

**GALATASARAY UNIVERSITY**  
**GRADUATE SCHOOL OF SCIENCE AND ENGINEERING**

**LIFE CYCLE ASSESSMENT AND COST ANALYSIS**  
**OF PAPER BOOKS AND E-BOOKS**

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E-BOOKS**

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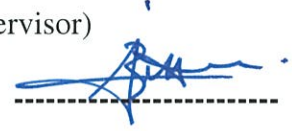
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## LIST OF SYMBOLS

<b>A</b>	: Aquatic Ecotoxicity
<b>AA</b>	: Aquatic Acidification
<b>AD</b>	: Abiotic Depletion
<b>AE</b>	: Aquatic Eutrophication
<b>AP</b>	: Acidification Potential
<b>C</b>	: Carcinogens
<b>LCA</b>	: Life Cycle Assessment
<b>E-book</b>	: Electronic Book
<b>EP</b>	: Eutrophication Potential
<b>EQ</b>	: Damage on Ecosystem Quality
<b>FAEP</b>	: Freshwater Aquatic Ecotoxicity Potential
<b>FDP</b>	: Fossil Depletion Potential
<b>FEP</b>	: Freshwater Eutrophication Potential
<b>GHG</b>	: Greenhouse Gas Emission
<b>GWP</b>	: Global Warming Potential
<b>HH</b>	: Human Health
<b>HTP</b>	: Human Toxicity Potential
<b>IR</b>	: Ionizing Radiation
<b>L</b>	: Land Occupation
<b>MDP</b>	: Metal Depletion Potential
<b>ME</b>	: Mineral Extraction
<b>mPt</b>	: Millipoint
<b>NC</b>	: Non-carcinogens
<b>NRE</b>	: Non-renewable Energy
<b>ODP</b>	: Ozone Depletion Potential
<b>OLD</b>	: Ozone Layer Depletion
<b>PMF</b>	: Particulate Matter Formation
<b>POCP</b>	: Photochemical Ozone Creation Potential
<b>POF</b>	: Photochemical Oxidant Formation
<b>Res</b>	: Resource Consumption
<b>RI</b>	: Respiratory Inorganics
<b>RO</b>	: Respiratory Organics
<b>TAP</b>	: Terrestrial Acidification Potential
<b>TE</b>	: Terrestrial Ecotoxicity
<b>UN</b>	: United Nations
<b>WDP</b>	: Water Depletion Potential

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## **ABSTRACT**

Sustainability is defined as meeting the needs of the present without compromising the ability of future generations to meet their own needs. In 2012, 17 sustainable development goals were set by United Nations in order to solve environmental, economic and social problems. Headings of these goals are no poverty, zero hunger, good health and well-being, quality education, gender equality, clean water and sanitation, affordable and clean energy, decent work and economic growth, industry innovation and infrastructure, reduced inequalities, sustainable cities and economies, responsible production and consumption, climate action, life below water, life on land, peace justice and strong institutions, partnership for the goals.

One of the sustainable development goals, which is responsible production and consumption, has started to become more and more important. Environmentally friendly management of consumed products during their life cycles and reducing harmful effects of wastes on both human health and environment are significant part of this goal. Analyzing the impacts of the products used in daily life and making improvements to reduce impacts occurred during product life cycles will be an important step to achieve this goal. Moreover, in the case of alternatives, preferring products that have less environmental impact will help to be close to the responsible consumption goal.

Several studies have been done in order to achieve this sustainability goal. Environmental impacts of products during life cycle were examined in literature. One of the important field is book publishing. Each year nearly 100 million ton paper is used to produce only printing and writing paper. Because of raw materials of these books comes from trees, there is serious impacts on the environment and these impacts have to be evaluated. E-book, which shown as an alternative to paper book, can be read from electronic device.

Because of these electronic devices have environmental impacts, their impacts also have to be evaluated.

Based on these objectives, environmental impact comparison between printed books and e-books has been done with life cycle assessment approach. Firstly, environmental impacts of printed books and e-books were examined. Book production stages and data were collected from a publishing house, which prints paper books. Data and production process of e-reader were taken another study. Distribution routes were designed according to location of supplier's warehouses and cargo branches.

First of all, life cycle stage which cause the most impact have been found out. After that, according to reading habits of people, two different cases were applied and impact caused by product distribution phase were compared between readers who live in urban areas and readers who live in rural areas. With addition to electronic book scenario, reading options with less environmental impact have been determined for readers who have different reading habits and living different areas. Results showed that production stage of the each product have the highest environmental impact. While paper book has less impact than e-book for readers who read less, e-book has less impact for readers who read much. Also, readers live in rural area have to read more than readers who live in urban area in order to make e-book reading cleaner option.

In the second part of the study, cost analysis was conducted to determine which reading option would be cost effective for which book reading rate. Result of this section showed that increase in book reading rate makes e-book cost effective option. Above the reading nearly five books in a month, e-book reading is cost effective option.

As a result of life cycle and cost analysis, it can be said that reading the electronic books after a certain point will be more environmentally friendly and cost effective solution. For the environmental impact assessment, 23 books in three years for the urban area and 21 books in three years in the rural area will be a critical point. It means that e-book reading will be a cleaner option reading above this number of books, while paper book will be a cleaner option below this number of books. For the cost analysis, reading five books in a month, totally 180 books in three years will be the critical point of cost analysis.

In previous studies, environmental impacts of printed books and e-books have been compared but no study have been carried out including distribution process for the reader living in rural areas. This study will contribute to the literature in terms of which reading option will be more environmentally friendly for the reader who live in rural areas.



## ÖZET

Sürdürülebilirlik, gelecek kuşakların kendi ihtiyaçlarını karşılayabilme yeteneklerini tehlikeye atmadan bugünkü kuşakların ihtiyaçlarını karşılamak olarak tanımlanmaktadır. Birleşmiş Milletler tarafından 2012 yılında dünyanın karşı karşıya olduğu çevresel, ekonomik ve sosyal sorunları çözmeyi amaçlayan 17 hedef belirlenmiştir. Bu hedeflerin ana başlıkları şunlardır: yoksulluğa son, açlığa son, sağlıklı bireyler, nitelikli eğitim, toplumsal cinsiyet eşitliği, temiz su ve sıhhi koşullar, erişilebilir ve temiz enerji, insana yakaşır iş ve ekonomik büyüme, sanayi, yenilikçilik ve altyapı, eşitsizliklerin azaltılması, sürdürülebilir şehir ve yaşam alanları, sorumlu tüketim ve üretim, iklim eylemi, sudaki yaşam, karasal yaşam, barış, adalet ve güçlü kurumlar, hedefler için ortaklıklar.

Sürdürülebilir kalkınma hedeflerinden bir tanesi olan sorumlu üretim ve tüketim kavramı gün geçtikçe daha fazla önem kazanmaktadır. Tüketilen ürünlerin yaşam döngüsü boyunca çevreye duyarlı yönetiminin sağlanması ve ortaya çıkan atıkların insan sağlığına ve çevreye olan zararlı etkilerinin azaltılması bu kalkınma hedefinin önemli bir parçasıdır. Günlük hayatta kullanılan ürünlerin çevresel etkilerinin iyi analiz edilmesi ve ürünlerin yaşam döngüleri boyunca sebep oldukları etkileri azaltacak iyileştirmeler yapılması bu hedefe ulaşmada önemli bir adım olacaktır. Bununla birlikte, alternatiflerin olduğu durumlarda çevresel etkisi daha az olan ürünleri tercih etmek bilinçli tüketim hedefine bir adım daha yaklaştıracaktır.

Sürdürülebilirliğin bu amacına ulaşmak için birçok çalışma yapılmaktadır. Literatürde ürünlerin yaşam döngüleri boyunca çevreye ne kadar etkide buldukları incelenmiştir. İnceleme yapılabilecek önemli alanlardan biri de kitap alanıdır. Dünyada her yıl ortalama 100 milyon ton kağıt yazı ve kitap kağıdı olarak kullanılmaktadır. Basılan kitapların hammaddesi ağaç olduğu için çevreye ciddi etkileri vardır ve bu etkileri ölçmek gerekmektedir. Basılı kitaba alternatif olarak gösterilen e-kitap da elektronik bir alet

aracılığıyla okunmaktadır. Bu aletlerin de çevreye etkileri bulunmakta ve bu aletlerin de çevresel etkilerini ölçmek gerekmektedir.

Bu hedeflerden yola çıkarak bu çalışmada basılı kitaplar ile elektronik kitapların çevresel etkileri, ürün yaşam döngüsü analizi yapılarak karşılaştırılmıştır. İlk olarak basılı kitapların ve elektronik kitapların çevresel etkileri incelenmiştir. Basılı kitap için veriler bir matbaadan alınmıştır. E-kitap okuyucu verileri ise başka bir çalışmadan alınmıştır. Ürün dağıtım rotası ise tedarikçilerin depoları ve kargo şubelerinin lokasyonlarına göre oluşturulmuştur.

İlk olarak, ürün yaşamının hangi evresinde etkilerin en fazla olduğu bulunmuştur. Daha sonra, farklı okuma alışkanlarına sahip kişiler için iki farklı vaka uygulaması yapılmış ve ürün dağıtım aşamasının sebep olduğu çevresel etkiler, kırsal alanlarda yaşayan okurlara kitapların ulaşım süreci ile kentsel alanlarda yaşayan okurlara kitapların ulaşım süreci karşılaştırılarak ortaya koyulmuştur. Elektronik kitap okuma senaryosu da eklenerek üç farklı senaryo ile farklı okuma alışkanlıklarına sahip, farklı yerlerde yaşayan okurlar için hangi okuma seçeneğinin daha az çevresel etkisi olduğu hesaplanmıştır. Sonuçlar, üretim aşamasının her iki ürün için de en yüksek çevresel etkiye sebep olduğunu göstermiştir. Az kitap okuyan okuyucu için basılı kitaplar daha az çevresel etkiye sebep olurken, çok kitap okuyan okuyucu için e-kitabın daha az çevresel etkiye sahip olduğu bulunmuştur. Bununla birlikte, kırsal bölgede yaşayan okuyucu için e-kitabın daha çevreci bir seçenek olması için kentsel bölgede yaşayan okuyucuya göre daha fazla kitap okumalıdır.

Çalışmanın ikinci kısmında ise okur için önemli bir kriter olan maliyet analizi yapılmış ve aylık ortalama okunan kitap sayısına göre hangi okuma seçeneğinin daha az maliyetli olacağı hesaplanmıştır. Sonuçlar, okuma oranının artmasının e-kitap seçeneğini daha az maliyetli hale getirdiğini göstermiştir. Aylık ortalama beş kitabın üzerinde okuyan bir okur için e-kitap daha az maliyetli olacaktır.

Yaşam döngüsü ve maliyet analizinin ortak sonucu olarak okuma oranının yükselmesi ile belirli bir noktadan sonra elektronik kitap okumanın çevresel açıdan daha temiz ve ekonomik açıdan daha düşük maliyetli bir seçenek olacağı söylenebilir. Çevresel etki karşılaştırmasının sonucunda kentsel bölge için üç yılda 23 kitap, kırsal bölge için üç yılda 21 kitap okumanın kritik nokta olacağı yani bu sayının üstündeki okumalar için

elektronik kitap okumanın daha çevreci bir seçenek olacağı, altındaki okumalar için ise basılı kitap okumanın daha çevreci bir seçenek olacağı saptanmıştır. Maliyet analizi sonucunda ise ayda beş, toplamda 180 kitabın kritik nokta olacağı bulunmuştur.

Önceki çalışmalarda basılı kitaplar ile e-kitapların ürün yaşam döngüsü karşılaştırılması yapılmış fakat kırsal bölgede yaşayan okurun kitaba ulaşım sürecini dahil eden herhangi bir çalışma yapılmamıştır. Bu çalışma kırsal bölgede yaşayan okur için hangi okuma seçeneğinin daha çevreci olacağını noktasında literatüre katkı sağlayacaktır.





## 1. INTRODUCTION

Environmental problems are becoming more and more dangerous every day. Human beings and their industrial actions are the main contributors of these problems. In order to protect the nature from bigger environmental problems, governments, companies and citizens should take actions. New environmental friendly products and systems should be developed or at least less harmful solutions should be chosen.

United Nations determined 17 sustainable development goals in order to live in a better and more sustainable world. Headings of these goals are no poverty, zero hunger, good health and well-being, quality education, gender equality, clean water and sanitation, affordable and clean energy, decent work and economic growth, industry innovation and infrastructure, reduced inequalities, sustainable cities and economies, responsible production and consumption, climate action, life below water, life on land, peace justice and strong institutions, partnership for the goals. The aim is to achieve these goals by 2030. One of these goals, which is responsible production and consumption, aims doing more and better with less. Increasing resource and energy efficiency, better life quality for all, sustainable infrastructure are some of the subtitle of this goal (UN, 2019).

Industrial activities, which target overproduction, is the main responsible of the environmental impacts. Production volumes should not exceed the actual need of the society. If production and energy usage stay at required volumes, environmental impacts will reduce.

On the other hand, humans have to change their current lifestyles as well. Global population will reach 9.6 billion by 2050 and if humans continue their current lifestyles, almost three planets will be needed in order to provide natural resources that are necessary for their lifestyle (UN, 2019).

Responsible production and consumption should be implemented in every division of life. However, just using less is not enough. Determining which way of production is better and which product is more environmentally friendly are critical issues for responsible production and consumption goal.

One of the discussed topics about this issue is environmental impacts of paper book and e-book solutions. Each year nearly 100 million ton paper is used to produce only printing and writing paper (FAO, 2016).

Because of raw material and production process of paper book, there is a belief that paper books cause more pollution than e-books. In fact, definite judgment will not be true before doing some scientific researches.

While paper book production results in high paper consumption, raw materials of electronic devices and used energy may cause more pollution. In addition to that, high usage rate can decrease the effect of e-reader due to allocation of impacts. Moreover, cost effectiveness of products are significant from customer perspective. Readers will not focus on just environmental effects, they want to choose also the cost effective option. In order to reach an objective decision between these advantages and disadvantages, scientific comparison have to be conducted. The focus of this study is comparison, which considers both environmental and economic parameters.

The aim of this study is to determine the environmental and economic impacts of reading either paper book or e-reader for readers who live in rural areas, in order to suggest suitable options for reading activity.

Firstly, Life Cycle Assessment method was used to define environmental effects of reading from paper book and e-reader. The reason to use this method is to analyze environmental impacts of products during whole life cycles. This method provides environmental impact analysis of a product or a system from raw material extraction to the end-of-life.

