

**HOLISTIC APPROACH FOR ASSESSING
SUSTAINABLE DESIGN OF CONSUMER
PRODUCTS**

BY

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Dedicated to my beloved parents.

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LIST OF ABBREVIATIONS

LCA	:	Life Cycle Assessment
KSA	:	Kingdom of Saudi Arabia
GHG	:	Greenhouse Gases
CO ₂	:	Carbon Dioxide
MRI	:	Midwest Research Institute
USEPA	:	United States Environmental Protection Authority
REPA	:	Recourses and Environmental Profile Analysis
ISO	:	International Organization of Standardization
SETAC	:	Society of Environmental Toxicology and Chemistry
SO ₂	:	Sulphur Dioxide
P	:	Potassium
1,4-DCB	:	1, 4 Dichlorobenzene
DALYs	:	Disability Adjusted Life Years
WCED	:	World Commission on Environment and Development
SD	:	Sustainable Development
UNEP	:	United Nations Environment Program

WWF	:	Worldwide Fund for Nature
DfSB	:	Design for Sustainable Behavior
LCD	:	Liquid Crystal Display
USA	:	United States of America
UK	:	United Kingdom
kWh	:	Kilo Watt Hours
PET	:	Polyethylene terephthalate
VOCs	:	Volatile organic compounds
GWP	:	Global Warming Potential
EP	:	Eutrophication Potential
POCP	:	Photochemical Smog Potential
AP	:	Acidification Potential
EMC	:	Environmental Weighted Material Consumption
LED	:	Light Emitting Diode
MW	:	Mega Watts
LCI	:	Life Cycle Inventory
LCIA	:	Life Cycle Inventory Analysis

J1	:	High-range Juicer
J2	:	Mid-range Juicer
J3	:	Low-range Juicer
GLO	:	Global
APOS, S	:	Allocation at the Point of Substitution
RER	:	Europe
RoW	:	Rest-of-the-World
I1	:	High-range Irons
I2	:	Mid-range Irons
I3	:	Low-range Irons
M1	:	High-range Hand Mixer
M2	:	Mid-range Hand Mixer
M3	:	Low-range Hand Mixer
HMDA	:	Hexamethylene Diamine
ABS	:	Acrylonitrile Butadiene Styrene

ABSTRACT

Full Name : Hammad Masood

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Rapid urbanization of the world has led to significant increase in the use of consumer products. Hence, there is a growing demand of products that are energy efficient, environment friendly, and sustainable. Various manufacturers of these products employ different strategies, methods, and tools to achieve sustainable design. In this thesis, a holistic approach is adopted to measure the sustainability of nine consumer products by incorporating price, energy efficiency, and environmental impacts of these products into sustainability analysis.

Products included three irons, three hand mixers, and three juicers designed, produced, and distributed by different manufacturers. Furthermore, they belonged to three different price ranges: low, medium, and high. First, energy consumption of these products was measured and then products were disassembled to generate a detailed list of components, materials, and processes used to manufacture them. Next, life cycle assessment (LCA) was conducted to compare the environmental impacts of these products. LCA is a methodological framework for analyzing environmental impacts of a product throughout its life. All stages, including material extraction, component manufacturing, assembly, distribution, and use

of the product are considered in LCA. SimaPro, a software to determine environmental impacts, was used to conduct the analysis. Six environmental impact categories were used to compare the sustainability of these products: global warming potential, terrestrial acidification, water eutrophication, terrestrial ecotoxicity, human carcinogenic toxicity, and non-carcinogenic toxicity. End-of-life analysis was also conducted using appropriate assumptions about recycling rates of various materials.

The results of this study showed that low cost products, in general, consume more energy and are more damaging to the environment as compared to the expensive products. For example, expensive juicer consumed 45% less power than the low-cost juicer. Similar trends were observed for six environmental impact categories. It was found that this difference in environmental performance is driven by the use of efficient motors, low impact materials, and optimized design of expensive products. This study indicates that there is a need to increase customers' awareness about the environmental impact of various products so that it can influence their decision while purchasing such products.

ملخص الرسالة

الاسم الكامل: حماد مسعود

عنوان الرسالة: نهج متكامل لتقييم التصميم المستدام لأجهزة المستهلك

التخصص: هندسة ميكانيكا

تاريخ الدرجة العلمية: أبريل ٢٠٢٠

نتج عن التمدن المتسارع حول العالم ازدياد كبير في استخدام الأجهزة المنزلية وغيرها. لذا أصبح هنالك طلب متنامي على الأجهزة الموفرة للطاقة، والصديقة للبيئة، والمستدامة. العديد من مصنعي هذه الأجهزة يستخدمون استراتيجيات وأساليب وأدوات مختلفة لتحقيق التصميم المستدامة. في هذه الأطروحة، تم اعتماد نهج شامل لقياس استدامة تسعة أجهزة منزلية، أخذًا في عين الاعتبار: السعر، كفاءة الطاقة، والتأثيرات البيئية لهذه الأجهزة.

