Comparative analysis of linear and circular manufacturing system paradigms for a steel-based product.

A case study of a mailbox manufacturing company.

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Abstract

Manufacturing industry has exerted tremendous impact on the natural environment. The aim of this thesis is to evaluate the consequences of shift from linear manufacturing system to circular manufacturing system in order to decouple the environmental burden of production and consumption process in relation to quantity of carbon footprint, cumulative energy demand, natural resource consumption, waste generated and recovered presently.

In response to this, life cycle assessment (LCA) is used to quantify and compare the associated environmental impact of the current manufacturing system of both Linear manufacturing system and the circular manufacturing system.

The thesis therefore asserts that circular manufacturing system (CMS) is more sustainable compared to linear manufacturing system (LMS) in relation to its reduction capacity of the prevailing environmental indicators most especially global threat of natural resources depletion and climate change confronting biodiversity. The result shown that CMS seems more sustainable compared to LMS in relation to the studied environmental indicators.

Further to this, emerging circular manufacturing system, its transitional shift, challenges, and its relationships with other manufacturing dynamic for consideration are also highlighted and discussed. It was concluded that these prominent challenges are caused by organizational management in relation to leadership ship and communication (OLC), has the highest impact value. Similarly, the consequential effect was seen on the level of implementation of government policy (GPI) and deployment of state of art design, knowledge and technology (DTK) for the paradigm shift. So, it is suggested that OLC should be given due consideration.

Keywords: The manufacturing system, green supply chain management circular economy, life cycle analysis, cumulative energy demand, global warming potential.
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#### 5.1 Results

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1 Introduction

1.1 Background

The increasing global population, migration, and urbanization are accompanied with developmental challenges. Such challenges include higher demand for physical infrastructure, services, energy as well as natural material resources, all of which increases greenhouse gases (GHGs) emissions in our society. The global pursuit of sustainable society aims to change the narratives by targeting a global warming temperature limit of 1.5 °C by the year 2100, compared to the pre-industrial era [1][5].

Climate change is one of the greatest threats facing humanity today. According to the National Aeronautics and Space Administration (NASA), the magnitude of climate change in the coming years will depend on the amount of GHG emitted globally [2]. In addition, research by Intergovernmental Panel on Climate Change (IPCC) consistently indicates that the net damage costs of climate change are significant and tend to increase over time if not well managed [4]. United Nations (UN) in 2015 developed a framework of 17 Sustainable Development Goals as shown in Figure 1 and 169 targets for implementation on a global scale for 2030 and beyond. It was an indispensable ambition for a sustainable development requirement in confronting the global challenge- climate change as well as building a sustainable future [2]. The Global Sustainable Development Report [3] (GSDR) recognized the power of science to understand and navigate relationships among social, environmental and economic development objectives for the (SDGs), thus manufacturing sector has been identified as the driver for the delivering of SDGs goal 12: Sustainable consumption and production.

![Figure 1: Framework of 17 Sustainable Development Goals [3].](image)

The growing demand for products and accessories in the building sector has made the sector a major contributor to the global sustainability challenges. The sector currently represents 24.2 percent of the GHG emission as well as 12 percent energy usage globally [6]. Organizations awareness of the environmental impacts from the manufacturing processes of their products and their roles in building a sustainable society are increasing [4].
Over the past years the linear manufacturing system (LMS) has devastated ecosystem and the environment to its limit, thus, there is a need to move to more sustainable manufacturing systems [6]. The level of environment awareness, economic barriers, required technical skills, waste that are difficult to recycle and consumer acceptance has been identified for the adherence to the LMS [8]. However, efforts in reversing the trends with a sustainable manufacturing system has been suggested as a means of reducing consumption of fossil fuel and extraction of virgin raw materials, modification of operational process, and practice, change in consumption habit, organizational culture as well as extending the usefulness product life [9][6].

LMS has been experiencing paradigm shift over the last few decades by ensuring optimization of associated processes and products qualities with lean resources as well as stewardship strategies for environmentally friendly operations and products [6]. Consequently, some organizations have successfully implemented operational efficiency processes within LMS which delivers eco-efficient products which are intended to serve only one life cycle [9].

In the development and implementation of sustainable manufacturing framework, a systemic approach that take into consideration strong and mutual interactions among business model, product design and supply chains enabled through state-of the-art infrastructure and innovations [9].

1.2 Problem statement

On a global scale, the manufacturing sector is the second biggest end-use sector in terms of energy consumption and carbon emission [1]. Typically, LMS processes has resulted in the increase of primary energy use, natural resources consumption, carbon emission and waste generation, all of which are threatening the biodiversity of the ecosystem [1]. The environmental impacts of the LMS contributed significantly to the global climates challenge which is one of the priority issues under the SDGs [6]. It is now globally acknowledged that this LMS from cradle to the grave is no longer sustainable considering its inefficient use of limited resources [5]-[8].

Within the manufacturing sector, the iron and steel manufacturing industry are highly energy intensive and therefore there is a need for strategies for high resource conservation, energy efficiency, and emissions reduction in the industry. The iron and steel manufacturing industry accounted for about 15% of overall energy use in the manufacturing industry is therefore of particular interest in the context of environmental impacts [7].

The transitioning challenges from the cradle-to-grave LMS to a sustainable cradle-to-cradle circular manufacturing system (CMS) has been identified as a pressing need [4]. However, this transition would require new knowledge and framework for a cost-effective technology, emissions reductions, end-use efficiency, resources efficiency, behavioural change and relevant policy has been enumerated as the measure to bridge the gap for pursuit by all the stakeholders [8][4].

SDGs (goal 12) points the urgent need for sustainable production systems and as well as consumption patterns. Therefore, this study examines the process and practices for sustainable production in a steel-based mailbox manufacturing
organization. It investigates to what extent the organization’s manufacturing process contribution, reduction possibilities with respect to both cradle-to-grave and cradle-to-cradle scenarios in the built environment.

1.3 Research questions
The following research questions are investigated in this study.

- What are the environmental implications of CMS compared to a LMS for a steel-based product, with focus on carbon footprint, cumulative energy demand, natural resource consumption, waste generated and recovered?

- What kind of challenges are associated with transition to CMS for a steel-based product case study and how can these be resolved?

1.4 Aim/ purpose
The overall aim of the thesis is to find measure/strategies for a sustainable manufacturing system for a steel-based manufacturing company.

The specific objectives of this study are to:

1. Compare the cumulative energy demand, carbon footprint, natural resource consumption, waste generated and recovered when using LMS and CMS for a steel-based mailbox manufacturing.

2. Examine the underlying challenges in the transition to CMS.

1.5 Limitation
The main limitations associated with this study has been my inability to investigate other environmental life cycle assessment indicators as well as simulating the CE of the CMS in relation to its acceptances across the sphere of the shareholders due to limited data.
2 Literature review

Systematic literature review was performed as shown in Figure 2, in order to find previous studies regarding the area of the thesis. The systematic literature was performed using well-known scientific database such as Scopus and Web of Science. The keywords considered were: “Linear Manufacturing system”, “Mailbox”, “life cycle assessment”, “Circular manufacturing system”, “steel-based product”, and ”sustainability”. A systematic evaluation of the results provided state-of-the-art knowledge, existing challenges, and future research direction in the thesis area, in connection to transition paradigms framework, green supply chain management, circular economy and life cycle assessment (LCA) which are pivotal to the research question.

Figure 2: Systematic literature review

2.1 Manufacturing systems

A manufacturing system is a complex interconnection of physical, engineering, economic, financial, demographic or social elements within a facility to transform raw materials into final products [11]. The elements include integrated equipment, the measurable parameters such as production rate, cycle time, total production time, capacity, unit cost, etc. The human resources are direct or indirect labour including human behavior within the manufacturing system [12].

LMS as illustrated in Figure 3 has being part of industrial evolution which has in practices over the last 150 years in which goods are manufactured from raw materials, sold, used and then discarded through landfilling or incinerated as waste [13]. It is characterized by the ’take, make, waste’ pattern.

Previous studies shows that LMS was built on two strong assumptions: boundlessness and easy availability of resources (energy and raw materials) as
well as a limitless regenerative capacity of the Earth [10]. However, the underlying assumptions of the linear model are not anymore true in the current global context and several key trends are threatening its sustainability, creating the need for an alternative manufacturing system model [11].