Lüleburgaz, a city is nearly 150 km away from Istanbul, is chosen for define contribution of transportation on environmental impacts. Because of limited number of book stores in rural areas, it is assumed that readers buy their books from e-commerce sites.

Three scenarios for reading activity is generated. These are readers who read paper book in Lüleburgaz, readers who read e-book in Lüleburgaz and readers who read paper book in Bakırköy. According to various reading rates, different environmental impacts are calculated for these three scenarios. Which reading tool is more environmentally friendly for readers who live in rural areas and urban areas will be demonstrated.

In the second part, cost analyses will be done for paper book and e-book reading options. Because of limited number of book stores in rural areas, cost calculation will done with assuming books and e-readers are bought from e-commerce sites. The aim is demonstrate which option is more cost effective for people who read much and who read less.

The main contribution of the study is adding the environmental impacts occurred during distribution of books to the rural areas. Other studies in the literature considers only readers who reach the books from urban areas mostly from bookshops. Also, this study is includes environmental and economic comparison together unlike the other studies.

The limitation of the study have occurred in inventory analysis part of the life cycle assessment. Some of the data and processes used in the study have not been found in the software database. Instead of these not found data and processes, similar ones have been used.

This study includes seven main parts: introduction, background, literature review, methodology, application, analysis and conclusion.

In the background part, paper book and e-book concept, statistics about reading activities, statistics about paper production and book publishing industry will be mentioned. In the literature review part, LCA studies about environmental effects of reading paper books and e-books as well as cost comparison between paper books and e-books will be investigated.

In the methodology part, definition of life cycle assessment and phases will be introduced and types of LCA and limitation of LCA studies will be mentioned. In addition, present value method for cost calculation will be represented.

In the application part, system boundary and functional unit of the study will be determined and inventories for each step will be explained. Results of the impact assessment will be analyzed in analysis part.

In the conclusion part, overall results will be discussed, limitations and suggests for future studies will be given.



## **2. BACKGROUND**

### **2.1 Paper Book Reading and Paper Industry**

Although books have been found in our lives for a long time, they have become widespread in daily life with the presence of printing press. Spread of book production supported easy accessibility of books. With this change, books became the main source of information but then Internet began to spread and started to become sources of information. Today, both paper books and online sources are the important sources of information.

EU households spent 1.1% of their total consumption expenditure on books and newspapers in 2016, while this value 1.8% of total expenditure in 1995. Slovakia has highest rate (2.1%) of their expenditure on books and newspaper in 2016 and lowest rate is from Bulgaria and Greece with 0.6% (Eurostat, 2018).

Although there is no certain statistics about expenditures of Turkey, total annual volume of Turkish book market is worth about \$1.591 million for 2017. While \$616 million of volume is educational books, \$806 million of volume is trade books (Turkish Publisher Association, 2017).

According to YAYFED (2017) statistics, total number of book published in 2017 is 407 million. Number of published book increased 1% compared to previous year. In addition, Figure 2.1 shows annual number of published book from 2010 to 2017. Although rate of increase is not constant, there is a gradual increase in number of published books from 2010 to 2017.

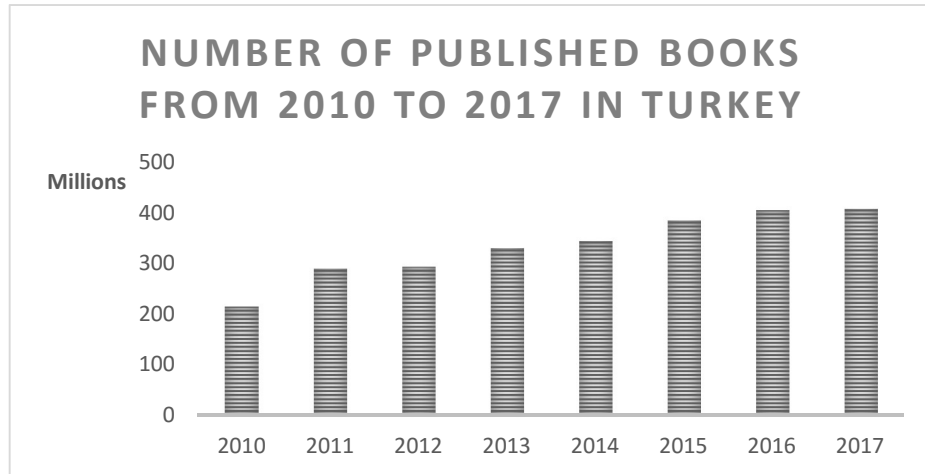


Figure 2.1: Number of Published Books from 2010 to 2017 in Turkey (YAYFED, 2017)

In order to understand paper book industry, paper industry should be observed. Paper industry has many areas to serve like newsprint, wood-free paper, packaging paper etc. Different pulps and pulping methods are used to produce these different products. There are two main pulping methods: chemical and mechanical pulping. In chemical pulping method, wood chips are cooked with some chemicals in order to reduce wood from cellulose fibers. In mechanical pulping, some mechanical methods are used instead of chemicals. High quality papers can not be produced from mechanical pulping, while chemical pulping method is used for production of high quality papers. Production of paper books is mainly made from wood free paper type, which is created mostly from chemical pulp rather than mechanical pulp (Das and Houtman, 2004).

Paper and cardboard production of Turkey was nearly 4 million ton in 2017 and only 5.6% of this production is wood-free paper. Although 247.000 ton wood-free paper produced in Turkey within 2017, nearly 1 million ton wood-free paper consumed. Therefore, import rate was highest for wood free paper in 2017 when compared to other paper and cardboard products (Istanbul Chamber of Industry, 2018). This statistic shows that Turkey imports nearly 80% of wood free paper need.

Furthermore, waste paper collection is significant source of paper industry. According to Istanbul Chamber of Industry (2018), the goal of the European Union is reaching 74% waste paper collection rate until 2020 and collection rate for 2017 was predicted 73%. On

the other hand, the aim of waste paper collection rate of Turkey was 54% for 2017 but only 38.1% percent of the paper and cardboard products went to the recycling process and remaining part underwent the disposal process. Table 2.1 shows the waste paper collection rates between 2014 and 2017 (Istanbul Chamber of Industry, 2018). Europe has a successful waste paper collection rate from 2014 to 2017. However; although targeted rate of Turkey a lot fewer than Europe, actual rate of waste paper collection of Turkey still under the targeted rates from 2014 to 2017.

Table 2.1: Waste Paper Collection Rates between 2014 and 2017 (Istanbul Chamber of Industry, 2018)

	<b>Actual Rate of Europe (%)</b>	<b>Targeted Rate of Turkey (%)</b>	<b>Actual Rate of Turkey (%)</b>
<b>2014</b>	71.6	44	37.3
<b>2015</b>	71.9	48	42.5
<b>2016</b>	72.5	52	40.8
<b>2017</b>	73.0	54	38.1

## 2.2 E-book Reading and E-reader Industry

Integrating paper book features in electronic devices brought out e-book term. E-book, a digital object includes textual or other content, can be used in different kind of electronic devices. The first e-book attempts started in the 1970s with the Project Gutenberg and the Oxford Text Archive. Later in the 1980s and 1990s e-books were published on CD-ROM in order to use in personal computers (Vassiliou and Rowley, 2008). Today, e-books are available in different kind of formats and there are lots of e-readers with different features.

One of the most popular ones is Kindle, an electronic device developed by Amazon for reading books, magazines, newspapers via connecting Kindle Store. Amazon launched its first model in 2007 and almost each year new versions are announced. These new Kindles come with new features and designs. One of the most important features added to Kindle is electronic ink technology. Kindle's e-ink technology shows the screen look

like paper book and strains eyes less than other screen types. At the same time, this technology consumes less energy when compared to traditional LCD screens (Hall, 2018).

According to the Federation of European Publishers report (2017); France, Germany, United Kingdom have 3%, 4.5% and 11.5% e-book share of the book market in 2015 respectively. Turkish Statistical Institute's report (2018) shows that while 60.335 number of new title paper book were published in 2017, number of published new title e-book was 1.767 according to ISBN of books. Although there is not a certain statistics about e-book share in Turkey book market, new published e-book share of the book market in Turkey is nearly 3% according to this statistic.

### **2.3 Reading Patterns**

Eurostat carried out a survey about average time spent on reading books in 15 countries between 2008 and 2015. Results show that Estonia is the first one with 13 minutes per day. Finland and Poland follows with 12 minutes per day. Turkey is in the middle of the list with average of seven minutes of period spent per day (Eurostat, 2018). Other part of Eurostat (2018) study indicates that people who reads book as main activity are living with highest share in Finland and Poland, with 16.8% and 16.4% respectively.

In addition, Republic of Turkey Culture and Tourism Ministry (2011) created a reading culture map in 2011. This map shows while average 7.2 books are read by a year in Turkey, regular readers' average is counted 14.5 books. It means that regular readers in Turkey read more than one book in a month.



### **3. LITERATURE REVIEW**

#### **3.1 Life Cycle Assessment Studies**

In this part, studies found in literature review about life cycle assessment of paper books and e-books are presented.

Kozak and Keolelan do the first comparison study of e-book and paper book reading in 2003. The study is about comparison between life cycle impacts of a college student reading 40 textbooks the same amount of digitalized form with using e-reader. Global warming, ozone depletion and acidification are three impact categories used in this study. Although results depend on inventories, printed textbooks are higher impact than e-books in three categories.

Hischier and Reichart's study (2003) covers life cycle assessment case study that compares environmental impacts of reading or watching daily news from online, a printed newspaper and TV. Results underline that internet newspaper causes more environmental impacts than TV news. In addition to that, TV news have more environmental impacts than printed newspaper.

The goal of Williams and Tagami's (2008) research is calculating energy consumption from distribution via e-commerce and conventional retail in Japanese book sector. Study indicates transportation and packaging stages are the main contributors of energy consumption.

The study of Enroth (2009) focuses on environmental impacts of printed and electronic teaching aids with calculating GHG emission. Cradle-to-grave life cycle approach was used and results demonstrate that electronic books contribute 10 times more GHG emission than printed books.

Moberg et al. (2010) analyse environmental impacts of printed and e-paper newspapers with using life cycle perspective. Most significant phase of life cycle for both system was found production of paper and e-reader. Unlike the other studies, this study compares European and Swedish scenarios. European electricity mix and waste flows and Swedish electricity mix and waste flows are calculated separately and compared. Swedish scenario has been found less pollutant in most categories due to its higher recycle rate and renewable energy sources.

Borggren et al. (2011) determine possible environmental impacts of paper books and their sale methods with life cycle approach. Totally 11 impact categories are used in this study. Distribution to customer from traditional bookshops and internet bookshops have been compared. Results showed that while most influential part is paper production, internet bookshop is a better alternative for global warming potential compared to traditional bookshop.

Study of Moberg et al. (2011) aims to define environmental impacts of an e-book read on e-reader and to show magnitude of the impact. Also, e-book and paper book product system were compared. LCA of e-book was assumed reading activity in Sweden and e-book reader was produced in China. Results show that highest impact of e-book come from production stage of e-book reader. Also, when e-book and paper book were compared, result indicates that number of books read on e-reader can change the results.

Wells et al. (2012) suggest a cradle-to-grave life cycle assessment for the paper book produced in United States and printed in Canada. In this study, three end of life scenario are taken into consideration to determine effects of waste scenarios on GHG emission. First scenario is all books end up in landfills, second one is all books are recycled and third one is half of them recycled.

Jeswani and Azapagic (2014) have a literature review about e-reading and conventional reading. This paper compares the findings of other articles. Impacts of e-readings depends on mostly source of power and production stage. According to article, reading 40 books or 290 newspapers or 70 reports on an e-reader is equals the impacts of their printed equivalents.

Hischier et al. (2014) demonstrate how data collection methods change result of the LCA studies. Desk-based and lab-based methods were used in order to compare impacts of electronic media devices and print media. Article concludes that data collection process is highly effective for results on LCA studies.

The aim of Esquer et al. (2015) is showing environmental impacts of printed newspapers in Mexico with cradle-to-gate life cycle approach. 10 impact categories have showed that electricity and printing operation were claimed highest impact stages.

Achachlouei et al. (2015) identifies stages causing main environmental impacts of e-book reading activities. Unlike the other studies' results, content production have been found main contributor to environmental impacts if number of reader are less. When number of reader increases electronic storage and distribution can have higher impacts.

Achachlouei and Moberg (2015) investigate potential environmental impacts of electronic and print version of a magazine in a life cycle perspective with 10 impact categories. Although there is no certain result about which one is better, it has been indicated total number of reader for each version, file size and use rate of tablet device are main factors affecting results.

Naicker and Cohen (2016) compare the environmental impacts of print and electronic books in South Africa. It includes 18 impact categories with focusing on effects of electricity mix on impacts. The study compares change of impacts when electricity is produced mostly from nuclear and renewable energy.

Amasawa et al. (2017) identify at what extent e-book reading reduces GHGs of book reading activities from that of reading only paper books. Customer segmentation procedure is done for analyse readers who reads only paper book, kindle user and other device users. According to survey results, Kindle and other device owners have higher reading rates than only paper book readers. This result has been integrated into life cycle assessment part and global warming potential for each customer segment have calculated.

Tahara et al. (2018) make a survey with consumers who buy at least one paper book and e-book last year. From the survey, they found the average distance and vehicle type for buying paper book and what kind of devices consumers use for e-book reading such as

laptop, tablets etc. Functional unit of the study is a 224 pages book. It analyses just greenhouse gas emission as environmental impact category in this study. Results compares the effect of screen size and read books by more than one person.

Summary of the life cycle assessment literature review part is presented in Table 3.1.



