marketing of product and company are according to responsible advertising norms? Provides damaging offerings? Directed towards vulnerable groups? Misrepresentation?

Apendix 1 Example issues related with each social and ethical topic

Inventory for Life Cycle Assessment

The data for life cycle inventory is not given in the appendix due to confidentiality issues. But can be made available upon request and agreement.

Traditional production route (DCCEFM)

Billet Production

Process	Material Input &Output			Amount	Unit
Melt Treatment &Billet Casting	Input	Virgin aluminum			gr
	Input	Aluminum scrap			gr
	Input	Alloying Elements	Si		gr
	Input	Alloying Elements	Fe		gr
	Input	Alloying Elements	Cr		gr
	Input	Alloying Elements	Mn		gr
	Input	Alloying Elements	Mg		gr
	Input	Alloying Elements	Cu		gr
	Input	Alloying Elements	Ti		gr
	Input	Alloying Elements	Zn		gr
	Input	Alloying Elements	Zr		gr
	Input	Grain refiner			gr
	Input	Lubricator			gr
	Input	Degassing Flux			gr
	Input	Water			lt
	Input	Compressed air			mm3
	Input	Electricity			kWh
	Output	AA 6082 billet			gr
	Output	Casting scrap			gr
Homogenization	Input	AA 6082 billet			gr
	Input	Electricity			kWh
Extrusion	Input	AA 6082 billet			gr
	Input	Lubricant			gr
	Input	Compressed air			mm3
	Input	Electricity			kWh
	Output	AA 6082 rod			gr
	Output	Extrusion Scrap			gr

Control Arm Production

Process	Material Input &Output		Amount	Unit
Annealing	Input	AA 6082 rod		gr
	Input	Electricity		kWh
Hot forging &Machining	Input	AA 6082 rod		gr
	Input	CO2		mm3
	Input	Graphite		gr
	Input	Compressed air		mm3
	Input	Industral water		m3
	Input	Tap Water		m3
	Input	Electricity		gr
	Output	Control arm		gr
	Output	Production Scrap		gr
	Non-hazardous waste	Wood		gr
	Non-hazardous waste	Cardboard		gr
	Non-hazardous waste	Paper		gr
	Non-hazardous waste	Plastic		gr
	Non-hazardous waste	Residual waste		gr
	Hazardous waste	Waste oil		gr
	Hazardous waste	Oil contaminated waste		gr
	Hazardous waste	Oil emulsions, slop water		gr
	Hazardous waste	Aerosol cans, and inorganic salts and other solids		gr
	Hazardous waste	Sanitary sewage		gr
Aging	Input	Control arm		gr
	Input	Electricity		kWh

Transportation

From	To	Type of Transport	Distance(kn	tkm	Notes
Neuman Aluminum Marktl/Austria	Raufoss Technology Raufoss/Norway	>32 t, EURO 5			Billet transport
Raufoss Technology Raufoss/Norway	Opel Rüsselsheim/Germany	>32t, Euro 5 Ferry			Finished part transport
Raufoss Technology Raufoss/Norway	Veolia	lorry 21t			Waste transport
Raufoss Technology Raufoss/Norway	Neuman Aluminum Marktl/Austria	>32 t, EURO 5			Scrap transport
Reverse logistics	Collection center Raufoss Technology				

Apendix 2 Life cycle inventory for traditional production route of front lower control arm

Alternative production route (DCCFM)

Aluminum Rod Casting

Process	Material Input &Output			Amount	Unit
Melt Treatment & Rod Casting	Input	Virgin aluminum			gr
		Aluminum scrap			gr
		Alloying Elements	Si		gr
			Fe		gr
			Cr		gr
			Mn		gr
			Mg		gr
			Cu		gr
			Ti		gr
			Zn		gr
			Zr		gr
		Grain refiner			gr
		Lubricator			gr
		Degassing Flux			gr
		Water			lt
		Compressed air			mm3
		Electricity			kWh
	Output	AA 6082 Rod			gr
		Casting scrap			gr
Homogenization	Input	AA 6082 rod			gr
		Electricity			kWh