In attempt to confront the sustainability and resources depletion, the manufacturing industry has being adopting various manufacturing system in the last decade such as lean manufacturing, green manufacturing and circular manufacturing system as a transition trend from a linear (take-make-dispose/waste) to a circular (closed loop) [14].

Figure 3: A typical linear manufacturing system (LMS).

Circular Manufacturing Systems (CMS) is an emerging paradigm system designed to function as closed loops of products, components and materials intentionally to be used for multiple lifecycles as shown in Figure 4 [14]. It is a systemic approach that create values at the product design and development stage coupled with environmental, social and governance (ESG) benefits for the manufacturing industry [15][17]. Previous studies enumerated that for every tonne of scrap used for steel production, emission of 1.5 tonnes of carbon dioxide, and raw material consumption of 1.4 tonnes of iron ore, 740 kg of coal and 120 kg of limestone were avoided [7][16].

Despite this increased interest, the implementation of CMS is still at its baseline. In fact, the remanufacturing intensity in the EU, i.e., the ratio of remanufacturing to new manufacturing, amounts to only 1.9% [18]. CMS closed loop of materials, components, and products through multiple lifecycles created complexity within system manifold [19]. This holistic lifecycle approach focusses on “value creation, delivery, use, recovery, and reuse [14]. This systemic approach to business models, product design, and supply chains leads to higher complexity in the system as these elements are characterized by mutual and dynamic interactions [20].

Figure 4: A typical circular manufacturing system (CMS).
2.2 Transition paradigm framework

The transition paradigm framework from linear manufacturing system (LMS) to circular manufacturing system (CMS) are synonymous to a two-way model of either-or combination of top-down (i.e. policy and legislation, supportive infrastructure and awareness) and bottom-up enablers[21] [25].

Previous studies have reported transition framework in relation to design, smart waste audit and reduction planning; smart waste collection; high-value mixed waste processing; waste to resource conversion and recycling and collaborative platform for industrial symbiosis among all the stakeholders value chain [26]. At an ecosystem level, external environment, business model, and ecosystem partner have been identified as in the transition framework [27]. In addition, 10R target framework (i.e. recover, recycling, repurpose, remanufacture, refurbish, repair, reuse, reduce, rethink, refuse) has been pro CO2 emission posed as an effective strategy for the transition from LMS to CMS [33][34]. Also, it is a diffusion of innovation framework from technological, organizational, and environmental aspects across manufacturing organization over limited timeline [31].

Studies identified uncertainty in quality, quantity, and timing of returning products to be classic and inherent challenges within the manufacturing industry hindering CMS [20]. The global circularity gap 2022 reports [24] that only 8.6% of what the world use are being recycle, which gives a circularity gap of over 90%, thereby breaching annual 100 billion tonnes of resources boundaries of extraction and consumption, and therefore placing a heavy burden on the environment, climate and societies [24]. Thus, there is a pressing need for transition framework in relation to input for production process, utility during the use phase, destination after use and efficiency of recycling [32]. The European Union identified economic, social and environmental coupled with various systemic intervention challenges within the proposed the sustainability framework slows down the transition [30]. Despite available transition framework that are target driven, there is lack of adequate support for transitioning among the stakeholders [28][29]. Also, suitable measuring tools are indicated to be still lacking [35].

2.3 Transition challenges

A critical analysis of the challenges affecting CMS transition within the manufacturing sector was obtained using literature review as listed in Table 1. The authors of this research study performed brainstorming sessions identified through the exploration of literature to narrow down the list of challenges five categories namely: 1. Organizational management in relation to leadership and communication, 2. Design, technology, and knowledge, 3. Business with respect to economics, 4. Government in relation to its policy & implementation, 5. Supply chain network are coded as OLC, DTK, BE, GPI, and SC respectively in Table 2. The above-mentioned final list of challenges to be analysed under DEMATEL (Decision Making Trial and Evaluation) method.
Table 1: List of key challenges of CMS

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>LIST OF KEY CHALLENGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ORGANIZATION LEADERSHIP COMMUNICATION</td>
<td>Lack of standardization system lack of clear, standardized quantitative measurements and goals Lack of positive culture Coordination with supply chain partners Managing product quality through recovered parts Unproductive management and poor administration Poor communication of information Inefficient take back mechanism poor leadership and management Lack of awareness about potential benefits product or service economy lack of public environmental awareness among the stakeholders Industrial symbiosis, Complex to measure and monitor the environmental practice Cross-functional conflicts, Fear of failure, financial constraints Lack of top management commitment Inadequate adoption of reverse logistic practices Lack of human resource Resistance to change and adopt innovation Uncertain future legislation Restrictive company policies toward product/ process stewardship Efficient management of end-of-life products and materials,</td>
</tr>
<tr>
<td>2 DESIGN, TECHNOLOGY AND KNOWLEDGE</td>
<td>Lack of standardization system Design issues owing to technological limitations Lack of environmental knowledge Lack of infrastructure and unavailability of advance tool shortage of advanced technology, Managing product quality through recovered parts Inefficient take back mechanism Disassembly of products is time-consuming and expensive Industrial symbiosis, Complexity of design to reduce consumption of resource/energy Lack of human resource Environmental awareness among the stakeholders</td>
</tr>
<tr>
<td>3 BUSINESS-ECONOMY</td>
<td>Lack of economic inducement High capital investment cost Revenue generation Complexity in deciding final price of product weak economic incentives, product or service economy, Sustainable procurement Environmental awareness among the stakeholders Industrial symbiosis Cost implications Financial constraints</td>
</tr>
</tbody>
</table>
2.4 Green supply chain management

Green Supply Chain Management (GSCM) is described as a system of design and management of flows of product, information, and financial resources within the complex production systems. The complex production system involves stakeholder including suppliers, manufacturer, distributor, wholesaler, distributor, and retailer, among others [49]. It measures organizational logistics management of services and its environmental performance in connection with social and economic indices [22].

According to some previous studies, adoption of GSCM were tied to its driving forces. The driving forces are internally oriented which are mostly organizational related in terms of cost reduction, economic benefits, commitment from managerial staff and organization stakeholders such as inventors and suppliers...
while the external driving forces are regulation, customers, competition, and society related [50]. Recent studies indicated that stakeholders GSCM structures have been grossly engulf with various trade-offs coupled with behavioral issues within the framework, ambiguity, complexity and uncertainty attached to the operationalization [51].

The relationship between green supply chain management and corporate performance has been initially studied and explored by some scholars but there was no unified statement to conclude the impact of green supply chain management on corporate economic performance, whether it was either positive or negative [23].

2.5 Circular economy

Globally, Circular economy (CE) is fast becoming more mainstream as significant number of organizations acknowledged it as a systemic shift that builds long-term resilience, generates business and economic opportunities, and provides environmental and societal benefits [53]. It is based on three principles, driven by design to eliminate waste and pollution, circulate products and materials (at their highest value) and regenerate nature as a resilient system that reduce GHG emissions across the value chain, retain the embodied energy as well as sequester carbon in soil and products respectively [53]. It is an identified measure on how CE tackles climate change that is good for business, people and the environment [22][23].

CE has been a metrics for measuring sustainability in relation to the triple bottom line- ESG and the SDGs [53][55]. It is a system for socio-economic change to spread new forms of consumption and product design across meso and macro level in various organization [53]. It is also a practice for cleaner production optimizing the performance and efficiency of processes and practices within an organization [55][56]. It is an economy system that are shifting from linear manufacturing system to circular manufacturing system as shown in Figure 5.

![Circular Economy](image)

*Figure 5: A typical illustration of a circular economy (CE)*
CE enables building a sustainable culture within the product development process by closing loops of resource usage along the value change within an organization and is described as a paradigm shift [59]. World economic forum, identify the world’s leading thinkers, scientists, innovators, politicians and business people as driver and enabler of the circular economy for the manufacturers with rethinking of its product and process framework [57].

Also, several important pillars supporting circular manufacturing system include the adoption of the service-based model; the use of asset tracking technology to monitor assets; and developing a well-organized processes and systems for taking back refurbishment within the manufacturing sector [31]. These are important strategy for harmonization of economic growth, environmental issues and resource scarcity [53].