تضمنت المنتجات ثلاث مكايي كهربائية، وثلاث خلاطات، وثلاث عصارات تم تصميمها وإنتاجها وتوزيعها من قبل مصنعين مختلفين. علاوة على ذلك، فإن أسعار هذه الأجهزة تتراوح بين منخفضة، متوسطة، ومرتفعة. أولاً، تم حساب الطاقة التي يستهلكها كل جهاز، ثم تم تفكيك الأجهزة وعمل قائمة مفصلة بكل المكونات والمواد وعمليات التصنيع المستخدمة لإنتاج تلك الأجزاء. بعد ذلك تم إجراء تقييم دورة حياة المنتج (LCA) لمقارنة التأثيرات البيئية للأجهزة. تقييم دورة حياة المنتج (LCA) هو عبارة عن إطار عمل منهجي لتحليل التأثيرات البيئية للمنتج خلال دورة حياته. كل المراحل تم أخذها في عين الاعتبار بما في ذلك استخراج المواد، وتصنيع المكونات وتجميعها، وتوزيع المنتج واستخدامه. برنامج SimaPro هو برنامج لتحليل التأثيرات البيئية للمنتجات وقد تم استخدام في هذه الدراسة. تم اختيار ست فئات تأثير بيئي لمقارنة مدى استدامة الأجهزة: الاحتباس الحراري، التحمض على الأرض، وفرة المغذيات في الماء، السمية البيئية على الأرض، السمية

المسرطنة، والسمية غير المسرطنة. تم إجراء تحليل نهاية العمر باستخدام الافتراض المناسب حول معدلات إعادة التدوير للمواد المختلفة.

أظهرت نتائج هذه الدراسة أن المنتجات منخفضة التكلفة، بشكل عام، تستهلك المزيد من الطاقة وأكثر ضرراً على البيئة مقارنة بالمنتجات باهظة الثمن. على سبيل المثال، استهلكت العصارة باهظة الثمن طاقة أقل بنسبة 45٪ من العصارة منخفضة التكلفة. ولوحظت اتجاهات مماثلة في ست فئات من الآثار البيئية. وقد وجد أن هذا الاختلاف في الأداء البيئي مدفوعاً باستخدام المحركات الفعالة والمواد منخفضة التأثير والتصميم الأمثل للمنتجات باهظة الثمن. تشير هذه الدراسة إلى أن هناك حاجة لزيادة وعي العملاء بالتأثير البيئي للمنتجات المختلفة حتى تتمكن من التأثير على قرارهم أثناء شراء هذه المنتجات.

CHAPTER 1

INTRODUCTION

Sustainability is a global issue and the focus of research and design activity for several decades. Climate change due to continuously increasing global warming is a major concern for several industries. Sustainable product design depends upon approaches to reduce the environmental impacts of products throughout their life cycle. For many consumer products majority of the environmental impacts are caused by material and energy consumption during the manufacturing and use phase. It is therefore important to analyze these products with a life cycle perspective. In this thesis a holistic approach is adopted to study the influence of mechanical design and price on the environmental impacts of nine different consumer products.

1.1 Consumer products and sustainability

Consumer products consist of wide range of devices that are used by households on daily basis. One such category of consumer products is home appliances. Due to the rise in income and living standards there is a substantial growth in this category of consumer products [1, 2]. This has led to ever increasing energy and material consumption by manufacturing and usage phase of these products [3]. Therefore, it is important to reduce the environmental impacts of these products by sustainable design techniques [4, 5].

Sustainable design focuses on reducing the use of resources throughout the life of a product [6, 7]. Several companies have successfully reduced the environmental impacts of their products. For example, Figure 1 illustrates 65% reduction in environmental impacts achieved by Nokia while redesigning a mobile phone [8].