Table 3.1: LCA studies about Paper Book and E-book

<b><i>LCA Studies</i></b>	<b><i>Methodology</i></b>	<b><i>Functional Unit</i></b>	<b><i>Impact Categories</i></b>	<b><i>System Boundaries</i></b>
<b><i>Kozak and Keolelan (2003)</i></b>	Comparison of college students textbooks' printed and electronic version	<ul style="list-style-type: none"> <li>○ 40 scholarly books</li> <li>○ iReb 11 10 Tablet</li> </ul>	GWP, ODP, AP	Cradle-to-gate
<b><i>Hischier and Reichart (2003)</i></b>	Impact analyse of using newspaper, television and internet for daily news	<ul style="list-style-type: none"> <li>○ 110 minutes TV</li> <li>○ 74 minutes Internet</li> <li>○ 136 g newspaper</li> </ul>	Not given	Cradle-to-grave
<b><i>Enroth (2009)</i></b>	Screening comparison impact between printed versus electronic teaching aids.	<ul style="list-style-type: none"> <li>○ For 5 years 5000 students per year</li> </ul>	GWP	Cradle-to-grave
<b><i>Moberg et al. (2010)</i></b>	Comparison between impact of printed on paper and tablet e-paper newspaper	<ul style="list-style-type: none"> <li>○ 40 pages printed newspaper</li> <li>○ iRex iLiad tablet 5 MB/day</li> </ul>	Energy, GWP, AP, EU, POCP, ODP, FEAP, HTP, AE, TE	Cradle-to-grave
<b><i>Borggren et al. (2011)</i></b>	Impact analysis of paper book and difference between traditional and internet sale	<ul style="list-style-type: none"> <li>○ 360 pages book</li> </ul>	Energy, GWP,AD, AP, EU, POCP, ODP, FEAP, HTP, AE, TE	Cradle-to-grave

<b>LCA Studies</b>	<b>Methodology</b>	<b>Functional Unit</b>	<b>Impact Categories</b>	<b>System Boundaries</b>
<b>Moberg et al. (2011)</b>	Comparison between e-book reading and paper book reading and to find stage caused highest impact	○ 360 pages book ○ 1.5 MB file e-book	Energy, GWP,AD, AP, EU, POCP, ODP, FEAP, HTP, AE, TE	Cradle-to-grave
<b>Wells et al. (2012)</b>	Carbon footprint assessment of paperback book produced in US and printed in Canada with different waste scenarios	○ 320 pages hardcover book	GHGs	Cradle-to-gate and Cradle-to-grave
<b>Jeswani and Azapagic (2014)</b>	Literature review about impacts of e-reading and print reading activities			
<b>Hischier et al. (2014).</b>	Print book and e-book life cycle comparison with different inventory data collection method	○ 163 MB magazine	GWP, MDP, FDP, TAP, FAEP, FEP, ODP, POFP, EQ, HH, Res	Cradle-to-grave
<b>Esquer et al. (2015).</b>	Impact analysis printed newspaper in North-western Mexico	○ 1 ton of printed matter	A, TE, L, TAP, AA, AE, NRE, ME, GWP, IR, C, RI, RC, OLD, NC	Cradle-to-gate

<b>LCA Studies</b>	<b>Methodology</b>	<b>Functional Unit</b>	<b>Impact Categories</b>	<b>System Boundaries</b>
<b><i>Achachlou ei et al. (2015)</i></b>	Impact analyse of production and consumption on magazines read on tablets	○ 163 MB magazine	HTP, POF, PMF, TAP, FEP, TE, FAEP, MDP, FDP, Energy	Cradle-to-grave
<b><i>Achachlou ei and Moberg, (2015)</i></b>	Impact comparison between print edition magazine and electronic edition	○ 184 pages magazine ○ 163 MB magazine	POH, PMF, TAP, FEP, MDP, FDP, Energy	Cradle-to-grave
<b><i>Naicker and Cohen (2016)</i></b>	Paper books produced and used in South Africa and e-book used in South Africa comparison	○ 21 printed textbooks ○ 21 e-books with iPad	GWP, ODP, TAP, FEP, HTP, POF, TE, FAEP, IR, L, WDP	Cradle-to-grave
<b><i>Amasawa et al. (2017)</i></b>	According to reading patterns comparison between paper book and e-reader or tablet	○ 360 pages book ○ Kindle ○ iPad	GWP	Cradle-to-grave (waste treatment of electronic devices were not included)
<b><i>Tahara et al. (2018)</i></b>	Comparison between reading from paper books and different electronic devices	○ 224 pages book ○ 2.4 MB same book e-version	GHGs	Cradle-to-grave

### 3.2 Cost Analysis Studies

In this part, studies found in literature review about cost analysis of paper books and e-books are presented.

Gray and Copeland (2012) analyze popular titles in a public library in order to define cost of electronic and print version. Circulation rate of e-books and paper books are taken into consideration. Circulation rate of e-book is found higher than printed version and average cost of each circulation is found cheaper than average cost of electronic version.

Ritchie and Skoglund (2015) present usage rate of paper books and e-books on library base. According to usage rates, cost per download e-book and cost per print book was calculated. Cost analysis showed that per download of e-book higher cost than print book in examined library.

Rao et al. (2016) analyze the difference between the prices of printed academic books and their digital versions. Results show that availability of electronic version is less than print version. However, most of the electronic version of academic books are cheaper than the print version.

Li (2016) compares the cost of identical books' electronic and print version. This study compares how many times electronic and print version of books are used in a library within five years. Results show electronic version of books are used substantially more than print version. For this reason, electronic version of books are generally more cost effective than print versions in library.

Summary of the cost analysis literature review part is presented in Table 3.2.



Table 3.2: Cost Studies about Paper Books and E-books

<i>Cost Studies</i>	<i>Methodology</i>	<i>Functional Unit</i>
<b><i>Gray and Copeland (2012)</i></b>	Cost calculation of printed books and their electronic versions with using circulation rate in a library	34 books
<b><i>Ritchie and Skoglund (2015)</i></b>	Usage rate of print books and e-books in a health library and cost per book according to usage rate	Not Given
<b><i>Rao et al. (2016)</i></b>	Comparison between price of printed academic titles and their electronic versions	717 books
<b><i>Li (2016)</i></b>	Printed book and their electronic versions' comparison with usage rates in a biomedical library	60 books

## **4. METHODOLOGY**

### **4.1 Life Cycle Assessment**

Life Cycle Assessment (LCA) is a standard methodology that estimates environmental impacts of a given product or process over the life cycle from cradle to grave. The first LCA studies was done in late 1960s and early 1970s when environmental issues became public concerns. One of the first studies which include resources, emission and waste flows was conducted by Midwest Research Institute (MRI) in order to compare different beverage containers. After a while, there has been growing interest in for LCA early 1980s. LCA has been applied without a methodology during 1970s and 1980s. LCA guides and handbooks started to produce in 1990s. Finally, ISO have formed two standardizations for LCA methods and procedures (Guinne et al. 2011).

ISO 14040 gives standards about principles and framework of LCA and ISO 14044 describes requirements and guidelines of LCA. According to ISO 14040:2006 “LCA considers the entire life cycle of a product, from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end of life treatment and final disposal. Through such a systematic overview and perspective, the shifting of a potential environmental burden between life cycle stages or individual processes can be identified and possibly avoided.”

LCA is a strong methodology because of the following five reasons (Wolf et al. 2012):

- Brings together wide range of environmental problems
- Analyses these problems with a scientific and quantitative way
- Allows to find environmental impacts of any defined system, such as good, service, company

- Associates resource use emissions over the entire life cycle of a defined system
- Provide a comparison between environmental impacts of different systems and possible improvement areas

#### 4.1.1 LCA Phases

LCA approach has four main phases. These are the goal and scope definition, inventory analysis, impact assessment and finally interpretation phase (ISO 14040, 2006). Figure 4.1 shows the four main phases of LCA approach.

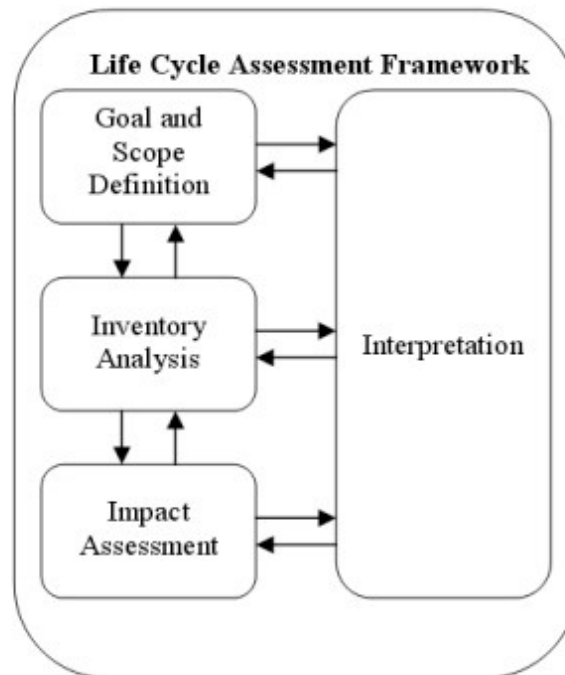


Figure 4.1: Life Cycle Assessment Framework (ISO 14040:2006)

##### 4.1.1.1 Goal and Scope Definition

Goal part in the first step includes identifying intended application, reasons of the study, target population. Scope part focuses on determining functional unit, system boundary, impact categories, limitations and sources of data (ISO 14040, 2006). During the iterative process of the analysis, the goals and scope can be arranged (Benedetto and Klemes, 2009).

Functional unit and system boundary are essential terms of LCA. Functional unit means quantified description of product's performance characteristics. It is important for comparability of LCA results especially when different systems are being assessed (ISO 14040, 2006).

System boundary defines which unit process will be included in the system. There are four main stages of a product or system: raw material acquisition, manufacturing, use/reuse/maintenance and recycle/waste management. In order to decide which stage should include in the study; the scope of the study, time and resources, required accuracy of the results should be assessed (EPA, 2006).

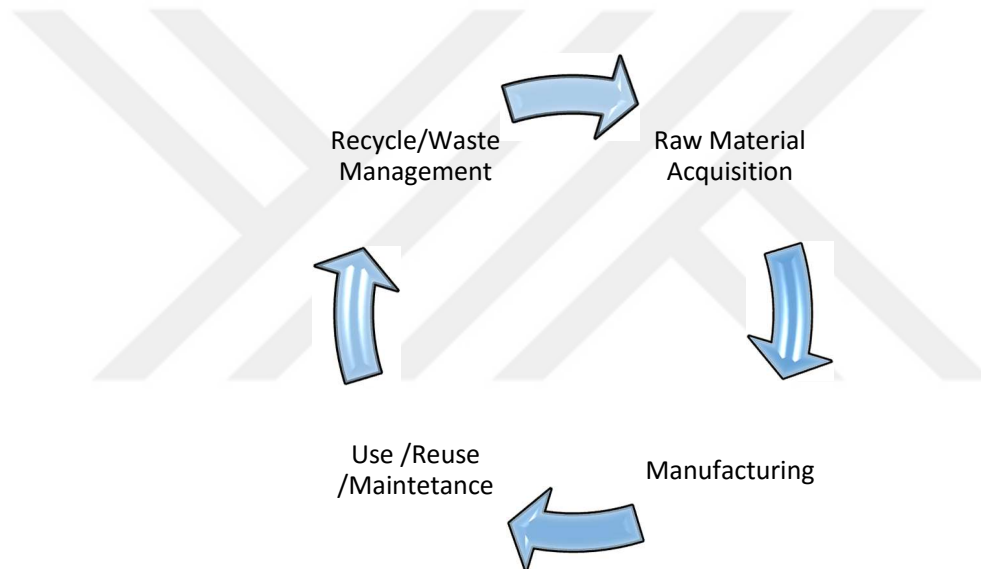


Figure 4.2: Main Life Stages of a Product or System (EPA, 2006)

#### 4.1.1.2 Inventory Analysis

In the inventory phase of LCA, required amount of energy and raw material, solid wastes, emissions and other releases are evaluated for the entire life cycle of a product or a system. Detailed analysis and accuracy of the data increases correctness of the LCA study (EPA, 2006).

Inventory analysis step starts with data collection process. Qualitative and quantitative data should be collected for processes include in system boundary. Collected data should be validated and calculated according to unit process and functional unit. After that,

processes shared with other product systems defined and allocation process should be done (ISO 14044, 2006).

#### **4.1.1.3 Impact Assessment**

This stage evaluates the potential environmental impacts of resources and releases defined in studied system. Impact assessment should be coordinated with other step of LCA especially goal and scope part. Objectives of the study should be meet with impact assessment part. If they have not meet, goal and scope of the study may be modified (EPA, 2006; ISO 14040, 2006).

Firstly, environmental impact categories such as global warming, acidification should be chosen. Life cycle impact results should be assign into impact categories. After that, impact results should be normalized and weighted in order to show most important potential impacts (EPA, 2006).

There are kind of life cycle impact assessment methods such as ReCiPe, LIME, Eco-Indicator 99, IMPACT 2002+, IPCC etc. While some of them focuses on single issue, some of them analyzes different impact and damage categories. IMPACT 2002+, one of the multiple issue method will be used in this study, will be introduced in this part.

IMPACT 2002+ method proposes feasible implementation of combined midpoint/damage-oriented approach. This method links 14 midpoint categories into four damage categories (Humbert et al., 2012). Figure 4.3 shows these categories with arrows, which are symbolize the relevant impact pathways between midpoint and damage categories.