However, manufacturers are really at the heart of this new revolution of transition that might cannibalize their regular product lines with new ones. Thus, a system of innovation and creativity approach in such uncertain, game-changing transitioning times are required. Also, findings shows that there has been inadequate drive toward implementation of CE strategies. Hence, there is need for possible value-focused innovative practices that embodies CE philosophy within the manufacturing sector [55].

2.6 Life cycle assessment

LCA as a tool can be used to achieve circular economy and sustainable development as well as to support the transition from LMS to CMS, for sustainability improvement in the manufacturing sector [78].

Several LCA studies of iron and steel manufacturing have been conducted around the world. Most of these studies are product-based with 1 kg of refined metal as its functional unit and evaluated environmental impacts in terms of use of materials, global warming potential, solid waste burden and gross energy requirement. These found that hot-dipped galvanized steel products result in higher environmental impacts compared with other steel products (slab, hot-rolled, cold-rolled, hot-dipped galvanized, and electro-galvanized steels) [61]. In a recent study which used water footprint calculation model from a life cycle assessment perspective, it was indicated that steel plant poses a serious risk to the water environment [60].

There are also several processes based LCA studies of which a recent one found that the production of pig iron in blast furnaces has the highest impact on greenhouse gas emissions and fossil fuel consumption [6].

Previous LCA studies showed that consideration of all relevant processes is necessary to identify hotspots [59]. However, the results of these studies varied substantially depending on the modeling assumptions [63][64]. Hence consistency has been lacking in the reported LCA studies [66]-[76]. Moreover, many of the studies focused on cradle-to-gate LCA with few midpoint impact categories [77]. Also, there are varying functional unit definitions which are either based on mass or final product, as well as varying system boundaries definitions in the reported LCA studies [76]. Limited inventory data and insufficient databases hamper the accuracy of LCA findings [78].
3 Theory

3.1 Life Cycle Assessment framework

According to the international organization for standardization (ISO) standards, LCA is defined as a method for analyzing and determining the environmental impact along the product chain of (technical) systems including conversions that occur in the manufacturing process as well as material chemistry in relation to formulation and structure as result of input/ output dynamism processes. This general description has been widely known as definitions of LCA [66][83].

The international standard now developing for LCA is based on the ISO 14040 series, which could be either qualitative or quantitative methods [67]. Qualitative methods (Red Flag approach & Material, Energy Toxicity – MET approach) draw conclusions straight from the life cycle while quantitative methods (Eco-points, Eco-indicator, Environmental-priority-strategies system (EPS) and Material Input Per Service unit (MIPS) concept) using card to evaluate the environmental impacts by mathematical processing of the data describing the lifecycle. The commonly used environmental effects are resource depletion, global warming, and ozone depletion. Human toxicity, ecotoxicity, photochemical oxidation, acidification, eutrophication, land use and Others (including solid waste, heavy metals, carcinogens, radiation, species extinction, noise).

The methodological framework of all the LCA techniques is based on ISO standards 14040-43 as shown Figure 6. A complete LCA consistent with ISO standards consists of four interrelated phases: 1. Goal definition and scope. 2. Inventory analysis. 3. Impact assessment with four sub-phases: classification, characterization, normalization, weighting. 4. Improvement assessment [82]. The iterative evaluation analysis procedure is analysis until the required level of detail and reliability is attained.

LCA system boundaries are:

- **Cradle-to-gate**: System boundary considers activities from materials extraction (cradle), transportation, processing and fabrication until product leave the factory (gate).

- **Cradle-to-grave**: System boundary considers activities from “Cradle-to-gate” plus activities associated with transportation to users, use/service life and the end of life (grave).

- **Cradle-to-cradle**: system beyond “cradle to grave”, where end-of-life products are reused, or recycled, recovered and disposal (in landfill) is avoided.
3.1.1 LCA tool

LCA with the use of well-established global accredited LCA tool such as SimaPro, Open LCA, Mobius, GaBi, Idemat, and Ecoinvent. IDEMAT (Industrial Design & Engineering Materials database), being a sustainability inspired LCI database of the Delft University of Technology with an integrated scenario of open and closed production process.

The IDEMAT database with its modular structure supplying inputs and outputs of unit processes of information as well as cumulative results of both descriptive as well as decision-oriented life cycle assessments. Modular structure data include modelling, uncertainty assessment, elementary flow representation and data format. It described attributional and consequential (change-oriented or decision-oriented) of product and services in relation to environmental relevance compliance. It also provides data on eco-costs as well as carbon footprint, CED and reserve depletion of the material selected.

The IDEMAT database contains LCI data that are represented to a large extent mass, energy, and environmental relevance according to ISO 14040/14044. The quality of the life cycle data and the user-friendly access to the database are reliable tool for environmental assessment, as well as the necessary backbone for an actual realisation of LCA approaches in relation to the geographical and technical scope of production, processes of product and services.

Generic datasets, allocation database, variability, and parameter uncertainty of unit process’ inputs and outputs, are expressed in quantitative terms on the level of individual unit processes system. The uncertainty inbuilt estimations in its database of the unit process level using deterministic mean values have been an advantage for reproducibility of LCI results.

3.1.2 Goal definition and scope

It is a LCA procedural phase whereby clear description of the study, product (or service) to be assessed, functional unit, system boundaries and desirable level of detail requirement is defined. It is a process of gathering data for the model of the life cycle, by choosing appropriate environmental effects to consider (local, global), and drawing conclusions to answer the questions asked at the beginning of the project. However, being an iterative process, the previously established goal of the study might be changed or alter needs to some extent when an insufficient or unavailable data or additional information arrives.

Figure 6: Framework of Life Cycle Assessment from ISO 14040 standards.
3.1.3 System boundaries and functional unit

System boundaries are the representation (process flow chart) of the LCA complex technical system of a model where the product must have clearly specified functions to be assessed. This consists of subsequent processes (cradle-gate-cradle) required to produce, transport, end of life and recycling. Moreover, being an environmental mechanisms model, it translates inflows and outflows of the life cycle that are created into the environmental impact’s contribution as shown in Figure 7.

Product systems are usually interconnected in a complex way with endless regression problem. To avoid such a problem the boundaries of the system must be defined with assumption. For instance, neglecting capital goods significantly underestimates environmental burdens, it has been shown, that the production of capital goods constitutes about 30% of the total environmental impact resulting from an average generation of electricity [23].

To narrow down the system boundaries, cut-off rules are adopted. Cut-off rules stated that if the mass or economic value of the inflow is lower than a certain percentage (a previously set threshold) of the total inflow it is excluded from further analysis. The same applies when the contribution from an inflow to the environmental load is below a certain percentage of the total inflow.

![Figure 7: Life cycle inventory for the manufacturing system](image)

3.1.4 Inventory analysis and allocation

The inventory phase is the core of an LCA. This phase all the material flows, the energy flows and all the waste streams released to the environment over the whole life cycle of the system under study are identified and quantified in a spreadsheet called inventory table as shown in Figure 8. The inventory phase has four separate sub-stages:

- Constructing a process flow chart
- Collecting the data.
- Relating the data to a chosen functional unit (allocation).
• Developing an overall energy and material balance (all inputs and outputs from the entire life cycle).

![Figure 8: Life cycle inventory template.](image)

**Allocation:** are multi-output processes for a process fulfils two or more functions or gives two or several of usable outputs mostly used in connection emissions and material consumption of some specific product during LCA. Various types of allocation are allocation based on physical parameters such as mass, energy, etc., allocation based on natural causality, allocation based on economic values (prices) and arbitrary allocation. However, this allocation process has been saddled with challenges of how to divide emissions and material consumption between several product or processes. Several methods such as Substitution of allocation, have been developed to deal with allocation. ISO recommends avoiding allocation if possible. This can be done by extending the system boundaries i.e., by including processes that would be needed to make the same by-product in the conventional way.

### 3.1.5 Impact assessment systems.

It is system that further process the inventory table to attain a higher level of aggregation by adopting single scoring template. The ISO standards for the aggregation process are either a compulsory steps (classification and characterisation) or optional steps (normalisation and weighting).

**Classification of Impacts:** The first step to higher aggregation of the data is classification. Inflows and outflows from the life cycle are gathered in a number of groups representing the chosen impact categories such as resource depletion, toxicity, global warming, ozone depletion, eutrophication, acidification, etc. The inventory table is rearranged in such a way that under each impact category, all the relevant emissions or material consumption (local or global) are listed (qualitatively and quantitatively).