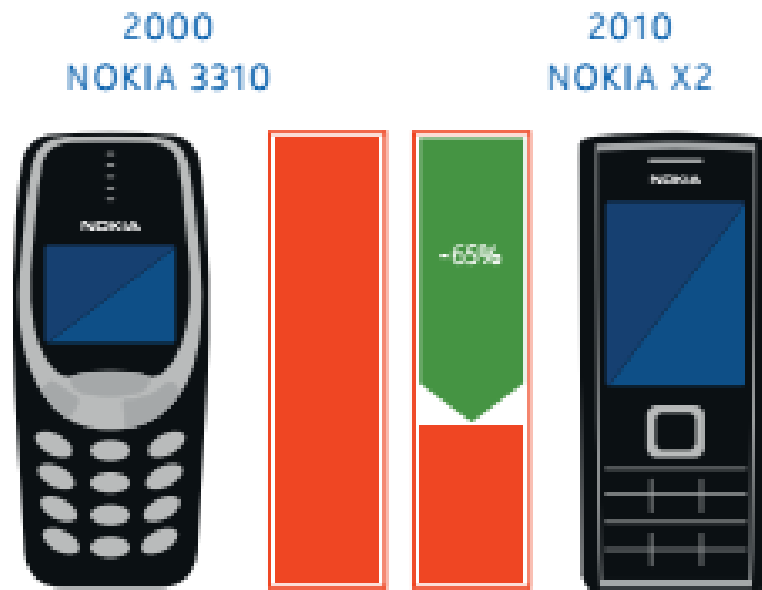


Figure 1 : Environmental impacts reduction in Nokia mobile phones [8]

To incorporate sustainability in product design several techniques are used by manufacturers. These techniques include eco-design [9], eco-efficiency [10], lids-wheels [11] and life cycle assessment (LCA) [12, 13]. LCA is one of the most frequently used technique in sustainable design. LCA is used to quantify the environmental impacts of a product, service, or a system. A summary of LCA methodology is presented below.

1.2 Life Cycle Assessment (LCA)

LCA is a technique to determine the environmental impacts of products and processes. LCA is standardized by ISO 14040 [14] and ISO 14044 [15]. These standards define LCA as the collection of data and evaluation of environmental impacts for inputs and outputs through all life stages of a product. Figure 2 illustrates various stages of product life cycle that are used in LCA.

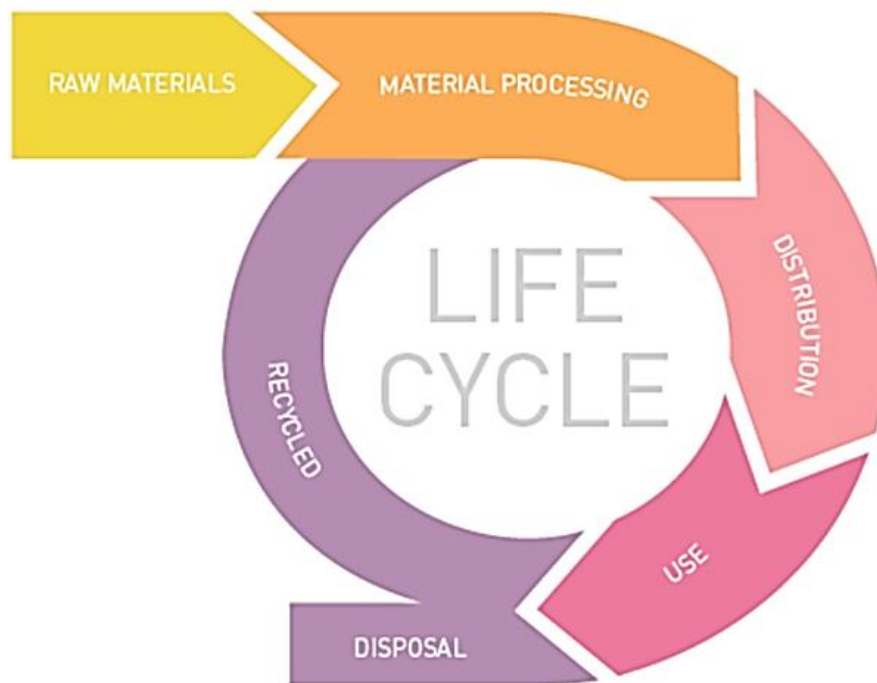


Figure 2 : Stages of product life cycle [12]

1.2.1 History and applications of LCA

One of the very first LCA was conducted in 1969 by Midwest Research Institute (MRI) to determine the environmental impacts of Coca Cola containers [13]. However, it was during 1990s when LCA was standardized by Society of Environmental Toxicology and

Chemistry (SETAC) [13]. This society introduced the first code of practice for LCA. After that ISO standardized the method and wrote the standard 14040 [14].

Several companies have used LCA in reducing the environmental impacts of their products and processes. For example, Unilever a leading Dutch company have performed LCA of more than 1600 products and have used the results to improve the sustainability of their products [13]. Philips used LCA to design energy efficient lighting system by reducing the use of hazardous materials [13]. Procter and Gamble used LCA to improve the sustainability of their supply chain [13]. Similarly, many other companies are using LCA to reduce the environmental impacts of their products and processes. The framework and steps involved in LCA are discussed next.

1.2.2 LCA framework

ISO 14040 divides LCA into four steps as shown in Figure 3. These four steps are goal and scope definition, inventory analysis, impacts assessment, and interpretation.