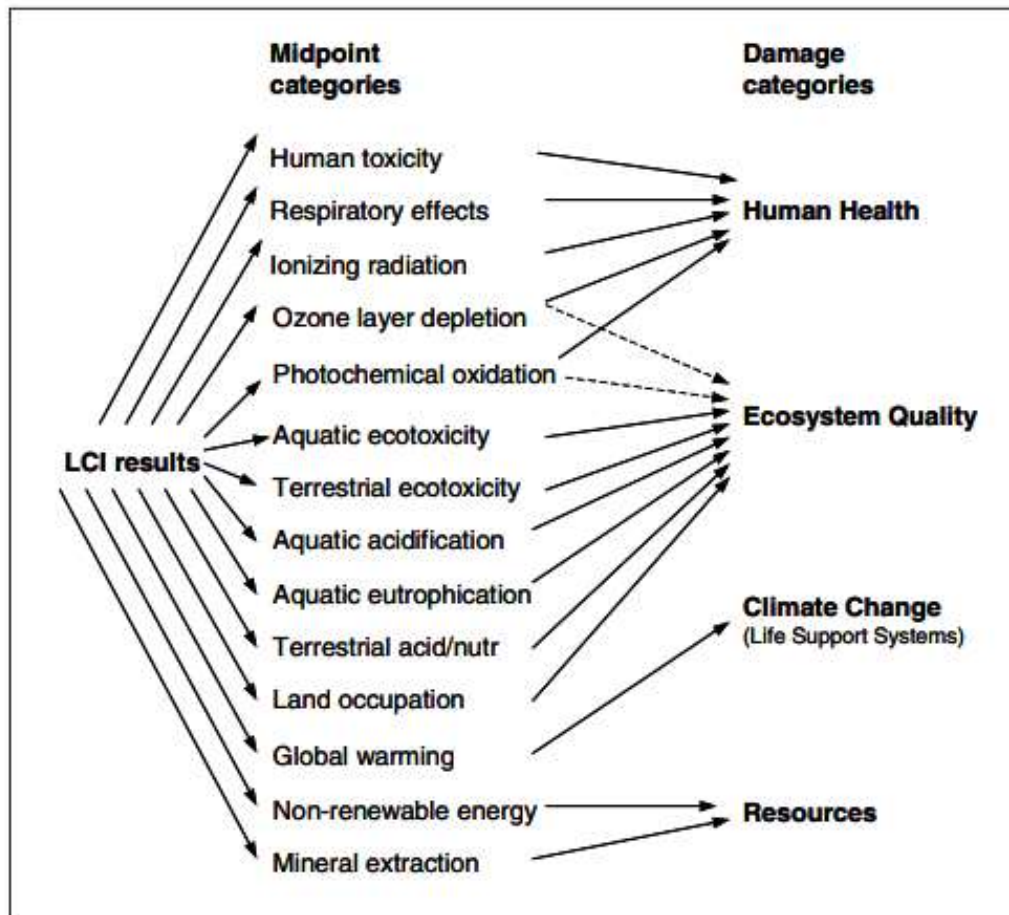


Figure 4.3: Midpoint and Damage Categories of IMPACT 2002+ Method (Humbert et al., 2012)

These 14 midpoint categories can be defined as follows (Humbert et al., 2012):

- Human toxicity (carcinogens and non-carcinogens) represents the chronic toxicological effects on human health. Chemical's concentration in the atmosphere which human uptake, drinking water consumption and intake of contaminants from agricultural products are some of the accounted sources for human toxicity category.
- Respiratory effects causes emissions into air and belong to the end-point human health damage category.
- Ionizing radiation meaning is radiation with enough energy to remove electrons from orbit of atoms. It has effects on both air and water, also belong to human health category.
- Ozone layer depletion means gradual thinning of Earth's ozone layer that protects the Earth from ultraviolet radiation and also causes the skin cancer and immune

system damages. For this reason, ozone layer depletion is belong to both human health and ecosystem quality categories.

- Photochemical oxidation is known as smog that can cause respiratory illnesses and difficult breathing.
- Aquatic ecotoxicity means toxic in the surface fresh water such as streams and lakes.
- Terrestrial ecotoxicity likes aquatic ecotoxicity, this damage represents the toxic on soil ecosystem.
- Aquatic acidification represents increase in levels of atmospheric carbon dioxide causes acidification in freshwater and marine ecosystem.
- Aquatic eutrophication presents the extreme plant and algal population in the aquatic ecosystem.
- Terrestrial acidification and nutrification shows the increase in level of acidification in soil.
- Land occupation shows needed land use for a determined activity.
- Global warming represents the increase in the temperature of the Earth's atmosphere because of greenhouse effect.
- Non-renewable energy shows the energy consumption comes from non-renewable energy sources.
- Mineral extraction represents the extraction of used materials from the nature.

#### **4.1.1.4 Interpretation**

The last step, interpretation gives a frame of the study according to previous steps. In this step, findings from inventory analysis and impact assessment are examined together and reach conclusion, explain limitations and provide recommendations (ISO 14044, 2006). When life cycle assessment have conducted to compare different products, more environmentally friendly solution can be determined. If a single product is analyzed, possible improvements can be determined in this part of the study.

### **4.1.2 Limitations of LCA Approach**

Although LCA is a strong tool in order to analyze environmental impacts of a product, some limitations are mentioned in literature. High data quality and availability is not possible sometimes and this situation influence results significantly. Time frame is the other limitation because of that LCA should consider environmental impacts over the longest period of time, possibly infinite time. Another one is making assumptions and modifying system boundary in order to exclude some elements (Benedetto and Klemes, 2009). In order to avoid limitations of LCA, big amount of data and elaborative study is needed.

### **4.1.3 Types of LCA Approach**

There are three main LCA approaches in literature: bottom-up process LCA, economic input-output model (EIO/LCA) and hybrid LCA. Process LCA is based on facility-level materials flow data. It can describe elements in supply chain correctly but because it depends on facility-level data when such data were unavailable it may cause errors. The economic input-output model LCA uses national sectoral data and has a holistic with aggregation in sectors. However, because of that these sectors may contain more than one product or activities, this model has some uncertainties. Hybrid LCA method combines bottom-up process LCA and top-down economic input-output model LCA and reduces overall uncertainty. It is done with using the process-sum method when data are available and then calculates a correction factor for excluded processes (Deng et al., 2011).

## **4.2 Cost Analysis**

Cost analysis is a process of determining cost of doing something in order to make profit/loss analysis or comparison between alternatives. There are kind of cost analysis methods such as present value (PV), future value (FV), payback period etc. In this study, present value method is used for cost analysis.



Present value method calculates worth of future cash flows in today's value. Discount rate reflects the time value of money is used to find present value. Inflation rate refers increase in general prices of goods or services (Dwaikat and Ali, 2018). Equation 4.1 represents the present value without inflation, while Equation 3.2 represents the present value with inflation.

$$P = F \frac{1}{(1 + i)^n} \quad (4.1)$$

Where

F = Future value

i = Discount rate

n = Number of periods

$$P = F \frac{(1 + f)^n}{(1 + i)^n} \quad (4.2)$$

Where

F = Future value

f = Inflation rate

i = Discount rate

n = Number of periods

Cost analysis process starts with identifying possible costs and revenues. There are kind of costs occur during lifetime of a product or project. These are investment cost, operational cost, maintenance cost and disposal cost (Miah, Koh, and Stone, 2017). Revenues come from sales and salvage values most of the time. After determining costs and revenues, present value calculations are done with taking inflation and discount rate into account. Finally, costs are subtracted from revenues in order to define net present value of a product or project.

## **5. APPLICATION**

LCA method and steps are explained in the previous methodology section. In this part of the study, firstly LCA will be applied considering different reading habits of people and assuming they live in Lüleburgaz, district in Kırklareli, and Bakırköy, district in İstanbul. The study uses LCA software tool SimaPro 9.0.0 version and data have been obtained from Ecoinvent 3 database.

Functional unit of the study is determined as reading one book in each month by a single user half an hour per day during a three-year period.

For the impact assessment part, IMPACT 2002+ method have been chosen to analyze the impact results. As mentioned before, this method focuses on four main damage categories: human health, ecosystem quality, climate change and resources. Results will be analyzed under these damage categories. In the second part of this section, cost analysis of reading book from paper book and e-book will be performed.

### **5.1 Paper Book**

First of all, exemplary paper book for this study is 344-page paperback book, printed in offset process. 60 g/m<sup>2</sup> paper is used for inner pages and 300 g/m<sup>2</sup> american bristol paper is used for cover of the book. Dimensions of the book is 120 × 200 mm<sup>2</sup> and weight is 264 g. The paper book is printed and disposed in Turkey and one paper book is bought and read by only one person.

System boundary of the printed book have been formed with cradle-to-grave approach from production to the end-of-life. Nevertheless, editorial work and packaging of the paper book were not taken into account for inventory analysis. Five main stages of the paper book system are shown in Figure 5.1.

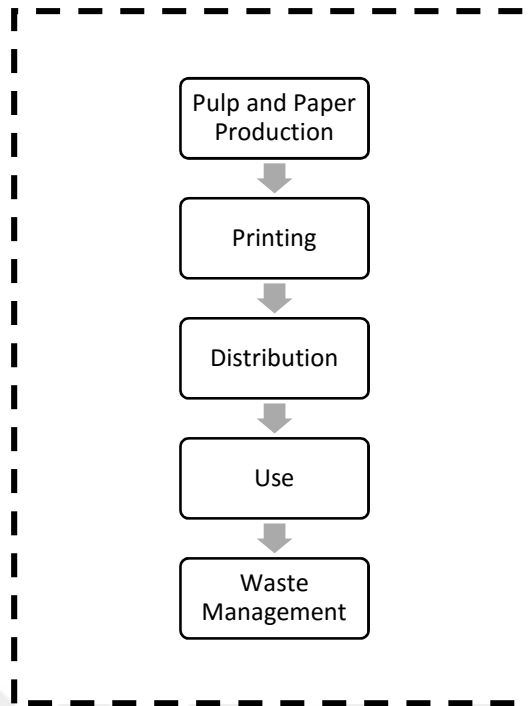


Figure 5.1. - System Boundary of Paper Book

### 5.1.1 Pulp and paper production

Paper production starts with forestry, followed by pulp production, end up with paper production (M'Hamdi et al. 2017). Inner pages of the book used for this study is made from wood-free uncoated paper and cover is made from american bristol paper. Because of database in SimaPro has wood-free uncoated paper, there is no need to add pulp and production stages and wood-free uncoated paper was directly added.

### 5.1.2 Printing

Printing technique used for the studied book is offset printing commonly used for large quantity with lower per unit cost. Offset printing uses generally aluminum plates, ink and water. The inked image on a printing plate is printed on a rubber cylinder and then transferred to paper (Poljak et al., 2013). After finishing printing part the paper cut into required sizes and they are bound with glue.

In this study, book production process have been analyzed in three main process according to the information taken from printing house. First of all, papers are printed with using printing ink in offset printing machine. After that, printed papers are cut into needed dimensions by cutting machine. Finally, prepared papers are glued by binding machine. Each three processes were assumed to take one minute for one paper book and totally three minutes for one paper book. However, because of unavailability of these processes in SimaPro software, only electricity consumption of each machine has been taken into account. Electricity consumption of each machine is as follows:

Table 5.1: Electricity Consumption of Book Processing Machines

Machine Name	Electricity Consumption
Offset Printing Machine	5.5 kW <sup>1</sup>
Book Cutting Machine	1.8 kW <sup>2</sup>
Binding Machine	1.5 kW <sup>3</sup>

There are four materials used in book production process: paper, ink, glue and aluminum plate. Paper and ink have been found in SimaPro and used, however, glue for book binding has not been found in the database so adhesive for metals was used instead of glue for binding. Also, aluminum plate has not been added the study because of unavailability of its amount.

### 5.1.3 Distribution

According to the assumptions made in this study, distribution process has been calculated from chosen printing facility to chosen e-commerce warehouse and from warehouse to

<sup>1</sup> [https://www.alibaba.com/product-detail/Top-Leader-ZR462II-4-Colour-Offset\\_60597905540.html?spm=a2700.7724838.2017115.1.68fc5ba6ICEsx4](https://www.alibaba.com/product-detail/Top-Leader-ZR462II-4-Colour-Offset_60597905540.html?spm=a2700.7724838.2017115.1.68fc5ba6ICEsx4)

<sup>2</sup> [https://www.alibaba.com/product-detail/Best-wholesale-website-Top-10-selling\\_60731295994.html?spm=a2700.7724857.normalList.7.35334539zArnGI&s=p](https://www.alibaba.com/product-detail/Best-wholesale-website-Top-10-selling_60731295994.html?spm=a2700.7724857.normalList.7.35334539zArnGI&s=p)

<sup>3</sup> [https://www.alibaba.com/product-detail/2018-New-Production-Single-Perfect-Binder\\_60701872280.html?spm=a2700.7724838.2017115.98.41082e56T07THB](https://www.alibaba.com/product-detail/2018-New-Production-Single-Perfect-Binder_60701872280.html?spm=a2700.7724838.2017115.98.41082e56T07THB)

the cargo branch. After arriving the cargo branch, the book is sent to the cargo distribution center from this place to the end-user.

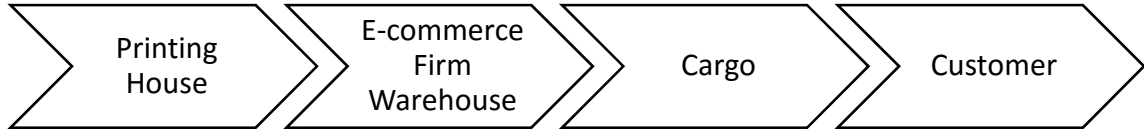


Figure 5.2: Distribution Process of Paper Book

In this part of the study, two scenarios have been prepared to define environmental impacts of transportation. Lüleburgaz, district of Kırklareli nearly 150 km away from Istanbul, has been chosen as an example of rural area, and Bakırköy, district of Istanbul, has been chosen as an example of urban area. The route of paper book product has been generated for these two options and it was assumed that products are transported by lorry in each stage.

In the Lüleburgaz scenario, the book is produced in printing house, then sent to e-commerce firm warehouse in İkitelli. When customer make an order, it is given to cargo branch in İkitelli. Cargo firm sends packages from branch to the regional distribution center and from there to the branch which do the delivery in Lüleburgaz. This route from printing house to Lüleburgaz is totally 176 km. However, distribution to the customer home in the Lüleburgaz was not included. It was assumed that customer takes package from cargo branch by walking. Total traveled distance is shown in Figure 5.3.

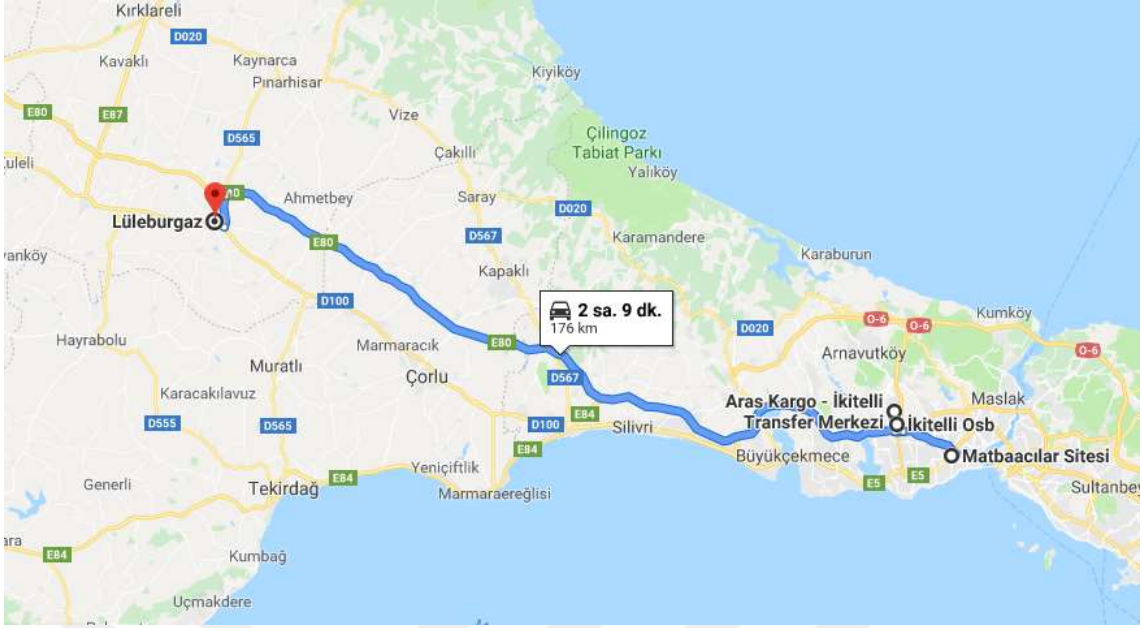


Figure 5.3: Route of Paper Book in Lüleburgaz Scenario (Google Maps, 2019)

In the second scenario, the book follows the same route until the regional distribution center. This time book is sent to the Bakırköy cargo branch from regional distribution center in order to reach customer. This route is 39,6 km, nearly 136 km shorter than the first route. Total traveled distance is shown in Figure 5.4.