**Characterisation:** is an aggregation process whereby the relative strength of the unwanted emission is evaluated and contributions to each environmental problem are quantified. An equivalence factor is applied to consolidate and indicates how many times a given compound contributes to the environmental impact category in comparison to a chosen reference substance. Environmental profile of potential impacts category (resource depletion, global warming, acidification, and ozone depletion) as well as its life cycle phases from cradle -gate-crade of the product or service is generated.
Normalisation: is a procedure to allow for comparation of the impact categories among themselves. It is performed to make the effect scores of the environmental profile comparable in a broader context, which makes the interpretation easier. However, lack of relevant figures representing annual contributions has making it difficult to evaluate.

Weighting (valuation): is an aggregation of the data in which the different impacts categories are weighted so that they can be compared among themselves, i.e., the relative importance of the effects is assessed. In comparative analysis the prime goal is to find out which one of the products fulfilling the same function is the best option. Determination of weighting principles are data from panel of experts, social evaluation, prevention costs, energy consumption, distance-to-target principle and avoiding weighting.

In practice, weighting is performed by multiplying a normalised environmental profile by a set of weighting factors, which reflect the seriousness of a given effect. A few European countries have formulated their weighting factors which are compromise between scientific, economic and social considerations but politically determined target values as conformity with policy decisions.

A weighting triangle indicates to what extent the result of an analysis is dependent on weighting factors. This approach can be used if three damage categories are considered. The sum of the three weighting factors represents 100% and appropriate accordingly.

3.1.6 Interpretation

Interpretation of LCA is a thoroughly analyse all the results obtained in relation to the goal and scope defined for the intended audience. It includes identification of significant issues, checks on completeness, sensitivity, and consistency of the analysis as well as development of conclusions, limitations, and recommendations. However, there are several issues to cover such as uncertainty and sensitivity.

Uncertainty: tried to address the weak points and inadequate data during the LCA. There are two main sources of uncertainty. First is the quality of the data – data often comes from different sources, estimates, assumptions, theoretical calculation, etc. Secondly subjective choices of the model, which cannot be avoided such as system boundaries, allocation rules, characterisation models. All these shortcomings such as gap between the inventory table and the impact assessment method must be highlighted when drawing conclusions from the analysis, not to mislead the audience.

Sensitivity analysis: is made to check how stable the results are. During sensitivity analysis the assumptions are changed and the LCA is recalculated, and the outcomes are compared, critical points are identified. The results of the sensitivity analysis shows if general conclusions drawn from an LCA are stable and reproducible.
3.2 Environmental Effects

The transformation of materials and energy into products and services to meet human needs and aspirations contribute significantly to scale of planetary changes. The environmental changes are: abiotic resource depletion, global warming, and ozone depletion, human toxicity, eco toxicity, photochemical oxidation, acidification, eutrophication, land use and others (including solid waste, heavy metals, carcinogens, radiation, species extinction, noise). In order with the context of this thesis, carbon footprint in relation to the global warming potential and cumulative energy demand would be presented as shown in Table 3.

Table 3: Life cycle assessment indicators

<table>
<thead>
<tr>
<th>Life cycle assessment indicators</th>
<th>Indicators assessed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming potential</td>
<td>GWP X</td>
</tr>
<tr>
<td>Depletion potential of the stratospheric ozone layer</td>
<td>ODP -</td>
</tr>
<tr>
<td>Acidification potential to land and water</td>
<td>AP -</td>
</tr>
<tr>
<td>Eutrophication potential</td>
<td>EP -</td>
</tr>
<tr>
<td>Acidification potential to land and water</td>
<td>AP -</td>
</tr>
<tr>
<td>Formation potential of tropospheric ozone photochemical oxidants</td>
<td>POCP -</td>
</tr>
<tr>
<td>Abiotic resource depletion potential, elements</td>
<td>ADP -</td>
</tr>
<tr>
<td>Abiotic resource depletion potential, fossil fuel</td>
<td>ADP -</td>
</tr>
<tr>
<td>Use of renewable primary energy (excluding resources used as raw materials)</td>
<td>CED x</td>
</tr>
<tr>
<td>Use of renewable primary energy resources used as raw materials</td>
<td>-</td>
</tr>
<tr>
<td>Use of non-renewable primary energy (excluding resources used as raw materials)</td>
<td>-</td>
</tr>
<tr>
<td>Use of non-renewable primary energy resources used as raw materials</td>
<td>-</td>
</tr>
<tr>
<td>Use of secondary material</td>
<td>-</td>
</tr>
<tr>
<td>Use of renewable secondary fuels</td>
<td>-</td>
</tr>
<tr>
<td>Use of non-renewable secondary fuels</td>
<td>-</td>
</tr>
<tr>
<td>Use of net fresh water</td>
<td>-</td>
</tr>
<tr>
<td>Non-hazardous waste to disposal</td>
<td>-</td>
</tr>
<tr>
<td>Hazardous waste to disposal</td>
<td>-</td>
</tr>
<tr>
<td>Radioactive waste</td>
<td>-</td>
</tr>
</tbody>
</table>

3.2.1 Carbon footprint using global warming potential (GWP)

Global warming potentials are emission metrics that can be used to implement comprehensive and cost-effective policies in a decentralised manner so that multi-gas emitters (nations, industries) can provide mitigation measures, according to a specified emission constraint, by allowing for substitution between different climate agents. These measures are function of whether a long-term climate change constraint has been set or no specific long-term constraint has been agreed upon [82]. This metric formulation requires knowledge of the contribution to climate change from emissions of various components over time. It can be calculated using equation (1).

The GWP index is a time-based integrated global mean of a pulse emission. It is a measure of 1 kg of some compound relative to that of 1 kg of the reference
gas CO$_2$. Studies show that using a 100-year time horizon as in the Kyoto Protocol, the effect of current emissions reductions that contain a significant fraction of short-lived species (e.g., CH$_4$) will give less temperature reductions towards the end of the time horizon, compared to reductions in CO$_2$ emissions only [81][83].

The Global Temperature Potential (GTP) metric provides an alternative approach by comparing global mean temperature change at the end of a given time horizon. Thus, GWPs remain the recommended metric to compare future climate impacts of emissions of long-lived climate gases. Globally averaged GWPs have been calculated for short lived species [83]. GWP values for time horizons of 20, 100 and 500 years as shown in Table 4. The uncertainties of these direct GWPs are taken to be ±35% for the 5 to 95% (90%) confidence range [83].

Indirect GWPs are indirect radiative effects which include the direct effects of degradation products or the radiative effects of changes in concentrations of greenhouse gases caused by the presence of the emitted gases (CO, NOx & Non-methane volatile organic compounds) or its degradation products. The indirect effects are ozone formation or destruction, enhancement of stratospheric water vapour, changes in concentrations of the OH radical with the main effect of changing the lifetime of CH$_4$ and secondary aerosol formation. Uncertainties for the indirect GWPs are generally much higher than for the direct GWPs. The indirect GWP will in many cases depend on the location and time of the emissions. Indirect GWPs sources are carbon monoxide, non-methane volatile organic compounds, nitrogen oxides, hydrogen, halocarbons chlorine- and bromine.

The Global Temperature Potential (GTP) is a relative emission metric that measures the ratio between the global mean surface temperature change at a given future time horizon (TH) following an emission (pulse or sustained) of a compound in relation to a reference gas. The GTP values for pulse emissions of gases with shorter lifetimes than the reference gas will be lower than the corresponding GWP values, thus making it significant when surface temperature change is being considered.

\[ GWP_{\text{total}} = \sum_i (m_i \times GW_{P_i}) \]

where

\[ GW_{P_{\text{total}}} = \text{global warming potential in kg CO}_2 \]
\[ -eq \text{ of full inventory of GHGs} \]
\[ m_i = \text{mass (in kg) of inventory flow (i)individual GHG} \]
\[ GW_{P_i} = \text{global warming potential of (i)individual GHGs} \]
Table 4: Excerpt from the list of GWP (IPCC 2014a).