Control Arm Production

Process	Material Input &Output		Amount	Unit
Annealing	Input	AA 6082 rod		gr
		Electricity		kWh
Hot forging &Machining	Input	AA 6082 rod		gr
		CO2		mm3
		Graphite		gr
		Compressed air		mm3
		Industral water		m3
		Tap Water		m3
		Electricity		gr
	Output	Control arm		gr
		Production Scrap		gr
	Non-hazardous waste	Wood		gr
		Cardboard		gr
		Paper		gr
		Plastic		gr
		Residual waste		gr
	Hazardous waste	Waste oil		gr
		Oil contaminated waste		gr
		Oil emulsions, slop water		gr
		Aerosol cans, and inorganic salts and other solids		gr
		Sanitary sewage		gr
Aging	Input	Control arm		gr
		Electricity		kWh

Transportation

From	To	Type of Transport	Distance	tkm	Notes
Raufoss Technology	Opel	>32t, Euro 5 Ferry			Finished part transport
Raufoss/Norway	Rüsselsheim/Germany				
Raufoss Technology	Veolia	lorry 21t			Waste transport
Raufoss/Norway					
Raufoss Technology	Neuman Aluminum	>32 t, EURO 5			scrap transport
Raufoss/Norway	Marktl/Austria				
Collection center	Raufoss Technology	>32t, Euro 5			Reverse logistics

Apendix 3 Life cycle inventory for alternative production route of front lower control arm

Traditional production route				
Melt treatment and ingot casting	Aluminum	Virgin Al		gr
		Scrap Al		gr
		Al Input		gr
	Alloying elements	Si		gr
		Fe		gr
		Cu		gr
		Mn		gr
		Mg		gr
		Cr		gr
		Zn		gr
		Ti		gr
	Grain refiner			gr
	Lubricator			gr
	Degassing Flux			gr
	Water			lt
	Compressed air			mm3
	Electricity			kWh
	AA 7075 Ingot			gr
	Casting scrap			gr
Homogenisation	AA 6082 billet			gr
	Electricity			kWh
Hotrolling	Hot rolled plate mass			gr
	Lossess			gr
Tempering	Plate			gr
	Electricity			kWh
Transport	Material acquisition			tkm
	Waste transport			tkm
Cutting	Electricity			kWh
	Lossess			gr
Milling	Electricity			kWh
	Lossess			kg
Door assembly	Electricity			kWh
Transport	Incoming freight aluminum plate			tkm
				tkm
	Al scrap transport			tkm
Assembly on the aircraft	Electricity			kWh
	Incoming freight BDH			kgm

Alternative production route				
Melt treatment and ingot casting	Aluminum	Virgin Al		gr
		Scrap Al		gr
		Al Input		gr
	Alloying elements	Si		gr
		Fe		gr
		Cu		gr
		Mn		gr
		Mg		gr
		Cr		gr
		Zn		gr
		Ti		gr
	Grain refiner			gr
	Lubricator			gr
	Degassing Flux			gr
	Water			lt
	Compressed air			mm3
	Electricity			kWh
	AA 7075 Ingot			gr
	Casting scrap			gr
Homogenisation	AA 6082 billet			gr
	Electricity			kWh
Extrusion	Hot rolled plate mass			gr
	Lossess			gr
Tempering	Plate			gr
	Electricity			kWh
Transport	Material acquisition			tkm
	Waste transport			tkm
Cutting	Electricity			kWh
	Lossess			gr
Milling	Electricity			kWh
	Lossess			kg
Door assembly	Electricity			kWh
Transport	Incoming freight aluminum plate			tkm
				tkm
	Al scrap transport			tkm
Assembly on the aircraft	Electricity			kWh
	Incoming freight BDH			kgm