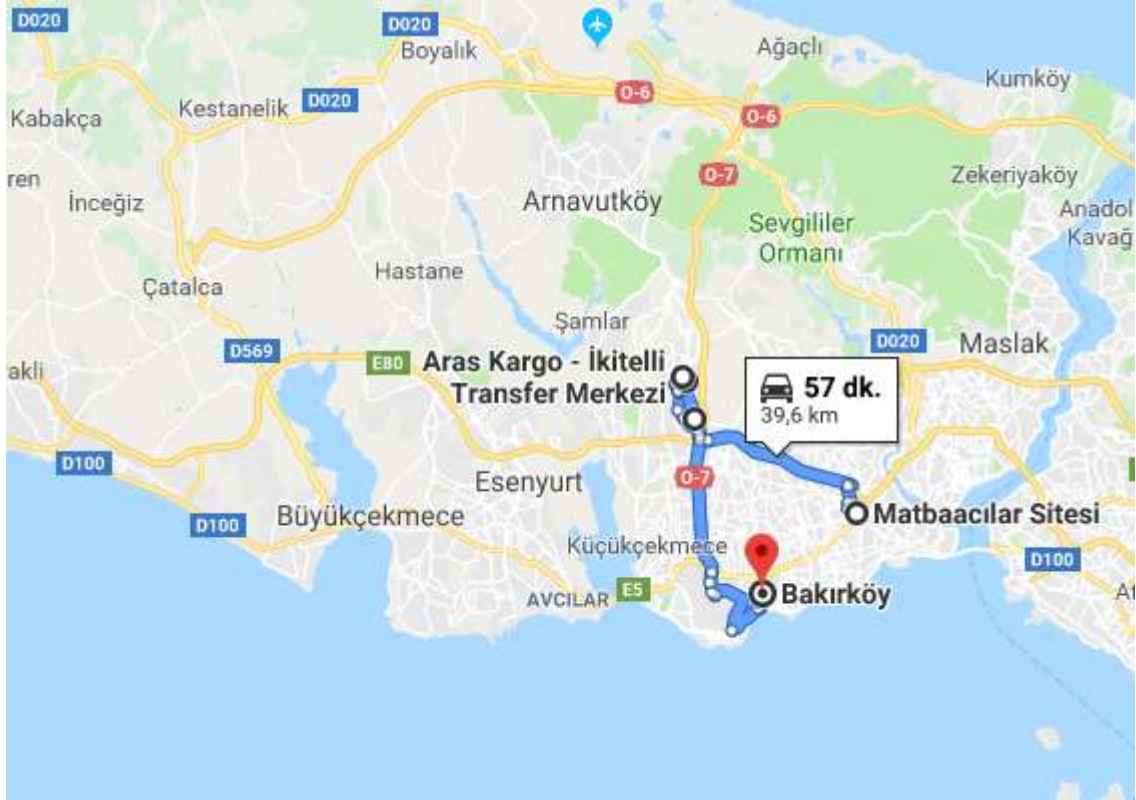


Figure 5.4: Route of Paper Book in Bakırköy Scenario (Google Maps, 2019)

#### 5.1.4 Use

During paper book reading activity, life cycle inventory can be only lightening. This study have assumed no lightening is used during reading printed book. For this reason, there is no inventory causes an impact during use part of the paper book.

#### 5.1.5 Waste Management

In this study, each book was assumed buy and read by one person and then the book will go to waste management. According to the Istanbul Chamber of Industry report (2018), paper and cardboard collection rate in Turkey is found nearly 40% in last few years. For this reason, it was assumed that 40% of the paper books go to recycling process and 60% of them go to disposal process.

## 5.2 E-Book

System boundary of e-book have been also formed with cradle-to-grave approach from e-reader production to the end-of-life. Although paper book and e-book are used for the same purposes, their life cycles are distinct from each other. Four main stages of e-book life cycle as follows:

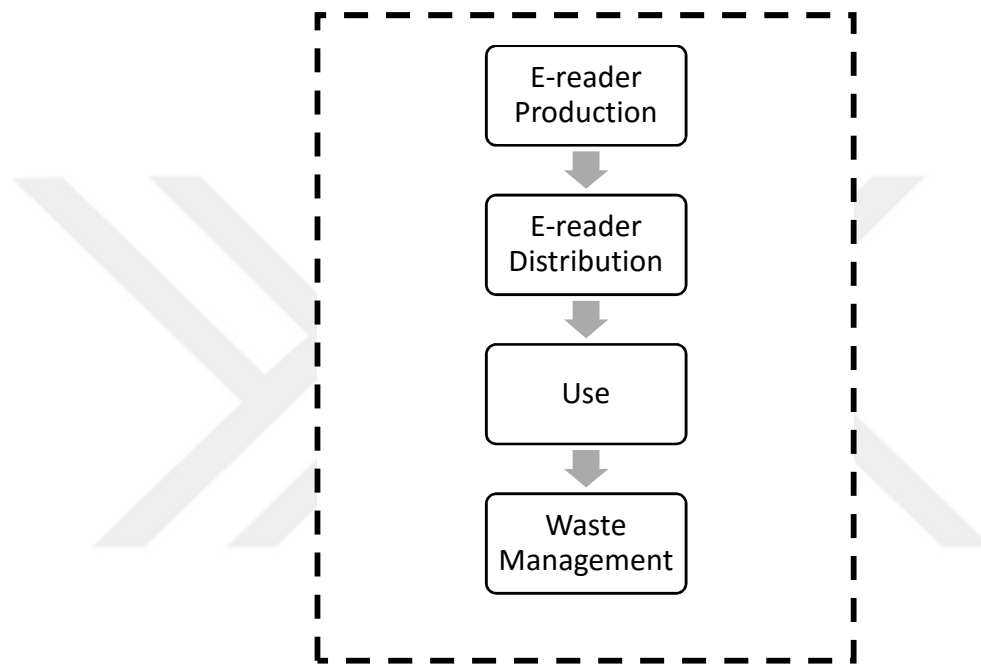


Figure 5.5: System Boundary of E-book

### 5.2.1 Production

Although today there are new models of Kindle e-readers, Amazon Kindle Wi-Fi third gen (2010) model has been used in this study because of the availability of data. Data for raw materials and assembly parts were taken from Teehan and Kandlikar (2013).

Amazon Kindle Wi-Fi third gen model has 19cm x 12.5cm x 0.5cm dimensions and total 312 g mass while 89 g is power supply part. This product consists of six main parts which are battery, display, casing, mainboard, power supply and interior parts.



Table 5.2: Main Parts of E-reader and Magnitudes (Teehan and Kandlikar, 2013)

	<b>Consist of</b>	<b>Mass</b>
<b>Battery</b>	Li-ion battery	51 g
<b>Display</b>	E-ink module	34 g
<b>Casing</b>	Mostly plastic components	59 g
<b>Mainboard</b>	Mostly electronic components	35 g
<b>Power Supply</b>	Plastic and electronic components	89 g
<b>Interior Parts</b>	Plastic and electronic components	45 g
<b>Total</b>		312 g

Because of some components are not available in SimaPro database, equivalent components have been chosen as in Theen and Kandlikar's study (2013). For example, e-ink display module was not found in SimaPro database instead of that LCD module is used.

### 5.2.2 Distribution

Like most of electronic devices, it was assumed that production of Kindles made in Foxconn Company located in Longhua Town, Shenzhen, China. The product is moved from the factory warehouse to the port of Shenzhen by road and from there to the regional distribution centre of Amazon in California, United States by ship. After that, the product is sent to the port of Ambarlı, Turkey by ship and length of total travel by ship is 28.718 km. Then, the product goes to the e-commerce firm warehouse and from there to the customer via cargo firm. The distribution process of e-reader is shown in Figure 5.6 and route of e-book in map is shown in Figure 5.7.

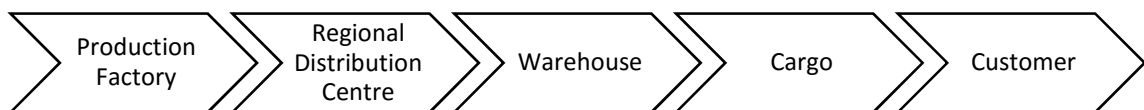


Figure 5.6: Distribution Process of E-reader

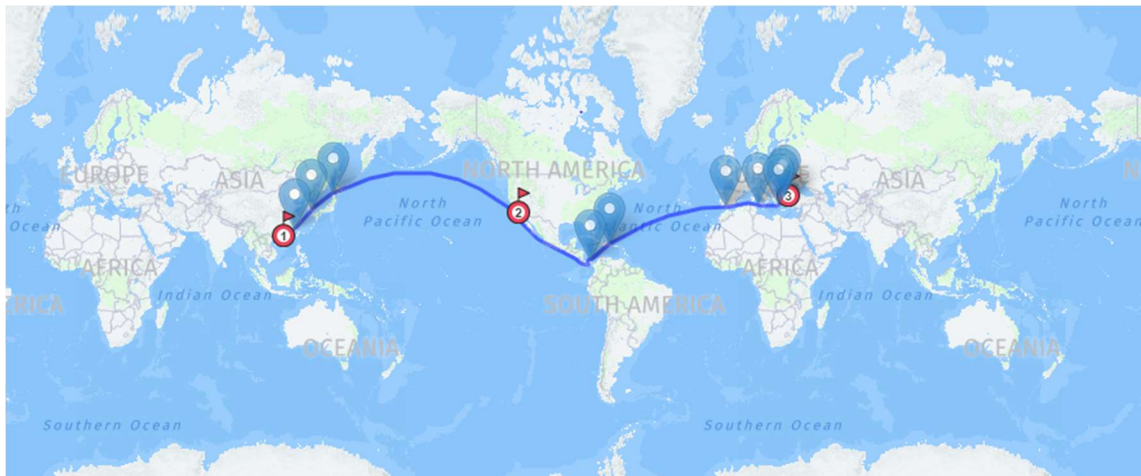


Figure 5.7. - Route of E-book Scenario

### 5.2.3 Use

Like paper book scenarios, lightning has not been included in e-book scenario. However, electricity consumed by e-reader during the use phase has been taken into account. Energy usage during reading e-book and downloading e-book is different for Kindle; however, there is no certain data about how much energy is consumed during these two phases. For this reason, calculation has been done according to assumptions about battery capacity and hours of operation with full charge of the device.

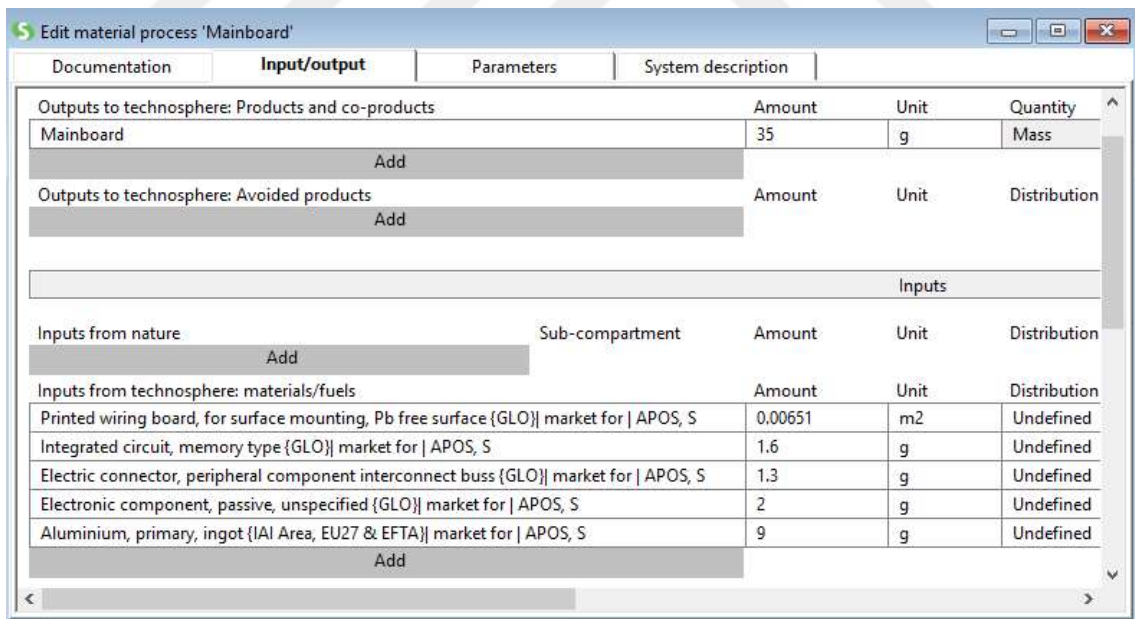
### 5.2.4 Waste Management

There is not a certain statics about waste treatment of electronic devices. For this reason, it was assumed that e-reader will be electronic scrap and will go to landfill when it completes its lifetime.

## 6. ANALYSIS

In the application, firstly, life cycle inventory's were entered into the SimaPro software, then results were calculated for different scenarios with using IMPACT 2002+ method. In the analysis part, results of impact assessment will be analyzed for different scenarios.

As an example of data entry process, some of the screenshots were taken from SimaPro software. First step of data entry, which is entering raw materials in order to form components of products. Figure 6.1 shows the process of data entering for mainboard of e-book.