<table>
<thead>
<tr>
<th>Substance</th>
<th>Molecule</th>
<th>Atmospheric lifetime (year)</th>
<th>Radiative efficiency (W/m² ppb)</th>
<th>GWP (kg CO₂ – eq /kg GHG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>CO₂</td>
<td>1.37E-05</td>
<td>01</td>
<td>1</td>
</tr>
<tr>
<td>Methane</td>
<td>CH₄</td>
<td>12</td>
<td>3.63E-04</td>
<td>84</td>
</tr>
<tr>
<td>Nitrous Oxide</td>
<td>N₂O</td>
<td>121</td>
<td>3.00E-03</td>
<td>264</td>
</tr>
</tbody>
</table>

3.2.2 Cumulative energy demand

The energy framework differentiates between renewable and non-renewable energies, primary and secondary energies and energy intended for energy purposes versus energy intended for material purposes. There are number of energy use indicators that are frequently used in LCA studies: cumulative energy demand (CED), non-renewable cumulative energy demand (NRCED), fossil energy use (FEU), primary fossil energy use (PFEU), and secondary energy use (SEU). However, due to the relevance and contexts of this thesis, CED is the most appropriate [74].

The CED has been widely applied to assess environmental burden of commodity production throughout the life cycle. It provides an indicator of the total energy usage (direct and indirect) during its whole life cycle of a product or services.

It might be appropriate for assessing the environmental performance of the various unit throughout the life cycle of the manufacturing process, which includes direct energy usage during the process as well as the indirect energy (i.e., embodied energy) due to the material consumption. Thus, cumulative energy demand may offer a comprehensive assessment method for process strategy as well as identifying energy saving potentials in their complex relationship between design, production, use and disposal.

Due to the existence of diverging concepts and the unclear basis for the characterization of the different primary energy carriers but all energy carriers have an intrinsic value. This intrinsic value is determined by the amount of energy withdrawn from nature for every process within the LCA. It is usually expressed in MJ equivalents. However, the CED is also widely used as a screening indicator for environmental impacts and performance. Furthermore, CED-values can be used to compare the results of a detailed LCA study to others where only primary energy demand is reported [48].
3.2.3 Resource depletion, waste generated and recovered

Resource depletion, waste generated and recovered a material accounting procedure using Conservation of mass theory in manufacturing engineering. It is a measure of the material balances that occur during the physical and chemical process of the input/output within the manufacturing system. The input and output are quantified (mass or mole or atomic species) of the material during the manufacturing processes.

For resource depletion, waste generated and recovered to be in place, the concept of metal recycling, re-use and re-manufacture has to be understood in order to effectively quantify the changes recorded during the process in relation to mass, moles, atomic reconfiguration. Also, it is a process of defining the relationship between the virgin raw material depletion rate as a measure for the sustainable future with respect to use of metals [72]. The validity table for process scenario is shown in Table 5.

Table 5: Validity of input/output for a steady state process [69].

<table>
<thead>
<tr>
<th>Type of balance</th>
<th>Without chemical reaction</th>
<th>With chemical reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Total moles</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Mass of a chemical compound</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Mole of chemical compound</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Moles of an atomic species</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Thus, metal available for these processes are called scrap. It is classified into three main categories: home, new and old scrap. It is widely recognised that recycling of metals results in significant savings in energy consumption (and hence reductions in associated greenhouse gas emissions) when compared to primary metal production [69]. Previous studies reported that energy savings for metal recycling over primary metal production of aluminium, nickel, copper, zinc, lead and steel (95%, 90%, 84%, 75%, 65% and 60%) respectively [68][71].

Previous studies [71] in Table 6 had reported in recycling rate and recycled content of some metal stock and flow in the form of ranges rather than specific values. Recycling rates are very dependent on application, location and metal prices, and product designed durability lifespan.

Table 6: Recycling rate and recycled contents % for various metal [72].

<table>
<thead>
<tr>
<th>Type of balance</th>
<th>Recycling rate</th>
<th>Recycled content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>63</td>
<td>80</td>
</tr>
<tr>
<td>Steel</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Copper</td>
<td>40</td>
<td>32</td>
</tr>
<tr>
<td>Nickel</td>
<td>70</td>
<td>33</td>
</tr>
<tr>
<td>Lead</td>
<td>66</td>
<td>63</td>
</tr>
<tr>
<td>Zinc</td>
<td>70</td>
<td>30</td>
</tr>
</tbody>
</table>
The embodied energy along with the associated greenhouse gas emissions consumed in secondary metal production by recycling do appreciably less than that consumed in primary metal production and decrease further in subsequent times when a metal is recycled [72].

The energy consumption for metal recycling Metal recycling involves collection, recovery refining and remelting. Energy is primarily fossil fuel based are dependent on the distance for collection, sorting technology, however, the cumulative energy consumption for scrap processing is tied to the above factors as well as lower that energy consumed during primary extraction phase [72].

Metal quality of a commercial recycling systems do not create 100% pure material due to material recovery process during the physical separation and thermodynamic streams that never achieve 100% material recovery coupled with some level of contamination of the scrap produced [71].
4 Case Study

4.1 The steel mailbox manufacturing company- Boxicon AB

Boxicon AB, formerly called Sbox Kvistrum AB is a Swedish group of companies in eastern Småland Kvistrum, that have worked with sheet metal, sheet metal constructions and powder coating since 1952 and are proud of their traditions and craftsmanship of, quality, security, and excellent environmental choice.

Production, painting and assembly takes place in Västervik and all components are from Sweden or the EU. The company manufactures and sells real estate boxes property box for apartment buildings and communities at lower price with less impact on the environment.

In year 2019 and 2020, the company stated selling property boxes in Norway and Sweden respectively with 15% market share as of today. The company was accredited by Sundahus, as an environmental compliance measure to ensure its process and product at the market and to be able to meet future environmental impact requirements on construction products.

The most common way to install property boxes are indoors hung on the wall, recessed in the wall, standing alone or standing on a furniture. A life cycle analysis on the mailbox sample as shown in Figure 9 with its material inventory in Table 7 would be evaluated using LMS and CMS scenario.

Table 7: Life cycle material inventory

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>Actual weight (kg)</th>
<th>% by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester Facade AE Semi-Gloss paint</td>
<td>1.733</td>
<td>3.5</td>
</tr>
<tr>
<td>Aluminium</td>
<td>0.050</td>
<td>0.1</td>
</tr>
<tr>
<td>Cold rolled Steel</td>
<td>47.52</td>
<td>96</td>
</tr>
<tr>
<td>Stainless round Steel</td>
<td>0.198</td>
<td>0.4</td>
</tr>
<tr>
<td>Summary</td>
<td>49.5</td>
<td>100</td>
</tr>
</tbody>
</table>
Figure 9: A typical Steel mailbox
5 Methodology

The present author presents two methods in this section in answering the research question of this thesis. Firstly, LCA methodology is applied for the steel mailbox as shown in Figure 9, which is used as a case study for the analysis of the environmental impact. The sequential order of the LCA analysis are the goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA). Secondly, DEMATEL (decision making trial and evaluation) method being a decision-making technique based on pairwise comparisons would be used in understanding the causes, effect and significant challenges of the paradigm shift from LMS to CMS.

5.1 LCA -IDEMAT database

LCA tool IDEMAT, being a sustainability inspired LCI database of the Delft University of Technology with an integrated scenario of open and closed production process has been the adopted tool for this study.

The functional unit and system boundaries are important for the scope of study to be properly defined for each scenario, LMS and CMS are the scenario scope of this study. It describes functional unit of the product, process of cradle-to-cradle (CMS) and cradle to grave (LMS). All the required data, measure and weight are recorded in the Life cycle Inventory and are related with the available databases. The unavailable dataset for a missing production process or material are replaced with the closest similar one from the available databases. IDEMAT database are explored with the aid of Excel calculation sheet, tables and graphs for interpretation.

5.1.1 Framework, goals, and scope definition

LCA framework according to ISO 14040/14044 is implemented in the thesis for analysis of the LMS and CMS scenario, to investigate the environmental impact of the steel mailbox as mentioned in section 3.1.1 in the scope and goal of this study.

5.1.2 System boundaries, functional unit, and reference flow

Functional unit and system boundaries are important for the scope of study to be properly defined for each scenario. For this study, functional unit of the steel mailbox is based on mass per unit in relation to one kilogramme. The considered scenario lifetime is 25 years. The system boundary of this LCA includes resources extraction, transportation, manufacturing, transportation, end user and end of life (disposal or recycling) phases for the LMS and CMS scenarios represented in the block diagrams shown in Figure 10 & Figure 11 respectively.