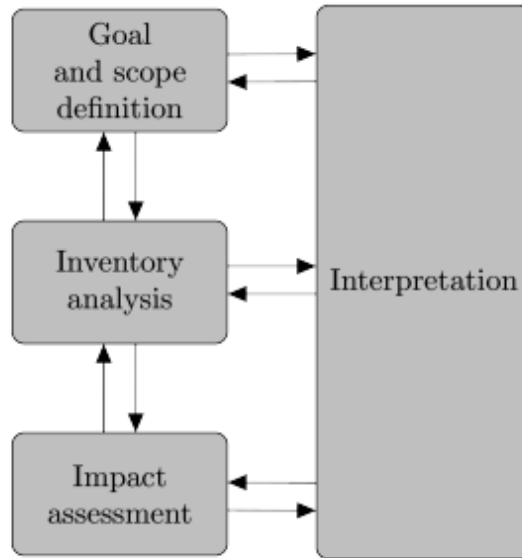


Figure 3 : LCA Framework [12]

Goal and scope definition

Defining the purpose of the study is first step of LCA framework. It delineates the intended application of the study, assumption of the study and target audience [13]. After defining the goal, the scope of the study is determined. Function (useful function/service of the product or process during its life), functional unit (quantification of the function), and reference flow (amount of product required to fulfill the function) are determined during this step [14].

Functional unit help to compare two different products and processes by using a common measure [12]. For example, while comparing paper and plastic grocery bags the carrying capacity of each bag should be normalized using an appropriate functional unit. Boundaries of LCA study and type of LCA study are also decided in this step. In general, there are four types of LCA studies [13]:

- Cradle to grave: includes complete life cycle of the product.
- Cradle to gate: limited to the manufacturing phase of the product.
- Cradle to cradle: includes recycling of the product.
- Gate to grave: includes the life cycle of the product after manufacturing phase.

Inventory analysis

Second step of LCA is inventory analysis. It is the most important step of LCA as it includes collection and modeling of LCA data. This step provides the information about amount of energy and resource consumed during the life cycle of product or process [14]. Several software packages have been developed to facilitate in this step. Two most commonly used software packages are Simapro and Gabi [12, 13].

Impact assessment

The third phase of LCA is impact assessment. Impact assessment is basically a characterization step in which the results of LCA study are classified into several environmental impact categories. The impact categories are selected based upon the impact assessment method used in the study. There are several impact assessment methods that have been developed by various research institutes and are used by LCA practitioners. Some of the most common impact assessment methods are CML, ReCiPe, TRACI, Eco-Indicator and Impact 2002+ [13]. The impacts methods used either midpoint or endpoint approach to quantify environmental impacts. Midpoint methods translate the environmental impacts into individual environmental problems like global warming, ecotoxicity, and eutrophication etc. [13]. Endpoint methods, on the other hand, translates

the impacts into aggregated categories of natural environment, human health, and resource depletion [13].

In this study ReCiPe 2016 v1.01 method is used to quantify the environmental impacts of consumer products. ReCiPe summarizes the environmental impacts into 18 midpoint and 3 endpoint categories [16]. This option provides user to report both midpoint and endpoint environmental impacts [17].

Interpretation

Last step of LCA is interpretation of results. In this step, environmental impact assessment results are analyzed so that conclusions and recommendations can be drawn from them. In particular environmental hotspots (life cycle phase having the largest impact on environment) are identified and validity of results are verified.

1.3 Research scope and purpose

The main objective of this thesis is to apply a holistic approach to compare the sustainable design of consumer products by incorporating their price and manufacturing processes in LCA. The research questions for this study are:

- Is there any difference in environmental impacts of products having the same functionality and specification but designed and made by different manufacturers?
- Is there any correlation between environmental impacts and price of products of same functionality and specifications?

1.4 Thesis outline

The present thesis is divided into five chapters. Existing literature about sustainable design and LCA is summarized in chapter 2. Several studies that used LCA to compare environmental impacts of various products are discussed in detail. Chapter 3 describes the methodology and details of LCA procedure used to compare various consumer products. In chapter 4, the results of LCA study are presented. Comparisons of environmental impacts based upon price and manufacturers are made and discussed. Moreover, the end-of-life results of different recyclability scenarios for all the products is also covered in chapter 4. Chapter 5 concludes the thesis by summarizing the findings and pointing the direction for future work.

CHAPTER 2

LITERATURE REVIEW

Sustainability has become an important aspect of product design. Several researchers have investigated sustainability of various products. Similarly, LCA has been extensively used to compare various products as it provides a quantitative analysis of environmental impacts. Following is a summary of several studies related to sustainable design and use of LCA to compare various products and processes.

2.1 Sustainable design

Sustainable development was first defined in Brundtland report as “... a development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs” [18, 19]. This definition was further refined by United Nations Environment Program (UNEP) as “... improving the quality of human life while living within the carrying capacity of supporting ecosystems” [20]. Three pillars of sustainable development defined by UNEP are shown in Figure 4 [21].