Outputs to technosphere: Products and co-products				Amount	Unit	Quantity
Mainboard				35	g	Mass
Add						
Outputs to technosphere: Avoided products				Amount	Unit	Distribution
Add						
Inputs						
Inputs from nature		Sub-compartment	Amount	Unit	Distribution	
Add						
Inputs from technosphere: materials/fuels			Amount	Unit	Distribution	
Printed wiring board, for surface mounting, Pb free surface {GLO} market for   APOS, S			0.00651	m2	Undefined	
Integrated circuit, memory type {GLO} market for   APOS, S			1.6	g	Undefined	
Electric connector, peripheral component interconnect buss {GLO} market for   APOS, S			1.3	g	Undefined	
Electronic component, passive, unspecified {GLO} market for   APOS, S			2	g	Undefined	
Aluminium, primary, ingot {IAI Area, EU27 & EFTA} market for   APOS, S			9	g	Undefined	
Add						

Figure 6.1: Mainboard of E-book Data Entry Process

Secondly, assembly process was done with gathering e-book components, which was defined in previous step. Figure 6.2 shows the assembly screen of e-reader in SimaPro.

Name	Status	Comment
Production of E-reader	None	

Materials/Assemblies	Amount	Unit	Distribution	SD2 or 2SD
E-book battery	51	g	Undefined	
Display module	34	g	Undefined	
Casing	59	g	Undefined	
Mainboard	35	g	Undefined	
Power Supply	89	g	Undefined	
Interior Parts	45	g	Undefined	

Processes	Amount	Unit	Distribution	SD2 or 2SD
Electricity grid mix 1kV-60kV, AC, consumption mix, at	1.11	kWh	Undefined	

Figure 6.2: Assembly Process of E-reader

Finally, other processes occurred during life cycle of product and waste scenario were included in the life cycle stage. After this part, data entry process was finish. Figure 6.3 shows the life cycle process of e-book reading from production to the waste scenario.

Name	Status	Comment
Life Cycle of E-book Reading	None	

Assembly	Amount	Unit	Distribution	SD2 or 2SD
Production of E-reader	1	p	Undefined	

Processes	Amount	Unit	Distribution	SD2 or 2SD
Transport, freight, sea, transoceanic ship {GLO} market	8960	kgkm	Undefined	
Electricity grid mix 1kV-60kV, AC, consumption mix, at	136.5	Wh	Undefined	
Transport, freight, lorry 16-32 metric ton, euro3 {RER} r	18.12	kgkm	Undefined	

Waste/Disposal scenario
Waste scenario of e-book

Figure 6.3: Life Cycle Processes of E-book Reading

## **6.1 LCA Results of Paper Book and E-book Scenarios**

### **6.1.1. Impact Assessment Results of Each Scenarios**

First of all, life cycle of one paper book for Lüleburgaz scenario has been demonstrated in Figure 6.4 with tree view. As it seen from the figure, while 70.8% of the environmental impacts come from production of paper book, 15.1% and 14.1% of environmental impacts come from distribution and waste management respectively. Paper as raw material is highest contributor of life cycle with 64.6% before enter production process. The second highest contributor of life cycle is distribution with 15.1%. Finally, waste management, 40% of recycled and 60% of landfill, contributes 14.1% to environmental effects.

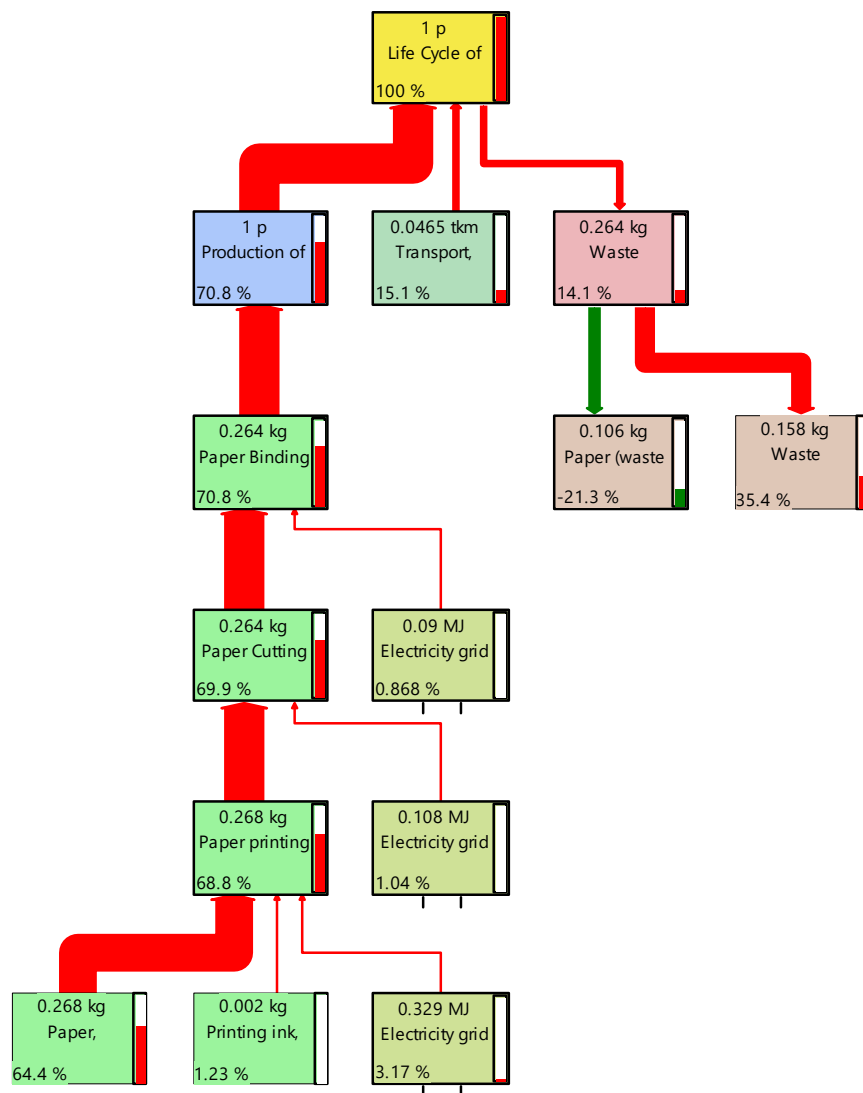


Figure 6.4: Life Cycle Impact Tree of One Paper Book for Lüleburgaz Scenario

Figure 6.5 represents impacts in four damage categories for production, transportation and waste scenario separately. In the production part, human health and ecosystem quality are the highest damage categories. Human health category is also the first damage category in distribution part. In contrast to that only ecosystem quality category has damage in the waste scenario part because of that recycling process decreases impacts 21.3% of the impacts.

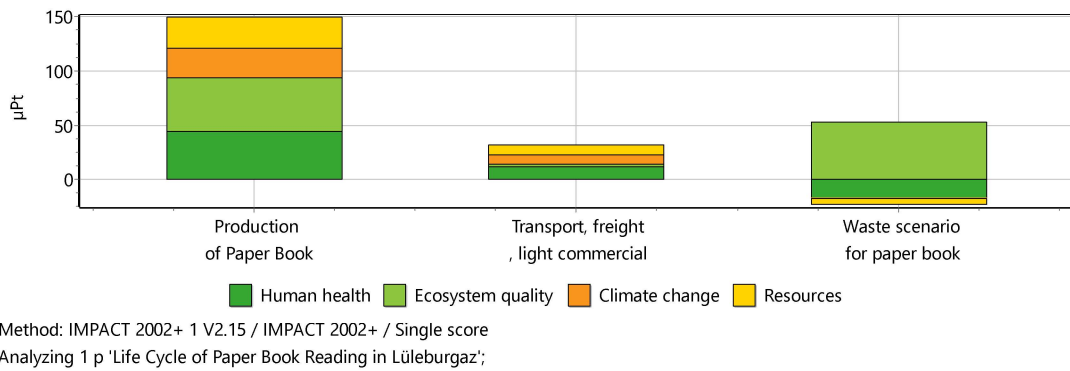


Figure 6.5: Impact Result of One Paper Book by Life Cycle Stages for Lüleburgaz Scenario

Figure 6.6 indicates the life cycle tree of paper book for Bakırköy scenario. Unlike the first scenario, 79.6% of the impacts come from the production and 72.5% come from paper as raw material. In this scenario, transportation has only 4.52% contribution to environmental impacts. When compared to first scenario, it can be said that there is a significant decrease in effect of distribution.

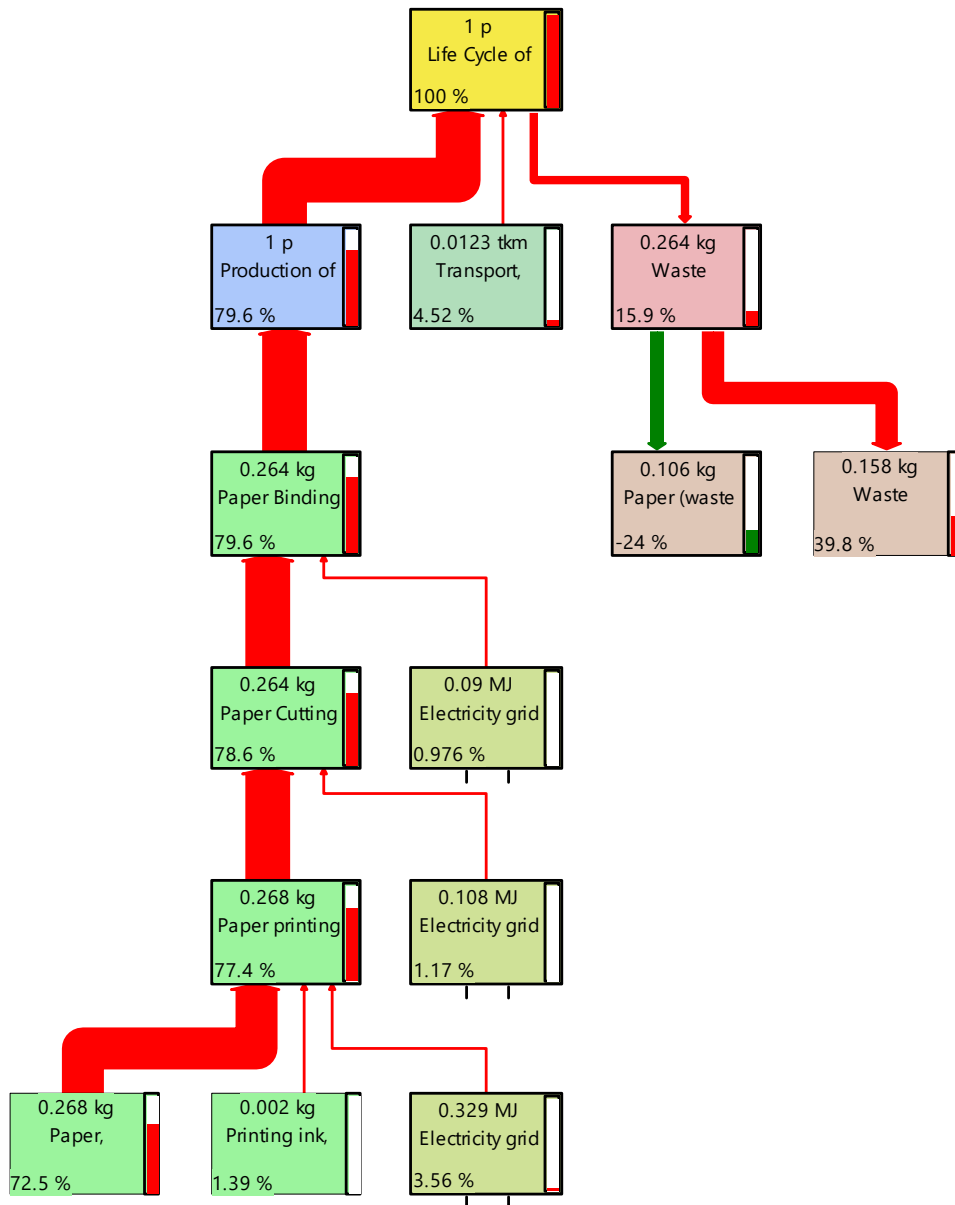


Figure 6.6: Life Cycle Impact Tree of One Paper Book for Bakırköy Scenario

Figure 6.7 shows the single score of Bakırköy scenario for four damage categories according to production, distribution and waste scenario respectively. In this scenario, effect of distribution part is very little. While total damage category is 188  $\mu$ Pt, distribution part constitutes 8.48  $\mu$ Pt part of total impacts.



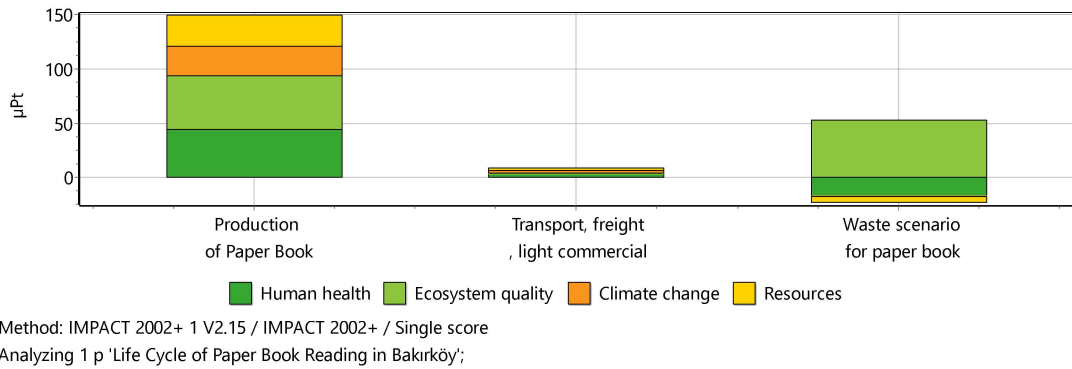


Figure 6.7: Impact Result of One Paper Book by Life Cycle Stages for Bakırköy Scenario

Figure 6.8 represents the life cycle of e-book reading activity from production of e-reader to waste management. Production of e-reader has the highest impact with 95.9%. Although it is not seen in this tree because of low percentages, waste management has only 2.57% of the impacts, use and transportation parts contribute 0.22% and 1.25% of the impacts respectively.