*Figure 10: LMS product and process scenario.*
5.1.3 Life cycle, inventory database and assumptions

The LCI step collected the required data, for the analysis of the production processes based on the LMS and CMS. The corresponding inventory data for the indicators were selected from the Idemat database [70]. However, closest alike data is selected for the polyester facade semi-gloss paint element. This study presented the used data and assumption for the analysis in Appendix I.

There are some assumptions related to the system boundary. The transportation was assumed to be global freight service via water from China and within Sweden (Stockholm to Växjö).

5.1.4 Life cycle impact assessment

LCIA is performed based on the LCI data, and the outcomes are processed with tables and graphical representation. The collected data with the help of the available Idemat database were evaluated for outputs in term of CED [MJ], and carbon footprint (kg/CO₂-eq). However, the impacts on human health, water or other natural resources were not considered in the LCIA.

5.1.5 Resource depletion

The resources depletion is estimated using general material balance for a steady state and physical process. It is expressed using differential mass balances equation 2-5 of the LCIA output data.

\[
\text{Input} + \text{generation} - \text{output} - \text{consumption} = \text{accumulation}
\]

where

\[
\text{Input} - \text{(feed or input enters through system boundaries)}
\]

\[
\text{Generation} - \text{(output produced within the system boundaries)}
\]

\[
\text{Output} - \text{(product, emission that leaves through system boundaries)}
\]

\[
\text{Consumption} - \text{(consumed within system)}
\]

\[
\text{Accumulation (build-up within system as a result of the processes)}
\]
for a steady-state continuous process, the accumulation term is zero. Thus, the above equation becomes:

\[
\text{Input} + \text{generation} = \text{output} + \text{consumption}
\]  

For physical process, since there is no chemical reaction, the generation and consumption terms will become zero, and the balance equation for steady-state physical process will be simply reduced to:

\[
\text{Input} = \text{output}
\]

\[
\text{Percentage relationship: } A = \frac{\text{output} - \text{input}}{\text{input}} \times 100
\]

### 5.1.6 Waste generated and recovered

Waste generated and recovering were estimated using the recycled content rate as highlighted in *Table 6* and *equation 6-7* of the LCIA output data.

\[
\text{Recovery rate (\%)} = \frac{\text{Quantity of the scrap recovered}}{\text{Quantity of the scrap available}} \times 100
\]

\[
\text{Recycled content (\%)} = \frac{\text{Quantity of the scrap reprocessed}}{\text{total quantity of material}} \times 100
\]

### 5.1.7 Life cycle interpretation

The obtained results from the LCA will be interpreted with respect to the main impact categories. These impact categories are CED, carbon footprint, natural resource consumption, waste generated and recovered. The interpretation of these parameters are made for the discussion and answering of the research question.
5.2 Introduction to DEMATEL method

DEMATEL method (Decision Making Trial and Evaluation) is a decision-making technique based on pairwise comparisons. It identifies the model of causal relations between the variables such as barriers, challenges, criteria and their exerted influences. The advantage of this method is that experts are able to be more fluent in expressing their opinions about the effects (direction and severity of effects) between factors. The present author explored the literature review as expert in this context.

The overall direct relationship matrix has been developed by entering the average value of all \( x_{nj} \) entries collected from all the literature and ranked with respect to Table 8. The initial normalized matrix using equation 10 and total relationship matrix was calculated using equation 11. For attaining a reflection of the noteworthy connection, the inner dependence matrix is established by rejecting the least significant relationship. So, to construct the causal digraph the threshold value (\( \alpha \)) is calculated using equation 12. The threshold value (\( \alpha \)) of the total relationship matrix allows to differentiate between the significant and insignificant results of the examined challenges.

5.2.1 Direct relation matrix

To identify the model of the relations among the number of identified challenges and matrix (\( n \times n \)) is generated. The effect of the element in each row is exerted on the element of each column of the matrix. If multiple experts’ opinions are used, all experts must complete the matrix. Arithmetic mean of all of the experts’ opinions is used and then a direct relation matrix \( X \) is generated.

Table 8: Scale used in DEMATEL method

<table>
<thead>
<tr>
<th>Numerical value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No influence</td>
</tr>
<tr>
<td>1</td>
<td>Very low influence</td>
</tr>
<tr>
<td>2</td>
<td>Low influence</td>
</tr>
<tr>
<td>3</td>
<td>Medium influence</td>
</tr>
<tr>
<td>4</td>
<td>High influence</td>
</tr>
<tr>
<td>5</td>
<td>Very high influence</td>
</tr>
</tbody>
</table>

\[
X = \begin{bmatrix}
0 & \cdots & x_{n1} \\
\vdots & \ddots & \vdots \\
x_{n1} & \cdots & 0
\end{bmatrix}
\]  

(8)

5.2.2 Normalization

To normalize the direct relation matrix \( N \), the sum of all rows and columns of the matrix is calculated directly. The largest number of the row and column sums can be represented by \( (K) \). To normalize, it is necessary that each element of the direct-relation matrix is divided by \( (K) \).
After calculating the normalized matrix, the fuzzy total-relation matrix $T$ can be computed as follows:

$$T = \lim_{{n \to \infty}} (N^1 + N^2 + \ldots + N^k)$$ (11)

$$T = N(I - N)^{-1}$$

### 5.2.4 The threshold value

The average figures of all the elements present in the matrix $T$ are added and divided by the number of elements present in the matrix to provide the threshold value ($\alpha$). This computation is done by utilizing the following equation:

$$\alpha = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} x_{ij}}{n^2}$$ (12)

$n^2$ is the total number of elements in the total matrix.

The threshold value is obtained in order to calculate the internal relations matrix. Only relations whose values in matrix $T$ is greater than the threshold value are depicted and set to zero showing causal relation and are not considered.

The sum of each row and each column of matrix $T$ are calculated as $D$ and $R$ respectively.

$$D = \sum_{j=1}^{n} T_{ij}$$ (13)

$$R = \sum_{i=1}^{n} T_{ij}$$ (14)
5 Results and Discussion

5.1 Results

In this chapter, the CED, carbon footprint, natural resource consumption, waste generated and recovered for both the LMS and CMS are given. Also, the challenges attached to the transition paradigm shift from LMS to CMS scenarios of a steel-based mailbox are presented and discussed.

*Figure 12-16* shown the LCI, CED, carbon footprint, natural resource consumption, waste generated and recovered for both the LMS and CMS scenario for the steel mailbox manufacturing. *Figure 12* is a graphical representation of the LCI of the mailbox -cold rolled sheet steel, stainless steel, aluminium and polyester façade AE semi-gloss paint.

![Inventory of materials](image)

*Figure 12: Life cycle inventory of the steel mailbox.*
5.1.1 Carbon footprint

*Figure 13* shows the carbon footprint (kg CO₂ -eq.) for each stage within the LCA framework for both the CMS and LMS. The carbon footprint environmental impact was more on the manufacturing system and beyond of life stage recorded beneficial recompense of carbon to the environment.

*Figure 13: Carbon footprint of both LMS and CMS.*
5.1.2 Cumulative energy demand

Figure 14 shows that the CED for each stage within the LCA framework of both CMS and LMS. The manufacturing system has contributed significantly to the environmental impact while other stages had minimal contribution.

![Cumulative Energy Demand of CMS and LMS](image)

*Figure 14: Cumulative Energy Demand of CMS and LMS*
5.1.3 Resources depletion

*Figure 15* shows the resources depletion for the LCI of both the CMS and LMS. It shows reduction of the resources depletion rate across LCI element for the CMS scenario compared to the LMS.

![Figure 15: Resources depletion of both CMS and LMS.](image)

5.1.4 Waste generated and recovered

*Figure 16* shows waste generated and recovered for both LMS and CMS. It shows recovery rate of the resources across LCI element of the LMS when switched to CMS scenario.

![Figure 16: Waste generated and recovered both CMS and LMS.](image)

5.1.5 Underlying challenges in the transition

The interrelationship of identified challenges is established with the application of the proposed DEMATEL framework. In *Table 9*, the overall direct relationship matrix is computed using *equation (11)* as mentioned above in *section 5.2*.