Apendix 4 Life cycle inventory for production routes of baggage door hinge

<table>
<tr><td>BOL</td><td colspan="2">Ink production</td><td>Flexography ink</td><td></td><td>kg</td></tr>
<tr><td rowspan="11">MOL</td><td colspan="2" rowspan="4">Printing</td><td>Machinery</td><td></td><td>kg</td></tr>
<tr><td>Electricity</td><td></td><td>kWh</td></tr>
<tr><td>Heat</td><td></td><td>btu</td></tr>
<tr><td>Solvent</td><td></td><td>kg</td></tr>
<tr><td colspan="2" rowspan="2">Machine Cleaning</td><td>Electricity</td><td></td><td>kWh</td></tr>
<tr><td>Solvent</td><td></td><td>kg</td></tr>
<tr><td colspan="2" rowspan="3">Distillation</td><td>Electricity</td><td></td><td>kWh</td></tr>
<tr><td>Machinery</td><td></td><td>kg</td></tr>
<tr><td>Solvent</td><td></td><td>kg</td></tr>
<tr><td colspan="2" rowspan="2">Transportation</td><td>Ink</td><td></td><td>kgkm</td></tr>
<tr><td>Solvent</td><td></td><td>kgkm</td></tr>
<tr><td rowspan="23">EOL</td><td rowspan="4">Incineration</td><td>Transportation</td><td>Waste ink</td><td></td><td>kgkm</td></tr>
<tr><td rowspan="3">Incineration</td><td>Solvent</td><td></td><td>kg</td></tr>
<tr><td>Resin</td><td></td><td>kg</td></tr>
<tr><td>Pigment</td><td></td><td>kg</td></tr>
<tr><td rowspan="20">OLAX 22 RecyclingProcess</td><td rowspan="4">Inputs</td><td>Ink paste</td><td></td><td></td></tr>
<tr><td>Extra solvent</td><td></td><td>kg</td></tr>
<tr><td>Floculant substance</td><td></td><td>gr</td></tr>
<tr><td>Water</td><td></td><td>gr</td></tr>
<tr><td rowspan="3">Transportation (Incoming freight)</td><td>Waste ink</td><td></td><td>kgkm</td></tr>
<tr><td>Solvent</td><td></td><td>kgkm</td></tr>
<tr><td>Floculent Substance</td><td></td><td>kgkm</td></tr>
<tr><td rowspan="6">Process Inputs</td><td>Pumps electricity</td><td></td><td>kWh</td></tr>
<tr><td>Floctuation tank electricity</td><td></td><td>kWh</td></tr>
<tr><td>Floctuation tank</td><td></td><td>kg</td></tr>
<tr><td>Decanter</td><td></td><td>kg</td></tr>
<tr><td>Distillation electricity</td><td></td><td>kWh</td></tr>
<tr><td>Distiller</td><td></td><td>kg</td></tr>
<tr><td rowspan="4">Outputs</td><td>Solvent</td><td></td><td>kg</td></tr>
<tr><td>Resin</td><td></td><td>kg</td></tr>
<tr><td>Pigment</td><td></td><td>kg</td></tr>
<tr><td>Water</td><td></td><td>kg</td></tr>
<tr><td rowspan="3">Transportation (Outgoing freight)</td><td>Solvent</td><td></td><td>kgkm</td></tr>
<tr><td>Varnish</td><td></td><td>kgkm</td></tr>
<tr><td>Pigment</td><td></td><td>kgkm</td></tr>
</table>

Apendix 5 Life cycle inventory of flexographic ink recycling

Inventory for Life Cycle Costing

The data for the cost breakdown structure is not given in the appendix due to confidentiality issues. But can be made available upon request and agreement.

Front lower control arm				Process Cost	Total Cost
BOL	Al Rod Supplier	Virgin aluminum			
		Recycled aluminum			
		Overhead			
		Casting	Acquisition costs		
			Labour cost		
			Process cost		
		Homogenisation	Acquisition costs		
			Labour cost		
			Process cost		
		Extrusion	Acquisition costs		
			Labour cost		
			Process cost		
		Waste threatment			
		Transportation			
	FLCA Manufacturer	Overhead			
		Forging	Acquisition costs		
			Labour cost		
			Process cost		
		Aging	Acquisition costs		
			Labour cost		
			Process cost		
		Machining	Acquisition costs		
			Labour cost		
			Process cost		
		Waste threatment			
		Transportation			
	Vehicle Manufacturer	Overhead			
		Acquisition costs			
		Labour cost			
		Process cost			
		Waste threatment			
		Transportation			
MOL	Owner	Fuel Consumption			
EOL	Authorized Treatment Center	Overhead			
		Collection			
	Shredder	Shredding & Sorting			
	Remelter	Transportation			
		Process cost			