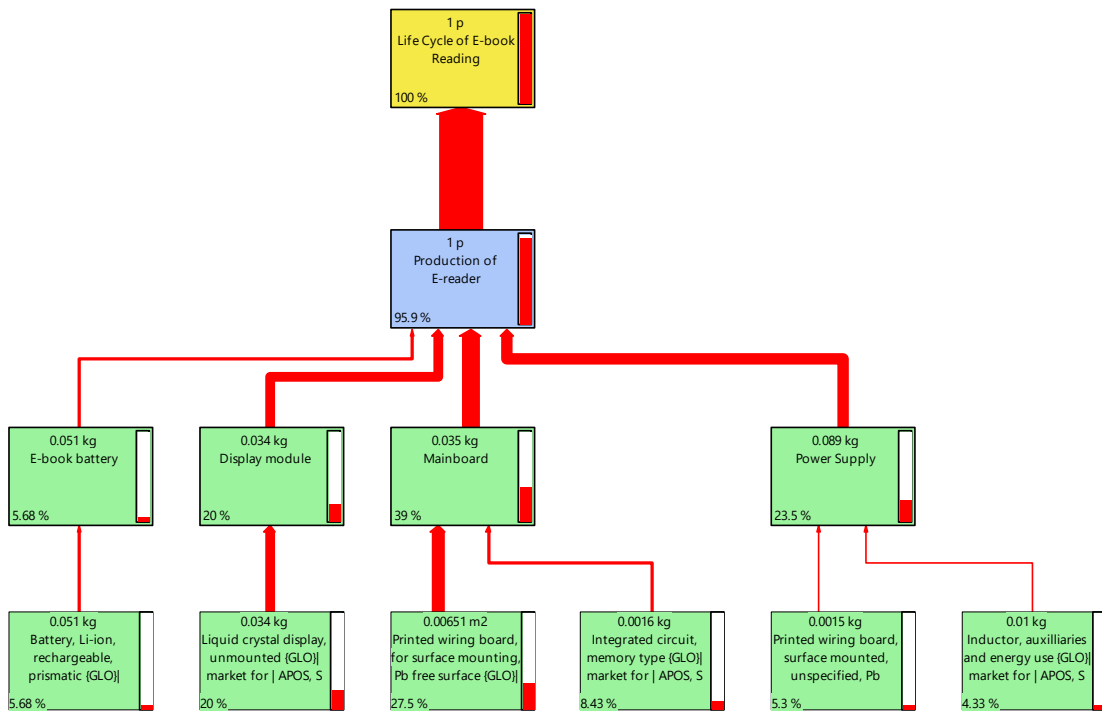


Figure 6.8: Life Cycle Impact Tree of E-book Scenario

The main observations regarding to two paper book scenarios are as follows:

- Paper as raw material has very high impact in paper book system. Adaptation to cleaner production processes in paper mills can decrease the impacts of paper book.
- Distribution is effective contributor in paper book system. Change in distribution distance have changed the distribution effect from 15.1% to 4.52% for one paper book.
- Production stage of e-reader very high impact for e-book system. Electronic components especially printed wiring board and liquid crystal display are the main source of impacts.

### **6.1.2 Impact Assessment Comparison between Three Scenarios**

After completing each scenario separately, in this part three scenario will be analyzed together. As a base case, it was assumed that readers who read one book in a month and totally 36 books are read in three-year period. As it seen from Figure 6.9, each scenario has different values in different midpoint categories. Lüleburgaz scenario has higher scores than Bakırköy scenario in each category due to only difference is more transportation. However, e-book scenario has lowest impact in carcinogens, non-carcinogens, ionizing radiation, ozone layer depletion, aquatic ecotoxicity, terrestrial ecotoxicity, land occupation, global warming and non-renewable energy impacts. On the other hand, e-book scenario has highest impacts in respiratory inorganics, terrestrial acid/nutri, aquatic acidification, aquatic eutrophication and mineral extraction.

One of the significant impact category is global warming potential. In the base case, e-book reading causes lowest global warming potential with 9.53 kg CO<sup>2</sup> eq., while Lüleburgaz and Bakırköy scenarios have 12.6 kg CO<sup>2</sup> eq. and 10.3 kg CO<sup>2</sup> eq. respectively.

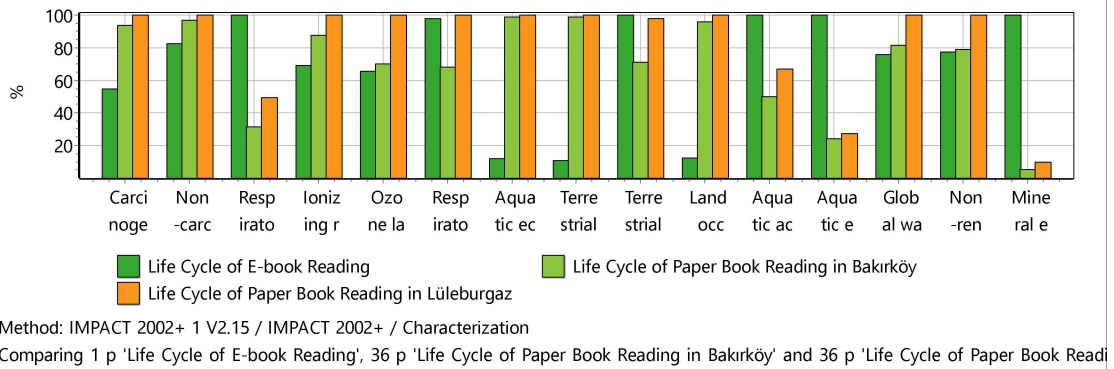


Figure 6.9: Base Case Impact Assessment Midpoint Result of Three Scenarios

In order to make better a comparison, single score approach can be helpful. Figure 6.10 shows the single score of three scenario in four damage categories. E-book reading has the lowest total value with 4.4 mPt, while Lüleburgaz and Bakırköy paper book scenarios have 7.6 and 6.75 mPt respectively. It can be said that e-book scenario has the lower impact than both Lüleburgaz and Bakırköy scenarios. However, it is not valid for each damage category. While e-book reading has less impact than others in ecosystem quality category, it has the highest impact in human health category. On the other hand, resource and climate change categories are near each other for all three scenarios.

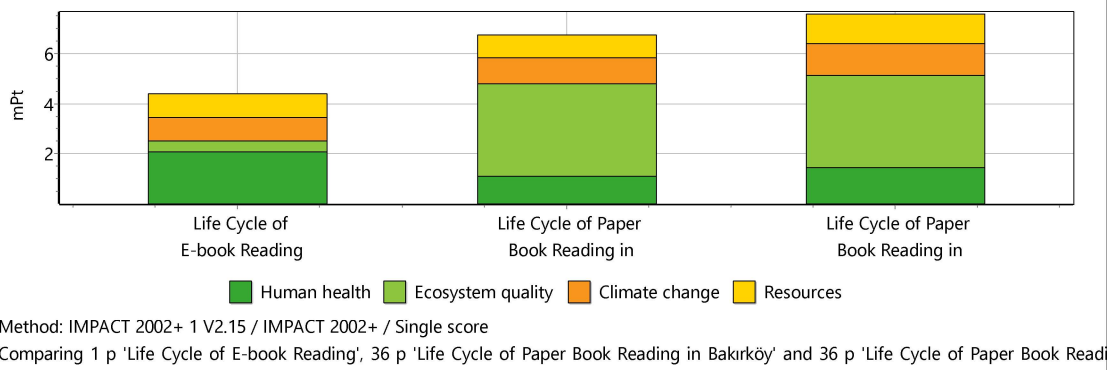


Figure 6.10: Base Case Impact Assessment Single Score Result of Three Scenarios

If we change the reading rate to one book in two months and total 18 books in three-year period, there will be too much change in results. Figure 6.11 represents reading 18 books in three years period. In this case, e-book reading has lowest value just for three midpoint

impact categories: aquatic ecotoxicity, terrestrial ecotoxicity and land occupation. There are huge differences in some impact categories which are respiratory inorganics, aquatic acidification, aquatic eutrophication and mineral extraction.

Result of global warming potential category shows that paper book scenarios have lower global warming potential than e-book scenario in alternative case. Bakırköy and Lüleburgaz scenarios' global warming potential have decreased to 5.14 kg CO<sup>2</sup> eq. and 6.29 kg CO<sup>2</sup> eq., while e-book scenario remains stable at 9.53 kg CO<sup>2</sup> eq.

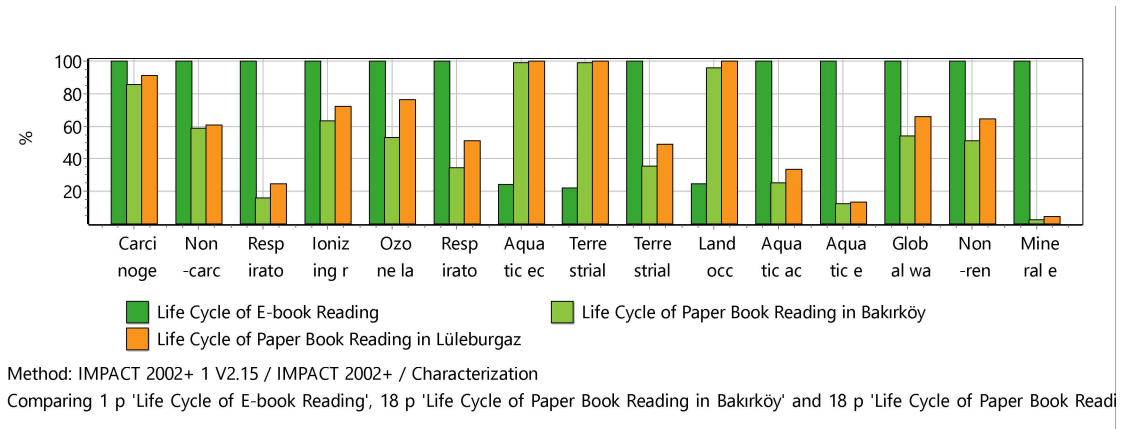


Figure 6.11: Alternative Case Impact Assessment Midpoint Result of Three Scenario

Single score result in Figure 6.12 indicates that e-book reading has higher impacts than other two scenarios for alternative case. This time, human health category has highest for e-book reading while ecosystem quality is highest for paper book reading. Although total impact of e-book reading is not change with number of read book, fall in number of read book decreases impacts of paper book scenarios. Result of alternative case shows that e-book can have more impacts compared to paper book reading for someone who read less.

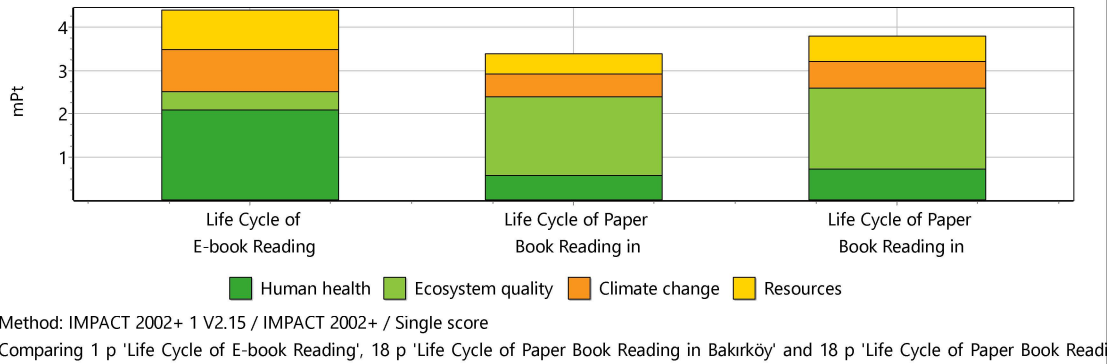


Figure 6.12: Alternative Case Impact Assessment Single Score for Three Scenarios

The main observations regarding the comparison between three scenarios are follows:

- E-book option is eligible for reading one book in a month according to single score and global warming potential category. On the other hand, paper book option is eligible for reading one book in two months according to single score and global warming potential category.
- Mineral extraction, aquatic acidification, aquatic eutrophication and terrestrial inorganics are midpoint categories which e-book system has very high impacts on.

### 6.1.3. Comparison between Lüleburgaz and Bakırköy Scenarios

As mentioned in methodology part, difference between these two scenarios is only distribution distance. Because of Lüleburgaz scenario has longer route than Bakırköy scenario, effects of distance will be analyzed in this part.

According to single score results, reading 23 books has nearly same impacts both e-book scenario and Bakırköy scenario. On the other hand, reading 21 books has nearly same impacts both e-book scenario and Lüleburgaz scenario. It means that distribution to Lüleburgaz has nearly same impact with impact of two paper books according to single score results.

If we compare only the global warming potential, results are slightly changed. Total global warming potential of e-book scenario is 9.53 kg CO<sub>2</sub> eq. While paper book reading in Bakırköy reaches this number with reading 33 paper books (9.42 kg CO<sub>2</sub>eq), paper book reading in Lüleburgaz scenario reaches this number with reading 27 books (9.44 kg CO<sub>2</sub>eq). There is nearly six paper books difference between two paper book reading scenario compared to e-book reading.

## **6.2 Cost Analysis of Paper Book and E-book**

In this part of the study, cost comparison between e-book reading and paper book reading will be done according to their costs during three-year period. Because of there is no revenue comes from reading activities, only investment cost and annual cost will be taken into account.

Investment cost is sale price of a Kindle for e-book reading and there is no investment cost for paper book option. Annual costs come from price of downloading book and electricity usage of device for e-books. Annual cost of printed books are price of books and shipment fee in some cases. Some e-commerce firms do free shipment opportunity when shopping cost is above a certain amount and they encourage people to do shopping above this amount. It was assumed that e-reader is used at the end of its lifetime and paper books are not sold after read. For this reason, there is no salvage value for both options. Time period is assumed three years because of that lifetime of e-readers is assumed like that in other studies (Awasawa et al. 2017; Achachlouei et al. 2015).

In the LCA part of the study, Kindle 3rd generation (2010) model is used due to data availability. Because of this model is not sold anymore, Kindle 6th generation (2016) model is chosen for cost analysis. This model can be used four weeks with single charge based on half hour of reading per day. Electricity cost was calculated based on this data. However, results showed that very few cost occurs from electricity consumption so this cost was not taken into calculation.

Prices of books were defined from a book seller website which sells both paper books and e-books. 24 books, e-books versions available from same publisher, were chosen. Price of paper versions and price of e-book versions can be seen from Table 6.1.