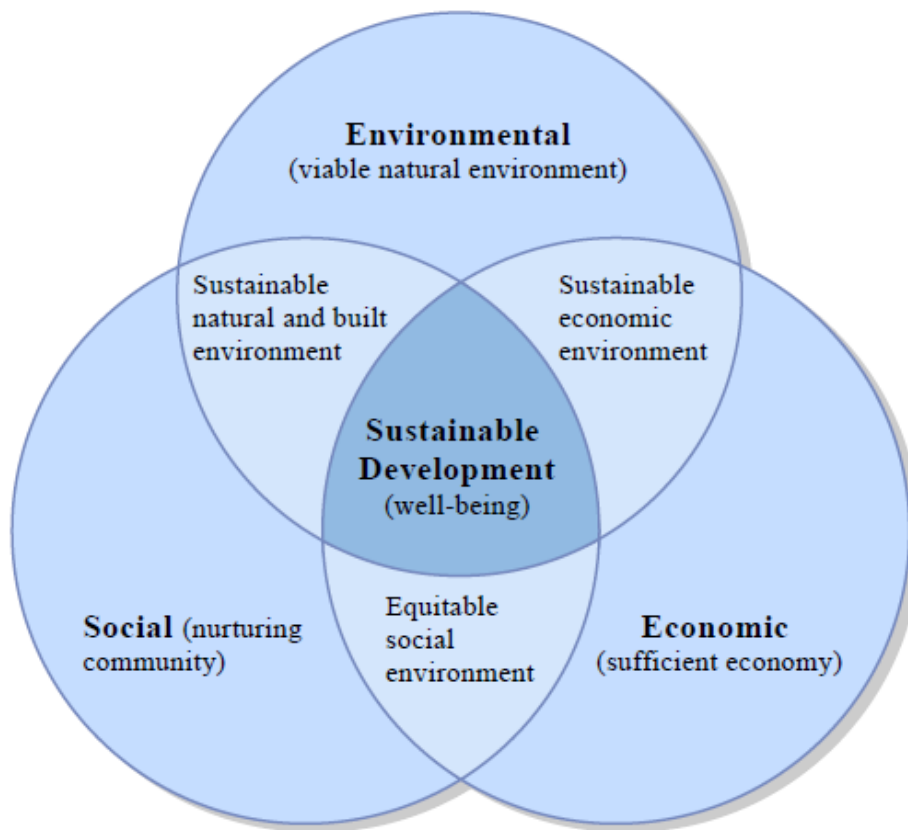


Figure 4 : Three pillars of Sustainable development [22]

Sustainable design plays an important role in sustainable development. Sustainable design tries to reduce or eliminate the environmental impacts through careful selection of design parameters [23, 24, 25]. It was found that 80% of environmental impacts are determined during the early stage of product design [26, 27]. Sustainable design considers the entire life cycle of a product including material selection, manufacturing, end-of-life, reuse and recycle [28, 29]. There have been several guideline and standards developed to help designers to improve the sustainability of their designs [30, 31, 32].

Ramani et al., [33] examined the integration of sustainable design principles in product design process. They found that decisions taken during design phase related to material

selection, manufacturing processes and end-of-life scenarios determine the product environmental impacts. They concluded that merging sustainable design thinking with traditional design methods is crucial for sustainable product realization.

Another aspect of sustainable design is to promote energy saving during the use of consumer products. The energy consumption of consumer products has increased manifold over the past few decades [34]. However, there is still a lot of room to reduce the energy consumption and hence increasing the sustainability of consumer products, for example, a study in Australia showed that 15% of electrical energy consumed in electric kettle is wasted [35]. Similarly, it is shown that energy consumption during the use is one of the major cause of environmental impacts of several products like washing machine [36], refrigerator [37] and TVs [38] etc. In summary sustainable design focuses on using less energy and fewer resources to meet the design requirements specified by the customer. Some important LCA studies that have been conducted to measure the sustainability of products and processes are summarized next.

2.2 Use of LCA for measuring sustainability of processes

The environmental impacts of additive laser manufacturing specifically Construction Laser Additive Direct (CLAD) and conventional machining processes are compared by Serres et al.,[39]. They used Simapro software and Eco Indicator 99 [40] method in their study. Comparison of impact categories of human health, ecosystem quality and resource depletion showed that CLAD process had less environmental impacts as compared to conventional machining processes. The results of this study are shown in Figure 5.