The threshold value ($\alpha$) is computed as 1.00284 (as shown in *appendix 3*), and the values lower than $\alpha$ were eliminated for obtaining the inter-relationships of challenges. The net cause/effect graph *Figure 17* is drawn using data from *equation 13 & 14* as shown in *appendix 2*. The result obtained has identified the cause of the challenge to be organizational management in relation to leadership and communication, green chain supply, business with respect to circular economy with the consequential effect/impact shown on design, technology and knowledge, and the implementation of government policies as shown in *Figure*
17. The legend of identified challenges used in Table 9 and Figure 17 were presented in Table 10.

Table 9: The overall direct relationship matrix

<table>
<thead>
<tr>
<th>REF NO</th>
<th>YEAR</th>
<th>OLC</th>
<th>GPI</th>
<th>DTK</th>
<th>SC</th>
<th>BE</th>
</tr>
</thead>
<tbody>
<tr>
<td>[36]</td>
<td>2020</td>
<td>0.14</td>
<td>0.43</td>
<td>0.29</td>
<td>0.00</td>
<td>0.14</td>
</tr>
<tr>
<td>[37]</td>
<td>2022</td>
<td>0.50</td>
<td>0.25</td>
<td>0.00</td>
<td>0.00</td>
<td>0.25</td>
</tr>
<tr>
<td>[38]</td>
<td>2020</td>
<td>0.25</td>
<td>0.42</td>
<td>0.08</td>
<td>0.08</td>
<td>0.17</td>
</tr>
<tr>
<td>[39]</td>
<td>2016</td>
<td>0.00</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
<td>0.00</td>
</tr>
<tr>
<td>[40]</td>
<td>2019</td>
<td>0.50</td>
<td>0.00</td>
<td>0.00</td>
<td>0.50</td>
<td>0.00</td>
</tr>
<tr>
<td>[41]</td>
<td>2013</td>
<td>0.33</td>
<td>0.33</td>
<td>0.00</td>
<td>0.33</td>
<td>0.00</td>
</tr>
<tr>
<td>[42]</td>
<td>2016</td>
<td>0.50</td>
<td>0.00</td>
<td>0.00</td>
<td>0.50</td>
<td>0.00</td>
</tr>
<tr>
<td>[43]</td>
<td>2016</td>
<td>0.33</td>
<td>0.17</td>
<td>0.17</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td>[44]</td>
<td>2017</td>
<td>0.25</td>
<td>0.00</td>
<td>0.25</td>
<td>0.00</td>
<td>0.50</td>
</tr>
<tr>
<td>[45]</td>
<td>2019</td>
<td>0.71</td>
<td>0.00</td>
<td>0.00</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>[46]</td>
<td>2019</td>
<td>0.71</td>
<td>0.00</td>
<td>0.00</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>[46]</td>
<td>2017</td>
<td>0.57</td>
<td>0.14</td>
<td>0.14</td>
<td>0.00</td>
<td>0.14</td>
</tr>
<tr>
<td>[48]</td>
<td>2017</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Figure 17: Net cause-effect diagram of the underlying challenges

Table 10: Legend of the identified challenges.

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Code</th>
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<tr>
<td>Organizational management in relation to leadership and communication</td>
<td>OLC</td>
</tr>
<tr>
<td>Design, technology, and knowledge,</td>
<td>DTK</td>
</tr>
<tr>
<td>Business with respect to circular economy</td>
<td>BE</td>
</tr>
<tr>
<td>Government in relation to its policy and implementation</td>
<td>GPI</td>
</tr>
<tr>
<td>Supply chain network</td>
<td>SC</td>
</tr>
</tbody>
</table>
5.2 Discussion

In this section, the CMS and LMS scenarios obtained result are presented for discussion in order to compare the environmental implications with respect to carbon footprint, CED, natural resource consumption, waste generated and recovered as well as the challenges associated with the transition.

- **Environmental implications**

  **Cumulative energy demand**

  The CED is an important driver of environmental impacts that has to be considered when performing LCA [74]. The analysis presented has revealed CED of each LCA stage and its environmental impacts for both scenarios LMS and CMS. The CED of the LMS accounted for 3,002 MJ while CMS had 2,050 MJ translating to a significant difference of 32% between the two scenarios.

  The breakdown of CED for both the LMS and CMS in Figure 14. It showed that the greatest CED was from the manufacturing stages within the sector which accounted for the significant share of the total energy demand. The current study found that the manufacturing of hot rolled steel is a significant hotspot which are consistent with those of other studies [49][50]. The result of the analysis indicates that switching from LMS to CMS would reduce CED [3].

  **Carbon footprint**

  The carbon footprint being the summing up of the GHG emissions resulting from every phase of the manufacturing system and its consequential environmental impacts was performed in the LCA [74]. The analysis presented has revealed carbon footprint contribution of 333.0 and 185.5 KgCO₂·eq for the LMS and CMS scenarios respectively.

  Thus translating to a significant carbon footprint differences of 45% between the two scenarios as presented in Figure 13. However, end of life (EoL) phase, the results show that in this phase the carbon footprint is recompensed in the CMS scenario. These finding further support the idea of paradigm shift from LMS to CMS [3].

  **Natural resource depletion.**

  The natural resources consumption which is synonymous to the paradigm shift from the LMS to CMS was shown in Figure 15.

  The result of the study indicates that aluminium, cold rolled sheet steel and stainless-steel round steel depletion rate could be reduced significantly using CMS compared to LMS scenarios. The identified reduction rate seems possible due to the recycling rate from the production and collection of scraps to be use within the manufacturing system. Polyester facade AE semi-gloss paint cannot be recovered for recycling rather treated for incineration.

  The present findings seem to be consistent with other studies that investigated the need for the CMS with use of scraps rather than virgin raw material in reducing carbon emission as well as reducing extraction of coal and limestone [16].
Waste generated and recovered

Waste generated and recovery question are shown in Figure 16. The findings of the current study on the subject of recovery support the previous research on the subject of high recycling rate of aluminium, cold rolled sheet steel and stainless-steel round steel respectively [16].

- **Challenges are associated with transition**

The second question in this study sought to examine the underlying challenges attached to the transitional paradigm shift from LMS to CMS. The present study identified challenges are organizational management in relation to leadership and communication, design, technology and knowledge, business with respect to economics, government in relation to its policy and implementation and the supply chain network.

**Organizational management in relation to leadership and communication**

Manufacturing organizations are key- stakeholders in the pursuit of the transition from LMS to CMS. Thus, the result identified manufacturing organizations are key drivers for a paradigm shift.

The most important underlying issues within manufacturing organization in this context could be enumerated as lack of top management commitment which has been identified as leading driver for implementation of the paradigm shift [37]. Thus, the will power and commitment by the top management within the organization would be required [39]. The sound planning system for the actualization of a well-defined environmental transitional goals with appropriate performance standards for the pursuit of the paradigm shift to CMS from LMS is lacking among organizations [38].

In addition, communication of the relevant information such as potential benefits of the pursuit of the paradigm shift board would be a motivation to employees to adopt newer practices as well as dissuading the possible resistance/fear of the transitional change within the manufacturing operations [39].

Furthermore, previous studies emphasised lack of satisfactory environmental knowledge has consequential effect on employee negative environmental behaviour [40]. Organizational culture built on trust and cooperation may serve as an encouragement for the adoption of the shift. However, if these are lacking, then a culture of impediment to the pursuit and implementation of the shift would be developed within the organization [39]. This study concluded that top management must embrace the environmentally sustainable culture within their organization as ways of achieving goals of the manufacturing industry in the pursuit of a sustainable manufacturing paradigm shift [40].

**Business with respect to circular economy**

The current study found that business with respect to circular economy within the manufacturing organization is seen as a challenge. The fear of investment in the exploratory business of changing the old system of LMS to a new CMS appear risky, thereby, systematically integration over a timeline has been the usual practice because failure could be managed effectively in that context [40][43].
Profit making is always prioritized by many of the business organizations, so key decisions were subjected to their preferential core value of profitability compared to other values [44]. Previous studies reported that lack of financial resources is an influential challenge especially for small companies for implementing new policies [45].