Table 6.1: Prices of E-books and Paper Books<sup>4</sup>

Name of the Book	Writer	E-book Price	Paper Book Price
<b>Beyaz Geceler</b>	Dostoyevski	4.25 TL	6.48 TL
<b>Kürk Mantolu Madonna</b>	Sabahattin Ali	8.2 TL	5.04 TL
<b>1984</b>	George Orwell	12.5 TL	21.39 TL
<b>Yabancı</b>	Albert Camus	6.5 TL	9.72 TL
<b>Türkiye'nin Yakın Tarihi</b>	İlber Ortaylı	13.9 TL	18.29 TL
<b>Hayvan Çiftliği</b>	George Orwell	8.25 TL	12.31 TL
<b>Dokuzuncu Hariciye Koğuşu</b>	Peyami Safa	5.9 TL	5.83 TL
<b>Kalp Ağrısı</b>	Halide Edip Adivar	11.5 TL	18.79 TL
<b>Huzursuzluk</b>	Zülfı Livaneli	11.5 TL	11.49 TL
<b>Simyacı</b>	Paulo Coelho	9.25 TL	14.26 TL
<b>Aşk ve Gurur</b>	Jane Austen	16.75 TL	18.29 TL
<b>Yeraltından Notlar</b>	Dostoyevski	7 TL	6.48 TL
<b>Sinekli Bakkal</b>	Halide Edip Adivar	18.25 TL	27.22 TL
<b>Tek Tabanca</b>	Nihat Genç	14.2 TL	11.67 TL
<b>Sevda Sözleri</b>	Cemal Süreyya	10.9 TL	17.63 TL
<b>Bir Nefeste Dünya Tarihi</b>	Emma Marriott	15.3 TL	13.33 TL
<b>Yaşamın Ucuna Yolculuk</b>	Tezer Özlü	5.99 TL	6.3 TL
<b>Steve Jobs</b>	Walter Isaacson	28 TL	25.28 TL
<b>Olasılıksız</b>	Adam Fawer	14.2 TL	19.25 TL
<b>Kuyucaklı Yusuf</b>	Sabahattin Ali	9.25 TL	5.78 TL
<b>Toprak Ana</b>	Cengiz Aytmatov	5.9 TL	5.83 TL
<b>Outliers</b>	Malcolm Gladwell	13 TL	22.98 TL
<b>Incognito</b>	David Eagleman	24 TL	19.5 TL
<b>Satranç</b>	Stefan Zweig	4 TL	5.19 TL
<b>TOTAL PRICES</b>		<b>278.49 TL</b>	<b>328.33 TL</b>

<sup>4</sup> <https://www.idefix.com/>

Table 6.2: Cost Types Used in E-book and Paper Book

Costs from Using E-book		Costs from Using Paper Book	
<b>Investment Cost</b>		<b>Investment Cost</b>	
<b>Cost of Kindle Whitepaper 3</b>	650 TL <sup>5</sup>	There is no investment cost	
<b>Annual Costs</b>		<b>Annual Costs</b>	
<b>Total cost of 24 e-books</b>	278.49 TL	<b>Total cost of 24 paper books</b>	328.33 TL
<b>Cost of Electricity</b>	This cost is ignored	<b>Cost of Shipment</b>	5 TL for each 3 books

While prices of paper books and shipment price are cost items for paper book reading, price of e-reader and price of e-books are cost items for e-book reading. Figure 6.13 and figure 6.15 show the cash flows of two options during three years. Cash flow of paper book reading includes cost of paper books and shipment, while cash flow of e-book reading includes cost of e-reader and e-books.

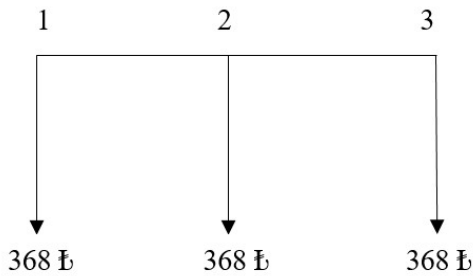


Figure 6.13: Cash Flow of Paper Book

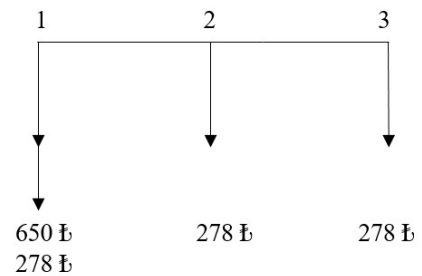


Figure 6.14: Cash Flow of E-book

<sup>5</sup> [https://urun.n11.com/e-kitap-okuyucu/amazon-kindle-new-touch-wi-fi-doknmatik-P32689502?G%C3%BC%C3%A7+Adapt%C3%B6r%C3%BC=-+HAYIR&K%C4%B1l%C4%B1f=-+HAYIR+%C4%B0ND%C4%B0R%C4%B0M+KULLANMAK+%C4%B0STEM%C4%B0YORUM&Ekran+Koruyucu=+HAYIR&Renk=Siyah&gclid=EAlalQobChMI4Nct\\_fv54QIVj4GyCh2CCADmEAQYASABEgKtz\\_D\\_BwE&gclid=aw.ds](https://urun.n11.com/e-kitap-okuyucu/amazon-kindle-new-touch-wi-fi-doknmatik-P32689502?G%C3%BC%C3%A7+Adapt%C3%B6r%C3%BC=-+HAYIR&K%C4%B1l%C4%B1f=-+HAYIR+%C4%B0ND%C4%B0R%C4%B0M+KULLANMAK+%C4%B0STEM%C4%B0YORUM&Ekran+Koruyucu=+HAYIR&Renk=Siyah&gclid=EAlalQobChMI4Nct_fv54QIVj4GyCh2CCADmEAQYASABEgKtz_D_BwE&gclid=aw.ds)



In order to do more realistic cost analysis, inflation rate and discount factor should be added to present value cost calculation. Inflation factor is assumed 20% and discount factor is 24% according to Central Bank of Republic of Turkey<sup>6</sup>. Because of books should be bought before reading, it is assumed that payments will done at the beginning of the periods. Table 6.3 represents the inflation and discount factors for each year.

Table 6.3 - Inflation and Discount Factor for Present Value Calculation

	<b>Inflation Factor</b>	<b>Discount Factor</b>
<b>1. year</b>	1	1
<b>2. year</b>	1.2	0.80
<b>3. year</b>	1.44	0.65

Table 6.4 represents the discounted costs of two options during three-year period. First year cost of e-book is high because of investment cost of e-reader. Each year costs are decreasing because of discount factor. At the end of the Table 6.4, total costs during three-year period is demonstrated.

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<sup>6</sup><https://www.tcmb.gov.tr/wps/wcm/connect/EN/TCMB+EN/Main+Menu/Statistics/Inflation+Data/Consumer+Prices>

Table 6.4: Discounted Costs of Paper Book and E-book Each Year

	<b>Two books each month</b>	<b>Four books each month</b>	<b>Six books each month</b>	<b>Eight books each month</b>	<b>Ten books each month</b>
<b>1. year</b>					
<b>Paper book</b>	368 TL	763 TL	1104 TL	1473 TL	1841 TL
<b>E-book</b>	278 TL 650 TL	556 TL 650 TL	835 TL 650 TL	1113 TL 650 TL	1392 TL 650 TL
<b>2. year</b>					
<b>Paper book</b>	356 TL	712 TL	1069 TL	1425 TL	1782 TL
<b>E-book</b>	269 TL	539 TL	808 TL	1078 TL	1347 TL
<b>3. year</b>					
<b>Paper Book</b>	344 TL	689 TL	1034 TL	1379 TL	1724 TL
<b>E-book</b>	260 TL	512 TL	782 TL	1043 TL	1304 TL
<b>Total</b>					
<b>Paper Book</b>	1069 TL	2139 TL	3209 TL	4278 TL	5348 TL
<b>E-book</b>	1458 TL	2267 TL	3076 TL	3885 TL	4694 TL

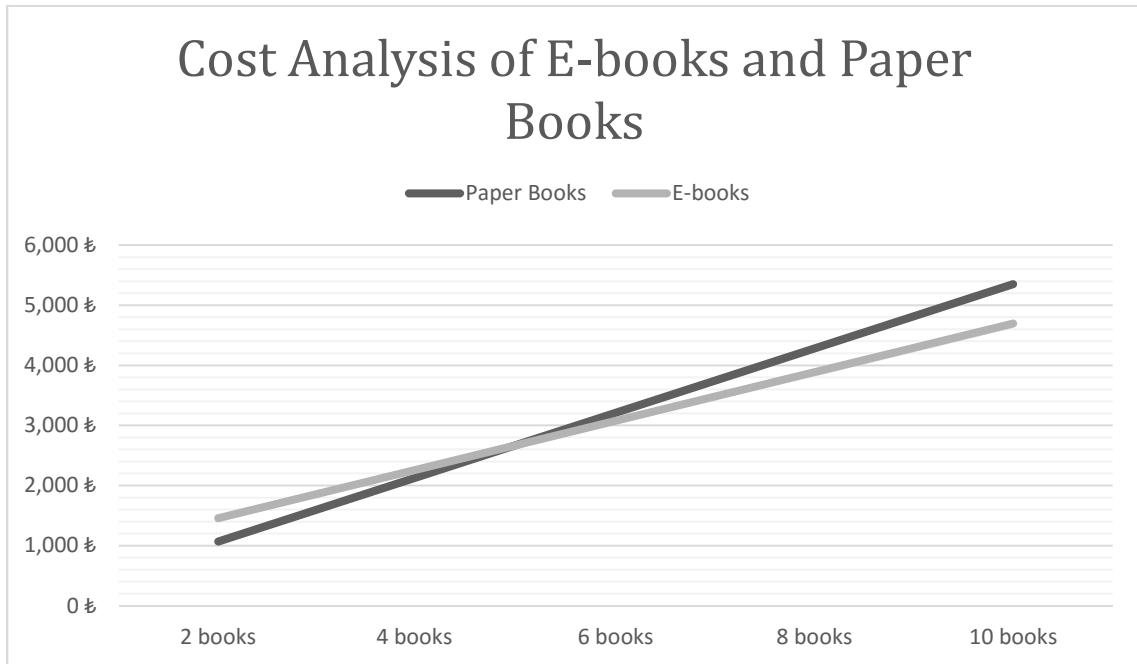


Figure 6.15 – Cost Analysis of E-books and Paper Books for Different Reading Rates

Figure 6.15 was created according to total costs of two options during three-year period. As it seen from the Figure 6.15, paper book is a cost-effective option for reading two books and four books in each month. However, it becomes reversed for reading six books in each month and above values. It can be said that, reading five books in each month can be a critical point. While below this number of book reading paper book is cost effective, above this number of book reading e-book reading will become cost effective option.

### 6.3 Results and Discussion

LCA results have showed that for some reading rates paper books are more environmentally friendly and cost effective and for some reading rates e-books are more environmentally friendly and cost effective option.

It also showed that nearly 21 books for rural area and 23 books for urban area are the critical points according to single score results. Below this number of book reading during three-year period, paper book option will become more environmentally friendly

option. Above this number of book reading during three-year period, e-book will become more environmentally friendly option.

According to results of global warming potential, 33 books reading is critical point for Bakırköy scenario. Above this number of book reading, e-book will less impact than paper book reading. 27 books are critical point for Lüleburgaz scenario. The difference is between Bakırköy and Lüleburgaz scenario is nearly six books during three-year period.

Readers who live urban areas cause less impact than readers who live in rural areas when readers buy their books from online stores because of shorter distribution process to rural areas. For this reason, critical point for book reading rates are different for rural readers and urban readers. Rural readers can choose the e-book reading although they read less books than urban readers.

Furthermore, impact assessment results of each scenario indicates that production part causes highest impact. 70.8% of the impacts come from production of paper book for Lüleburgaz scenario and 79.6% of the impacts come from production of paper book for Bakırköy scenario. Most of the impacts occur from paper as raw material. Also, production of e-reader has highest impact in the life cycle with causing 95.9% of the impacts. Printed wiring board and liquid crystal display are the materials, which cause most of the impacts.

Results of the four damage categories show that paper book scenarios have much impacts on ecosystem quality category, while e-book scenario has much impacts on human health category. The reason can be raw materials of the products. In order to produce paper, trees are cut for pulp production. This process can harm the environment and ecosystem quality impact category may be high for this reason. On the other hand, e-readers contain electronic components and emit radiation. This situation can increase the impacts in human health category.

Results of cost analysis showed that reading five books and totally 180 books during three-year period is critical point according to prices in Turkey. Below this number of book reading, paper book will become cost-effective option. Above this number of book reading, e-book will become cost-effective option.

Overall results show that, e-book reading is better option for readers who read more from both environmental and economic perspective. On the other hand, for reader who read less, e-book reading is not a preferable option from both environmental and economic perspective.



## 7. CONCLUSION

Governments, companies and citizens have to take precaution against the increasing environmental problems. Most of governmental and non-governmental organizations are collaborating and promoting sustainable behavior in order to raise awareness of citizens. To be able to guide the transition effectively, sustainable products or systems should be distinguished appropriately.

There are different methodologies to determine environmental impacts of products or systems. Life cycle assessment is one of the most powerful methods to calculate overall impact of a product or a system from raw material phase to the end-of-life. This method can be used for determining impacts of single products for possible improvements and also making comparisons between several products or systems to choose the more environmental friendly option.

In this study, life cycle assessment and cost analysis have been studied for e-book and paper book reading activities. The aim of this study also make environmental impact comparison between readers who live in rural area and urban area. In order to achieve this, one rural settlement and one urban settlement have been chosen and distribution route have been determined for them.

Life cycle assessment have been established on three scenarios: paper book reading in rural area, paper book reading in urban area and e-book reading. Firstly, impact assessment have been applied for one book reading activity for each scenario one by one. Main contributors of each scenarios have been appointed and impact categories that have highest values have been shown.

In the second stage of the analysis, impact assessment have been conducted to compare impacts of three scenarios with a base and alternative case in order to analyze for different reading rates. Results of two cases have showed that increase in reading book makes e-

book reading a better option compared to paper book reading. It has been found that e-book is more environmentally friendly than paper books for readers who read one books in a month. On the other hand, paper book have been found as an environmentally better option for readers who read one books in two months.

In the final stage of the analysis, difference between urban and rural area impact results have been analyzed. According to single score result, environmental impacts of distribution to rural area have been found nearly two paper books. Also, when global warming potential have been compared, impact of distribution to rural area have been found nearly six paper books.

In the cost analysis part, costs which occur during three-year period were calculated with present value method for e-book and paper book. Which reading option is cost effective for which reading rate have been determined.

The main contribution of this thesis is that there is no study that analyzes environmental impact that occur during distribution to rural and urban readers. Previous comparison studies of paper book and e-book usually analyze just for urban readers and mostly paper books are bought from traditional bookshops. This study provides environmental effects of e-commerce distribution for readers from rural and urban areas. Furthermore, there is no study analyzing both environmental impacts and making cost analysis together.

The main limitation of this thesis is using different inventories in life cycle assessment inventory analysis part because of the unavailability of necessary data and processes in software database. If more detailed inventory analysis can be done in future studies, more accurate results can be reached.

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## **BIOGRAPHICAL SKETCH**

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