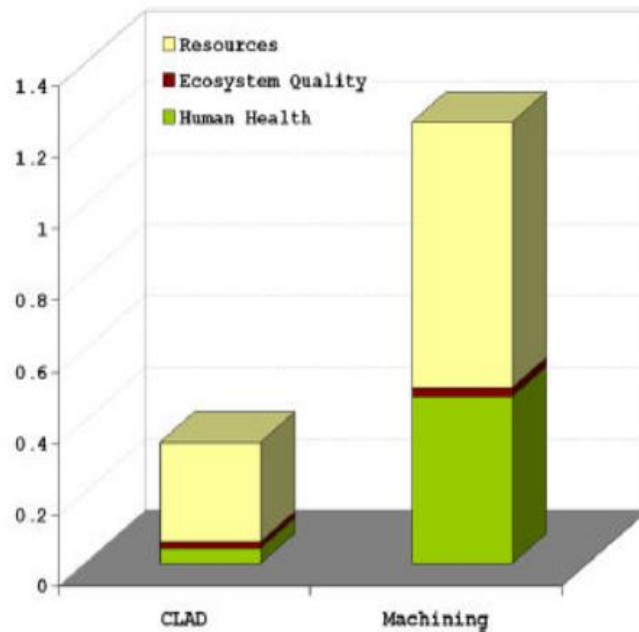


Figure 5 : Comparative environmental impact of CLAD and conventional machining [39]

Zhao et al., [41] compared environmental impacts of laser assisted manufacturing process with the conventional manufacturing process. The comparison was done on laser shock peening and laser assisted turning with their corresponding conventional machining processes. They reported 45% less environmental impacts in case of laser shock peening as compared to conventional shot peening process. Similarly, laser assisted turning showed 50% less environmental impacts as compared to traditional turning process.

Matarrese et al., [42] studied energy consumption and environmental impacts of injection molding process. The study showed that most of the impacts in injection molding machine is due to the energy consumption during the molding process. Kimura et al., [43] used LCA to measure the environmental impacts associated with a vending machine. They also suggested improvements for reducing environmental impacts of vending machines.

The environmental impacts of thick plate welding processes were compared by Sproesser et al., [44]. The thick plate welding technologies of laser arc hybrid welding (LAHW), manual metal arc welding (MMAW) and gas metal arc welding (GMAW) were compared in their study. They used Gabi software and CML 2002 method in their study. The results of their study (Figure 6) found that MMAW has highest environmental impacts compared to other welding processes. Results also revealed that LAHW has lowest impacts as compared to other processes.

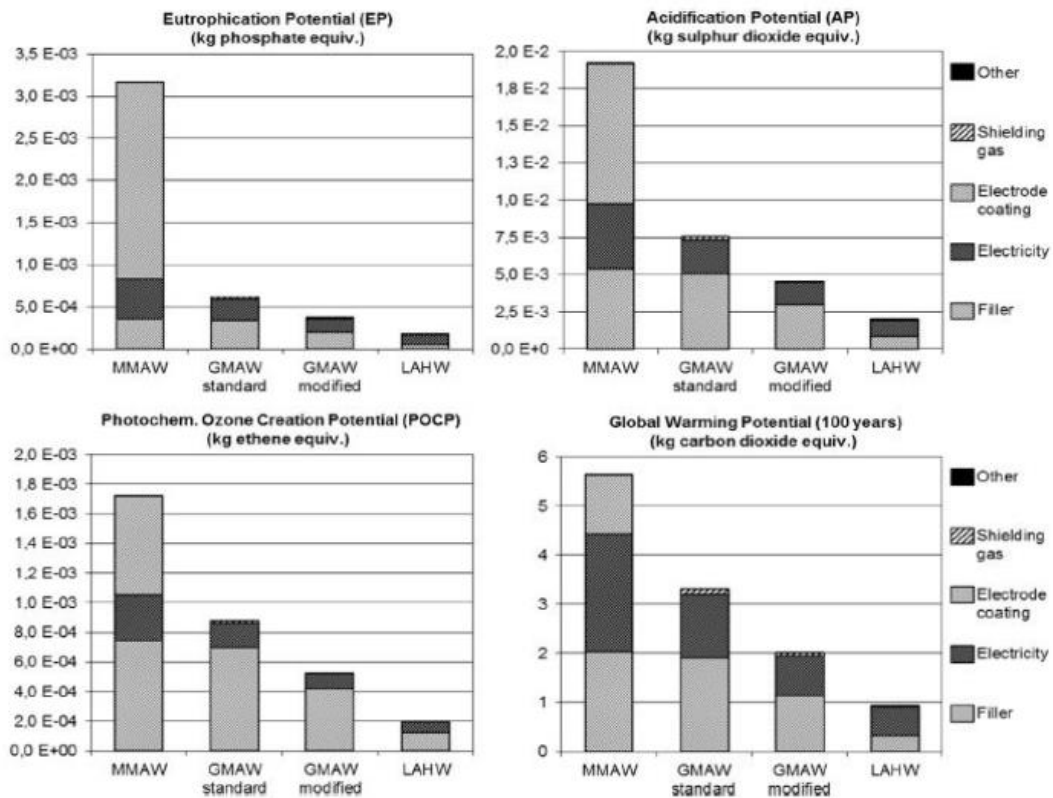


Figure 6 : Comparative environmental impact of different welding processes [44].