The design lifespan of the steel mailbox is 25 years, and this coupled with varying market sales of the product would make it difficult to forecast projection of the returned used product as a reliable source of raw material feed. Also, logistical issues across continental shelves can also be a challenge [20].

Design, technology, and knowledge

The challenges of paradigm shift from LMS to CMS has been synonymous to change in the system, technological configuration and specification across the manufacturing processes. These changes require various features in its operations and upgrade of technology [45]. Thus, skilled manpower to manage the new knowledge, design, technology and overall system of the manufacturing system would be required [48].

However, inability to synchronize and integrate the change to the design, technology and system configuration with insufficient skilled labour has been identified as a challenge to the paradigm shift [40].

Various education and training programme needed across board to be a bedrock of knowledge for employees on the subject of the environment and policies for the sustainable manufacturing paradigm shift [50].

Green supply chain network

The result of this study indicates that supply chain network is a part of the challenges of the transition to a sustainable manufacturing paradigm shift. The reluctance of suppliers to switch toward CMS initiative is due to their traditional thinking, thereby creating room for lack of dedicated suppliers [49].

Suppliers ought to be a cohesive element within the manufacturing sector for the paradigm shift, however, some studies shows that suppliers were not actively involved in the implementation. Most probably lack of understanding concerning possible benefits might be the reason for the negative attitude exhibited towards the shift [47].

Previous studies proposed provision of rewards and incentives for the establishment of stricter environmental regulations and the promotion of sustainable strategies by the manufacturing industries for suppliers, however, financial implication attached therein has being a bottleneck for the symbiosis relationship [49].
Government in relation to its policy & implementation

Another important finding was the government in relation to the implementation of its policies. Manufacturing industries must operate according to the environmental laws and regulations. However, these laws may be altered by the political factors of the countries [52].

Studies identified that swift political will coupled with sufficient support such as appropriate policies to replace obsolete technology by arranging certain subsidies and other benefits might encourage speedy implementation of the sustainability policies within the manufacturing industries. Thus, environmental educational initiatives as well as good communication by the government might ensure the speedy implementation of the transition shift to CMS [53].
6 Conclusion

The present study was set out to evaluate the environmental implications of CMS compared to a LMS for a steel-based product, with focus on carbon footprint, cumulative energy demand, natural resource consumption, waste generated and recovered, and various challenges associated with transition to CMS. The current LMS of a steel mailbox manufacturing company- Boxicon AB—was compared to a proposed CMS.

The evaluations are based on the assumptions, boundaries, and data choices, and have shown that CMS seems more sustainable compared to LMS in relation to the studied environmental indicators. The identified hotspots and potential climate impact are similar to those of the previous LCA studies which are cited in the literature. The finding from this study enhances understanding of areas to explore in proffering solution to the challenges attached to the transitional paradigm shift from LMS and CMS.

Although the result from the comparison of the two scenarios (LMS and CMS) aligned with previous expectations and only could function as a benchmark, it provides a valuable insight for the transition towards more sustainable alternatives in order to mitigate the environmental impact of the hotspots component/element within the manufacturing system. The results imply that there may be great potential for other components/elements that are sustainable.

The present study has attempted to strengthen our understanding by identifying the challenges which could pose critical impediment in the transition from LMS to CMS. Identified challenges were categorised into 5 most prominent group which are: organizational management in relation to leadership and communication, design, technology, and knowledge, business with respect to circular economy, government in relation to its policy and implementation, and supply chain network.

The current study was unable to analyse these variables in relation to the market, societal and cultural response to the paradigm shift. A further study/evaluation of organizational management in relation to leadership and communication, supply chain, business with respect to circular economy, government in relation to its policy and implementation, and network, to the paradigm shift is recommended within the manufacturing organization.
7 References


[70] Idemat database https://www.ecocostvalue.com/data/2020


[73] Isohara, T. et al. (2020). Standardization of the Life-Cycle Inventory Calculation Methodology Considering Recycling Effects of Steel Products for ISO and JIS Standards, the 15th meeting for the presentation of research papers by the Institute of Life Cycle Assessment, Japan.


[81] US Environmental Protection Agency Life-Cycle Assessment – LCA access http://www.epa.gov/ORD/NRMRL/lcaaccess
Appendix 1: Life cycle inventory database and assumptions used for the analysis

<table>
<thead>
<tr>
<th>Process</th>
<th>Resources</th>
<th>Extraction</th>
<th>Assumption</th>
<th>CED (MJ)</th>
<th>Carbon footprint kg CO2 equiv.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Polyester Facade AE Semi Gloss (kg)</td>
<td>1.732</td>
<td>5.139</td>
<td>0.415</td>
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<tr>
<td></td>
<td>Aluminium (kg)</td>
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<td></td>
<td>Scrap (kg)</td>
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<td>Scrap (kg)</td>
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<td>Stainless round steel (kg)</td>
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TRANSPORT

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<th>Resources</th>
<th>Extraction</th>
<th>Assumption</th>
<th>CED (MJ)</th>
<th>Carbon footprint kg CO2 equiv.</th>
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</thead>
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<td>A2</td>
<td>Polyester Facade AE Semi Gloss within Sweden (km)</td>
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</tr>
<tr>
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<td>Aluminium (China) (km)</td>
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<td>0.011</td>
<td></td>
</tr>
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<td>Scrap (km)</td>
<td>500.000</td>
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<td>Scrap (km)</td>
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<td>Stainless round steel (China) (km)</td>
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<td>Scrap (km)</td>
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MANUFACTURING

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<th>Extraction</th>
<th>Assumption</th>
<th>CED (MJ)</th>
<th>Carbon footprint kg CO2 equiv.</th>
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</thead>
<tbody>
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<td>A5 INSTALLATION</td>
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<td>Electricity for installation, low voltage domestic use</td>
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</tr>
<tr>
<td>MAINTENANCE</td>
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</tr>
<tr>
<td>B5 Painting</td>
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<td>65.587</td>
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<td>C1 Defabrication</td>
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<td>C2 Transport (km)</td>
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<td>Cold rolled sheet steel (within Sweden)</td>
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<td>0.001</td>
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<td>Stainless round steel (within Sweden)</td>
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<td>0.001</td>
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</tr>
<tr>
<td>C3 Waste processing for reuse, recovery</td>
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<tr>
<td>Aluminium (kg)</td>
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<td>Cold rolled sheet steel (kg)</td>
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<td>0.014</td>
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<td>Stainless steel round steel (kg)</td>
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<td>0.014</td>
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<td>C4 Disposal</td>
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<td>Cold rolled sheet steel (kg)</td>
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<td>BEYOND END of LIFE</td>
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</tr>
<tr>
<td>Material</td>
<td>Weight (kg)</td>
<td>Cause Value</td>
<td>Effect Value</td>
<td>Net Value</td>
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</tr>
<tr>
<td>--------------------------------------------</td>
<td>-------------</td>
<td>-------------</td>
<td>--------------</td>
<td>-------------</td>
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</tr>
<tr>
<td>Polyester Facade AE Semi Gloss</td>
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<tr>
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<td>0.000</td>
<td>-7.050</td>
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<tr>
<td>Cold rolled sheet steel</td>
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<td>0.000</td>
<td>-0.866</td>
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<td>Stainless round steel</td>
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<td>0.000</td>
<td>-0.866</td>
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</tr>
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</table>

**Appendix 2: Net cause-effect result of the analysis**

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<th>D=Ri + Ci</th>
<th>R=Ri - Ci</th>
<th>Identify</th>
</tr>
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<td>10.4202</td>
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**Appendix 3: Threshold analysis of the result**

<table>
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<tr>
<th>T-Matrix</th>
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<th>GPI</th>
<th>DTK</th>
<th>SC</th>
<th>BE</th>
</tr>
</thead>
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<td>GPI</td>
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<td>0.636</td>
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<td>0.743</td>
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<td>DTK</td>
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<td>0.864</td>
<td>0.919</td>
<td>0.914</td>
<td>1.044</td>
</tr>
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<td>SC</td>
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<td>0.905</td>
<td>1.200</td>
<td>0.789</td>
<td>1.147</td>
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<tr>
<td>BE</td>
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<td>0.9305</td>
<td>1.173</td>
<td>0.973</td>
<td>0.941</td>
</tr>
</tbody>
</table>

| Threshold (alpha) Value | 1.00284 |