Apendix 6 Cost breakdown structure and process costs of front lower control arm

Baggage Door Hinge				Process Cost	Total Cost
BOL	Al Plate Supplier	Flexographic ink			
		Solvent			
		Resin			
		Casting	Acquisition costs		
			Labour cost		
			Process cost		
		Ho mogenisation	Acquisition costs		
			Labour cost		
			Process cost		
		Hot rolling	Acquisition costs		
			Labour cost		
			Process cost		
		Tempering	Acquisition costs		
			Labour cost		
			Process cost		
		Waste threatment			
		Transportation			
	BDH Manufacturer	Overhead			
		Cutting	Acquisition costs		
			Labour cost		
			Process cost		
		Machining	Acquisition costs		
			Labour cost		
			Process cost		
		Waste threatment			
		Transportation			
	Air craft Manufacturer	Overhead			
		Acquisition costs			
		Labour cost			
		Process cost			
		Waste threatment			
		Transportation			
MOL	Use & Service	Fuel Consumption			
		Maintenance			
EOL	Aircraft Graveyard	Overhead			
		Collection			
	Shredder	Shredding & Sorting			
	Remelter	Transportation			
		Process cost			

Apendix 7 Cost breakdown structure and process costs of baggage door hinge

<table>
<tr><td colspan="4">Flexographic Ink Disposal&Recycling</td><td>Unit costs</td><td>Units</td></tr>
<tr><td rowspan="5">BOL</td><td rowspan="5">Ink production</td><td colspan="2">Flexographic Ink</td><td></td><td>euro/kg</td></tr>
<tr><td colspan="2">Solvent</td><td></td><td>euro/kg</td></tr>
<tr><td colspan="2">Resin</td><td></td><td>euro/kg</td></tr>
<tr><td colspan="2">Varnish</td><td></td><td>euro/kg</td></tr>
<tr><td colspan="2">Recovered material Transport</td><td></td><td>euro/kgkm</td></tr>
<tr><td rowspan="11">MOL</td><td rowspan="11">Flexographic Printing</td><td colspan="2">Overhead</td><td></td><td>of total</td></tr>
<tr><td colspan="2">Transportation</td><td></td><td>euro/kgkm</td></tr>
<tr><td rowspan="4">Printing</td><td>Solvent</td><td></td><td>euro/kg</td></tr>
<tr><td>Labor</td><td></td><td>euro/h</td></tr>
<tr><td>Electricity</td><td></td><td>euro/kWh</td></tr>
<tr><td>Natural gas</td><td></td><td>euro/kw</td></tr>
<tr><td rowspan="2">Cleaning</td><td>Solvent</td><td></td><td>euro/kg</td></tr>
<tr><td>Electricity</td><td></td><td>euro/kwh</td></tr>
<tr><td rowspan="3">Distillation</td><td>Labor</td><td></td><td>euro/h</td></tr>
<tr><td>Electricity</td><td></td><td>euro/kwh</td></tr>
<tr><td>Solvent</td><td></td><td>euro/kg</td></tr>
<tr><td rowspan="14">EOL</td><td rowspan="6">Waste Management</td><td colspan="2">Overhead</td><td></td><td>of total</td></tr>
<tr><td colspan="2">Transportation</td><td></td><td>euro/kgkm</td></tr>
<tr><td colspan="2">incineration</td><td></td><td>euro/kg</td></tr>
<tr><td rowspan="3">Distillation</td><td>Labor</td><td></td><td>euro/h</td></tr>
<tr><td>Electricity</td><td></td><td>euro/kWh</td></tr>
<tr><td>Solvent</td><td></td><td>euro/kg</td></tr>
<tr><td rowspan="8">Olax 22 Waste Ink Recycling</td><td colspan="2">Transportation</td><td></td><td>euro/kgkm</td></tr>
<tr><td colspan="2">Labor</td><td></td><td>euro/h</td></tr>
<tr><td colspan="2">Electricity</td><td></td><td>euro/kWh</td></tr>
<tr><td colspan="2">Solvent</td><td></td><td>euro/kg</td></tr>
<tr><td colspan="2">Floculant solution</td><td></td><td>euro/kg</td></tr>
<tr><td colspan="2">Solvent recovery</td><td></td><td>euro/kg</td></tr>
<tr><td colspan="2">Varnish recovery</td><td></td><td>euro/kg</td></tr>
<tr><td colspan="2">Pigment recovery</td><td></td><td>euro/kg</td></tr>
</table>

Apendix 8 Cost breakdown structure and unit costs of flexographic ink disposal and recycling

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