Liu et al., [45] in their study preformed LCA of refining process of petroleum in China. They showed that volatile organic compounds, like acrolein and chlorofluorocarbons, emitted during refining processes were the main cause for high environmental impacts. In

addition, several other studies are reported in literature have used LCA to analyze the environmental impacts of various industrial processes. These studies include: manufacturing of Latex [46], analysis of polyurethane pavement on road [47], biomass material processing [48] hydrogen production processes [49, 50], comparison of different biofuel generation process [51], comparison of 2G and 3G network [52], comparison of various copper recycling processes [53], comparison of cofiring and biomass-fired power plant [54] and comparison of different packaging processes [55]. In next section studies related to comparative environmental impacts assessment of consumer products are summarized.

2.3 Comparative LCA studies of consumers products

Sabina et al., [56] compared environmental impacts of two street lighting technologies in United Arab Emirates. These technologies included ceramic halide bulbs (CMH) and light emitting diodes (LED). A cradle to grave life cycle assessment was conducted using Simapro. It was found that LED have higher environmental impacts during manufacturing phases but lower impacts during operation. Conversely CMH have lower impacts during manufacturing phase but higher impacts during the operation (Figure 7 and Figure 8).

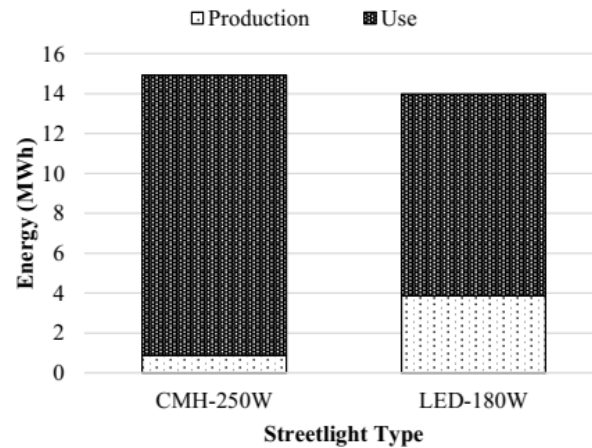


Figure 7 : Energy consumption comparison of CMH and LED [56].

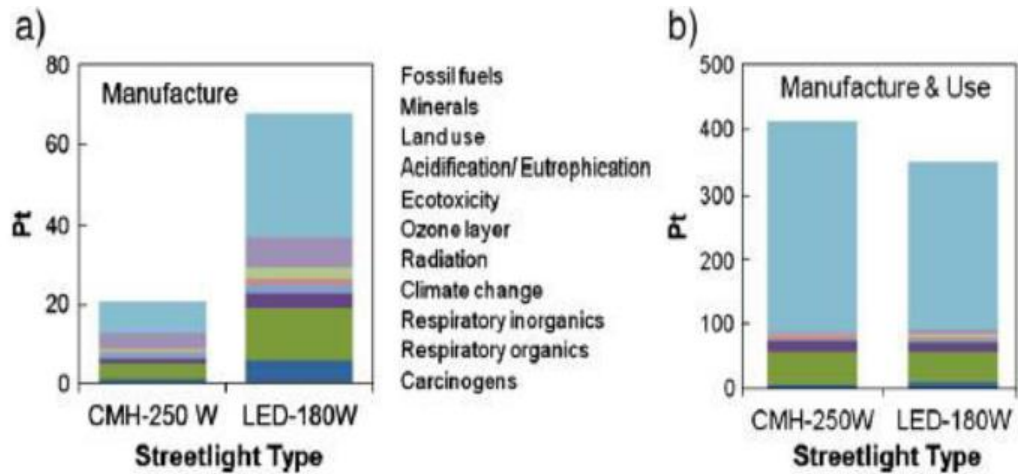


Figure 8 : Comparative environmental impact of CMH and LED [56].

Dyson a home appliance manufacturer conducted a study to compare the various products available for hand drying [57]. Their study concluded that Dyson hand dryer had lower environmental impacts as compared to other hand dryers available in the market as shown in Figure 9. Study also revealed that using paper towels for drying hands is less environmental friendly as compared to using a hand dryer.

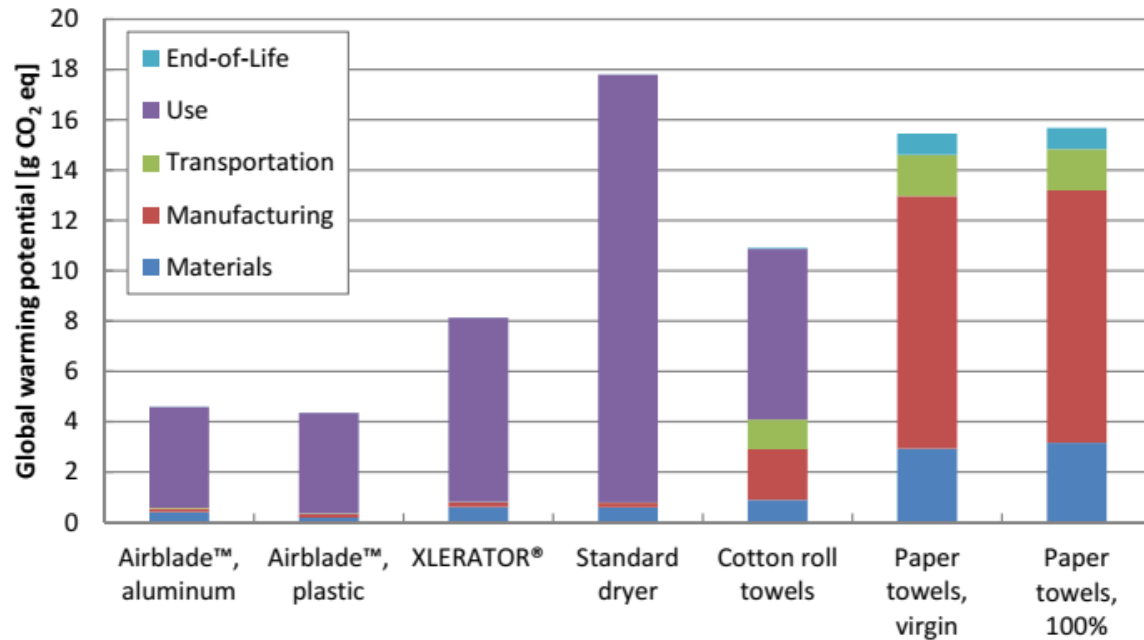


Figure 9 : Comparative environmental impact of different hand drying system [57].

Pina et al., [58] studied relationship between mechanical design and environmental impacts of five different induction hobs. These five different induction hobs belonged to five subsequent generations of the product. LCA was conducted using Simapro and Ecoinvent v2.2 database. Their study revealed that the mechanical design of induction hob has significant role in environmental impacts generated by these hobs. They found that by adopting compact design and reducing the wiring lengths greatly reduce the environmental impacts. Figure 10 summarizes the results of their study that shows the newest model G5 generated the lowest environmental impacts.

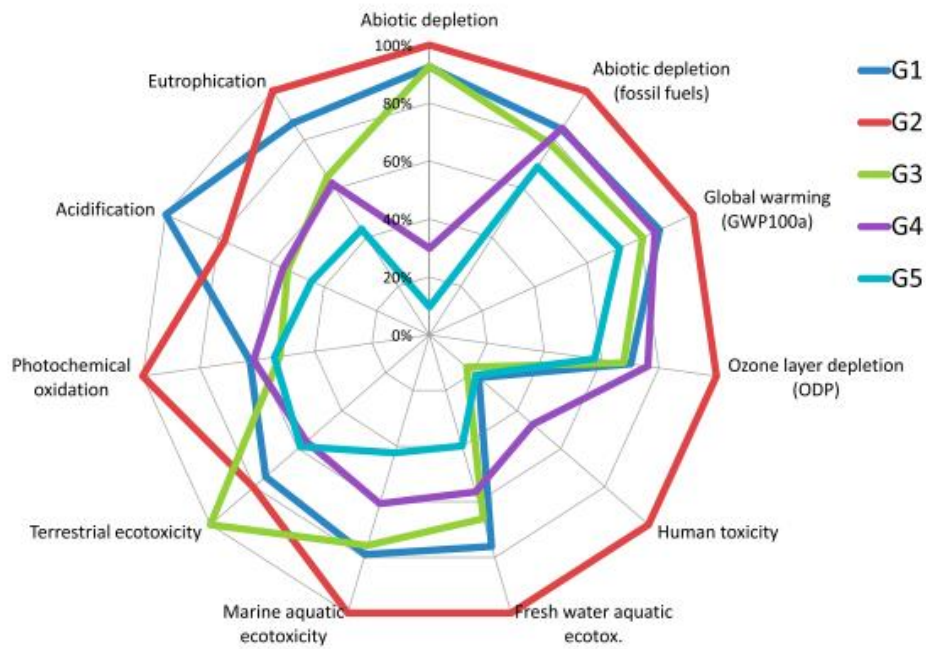


Figure 10 : Comparative environmental impact of different generations of induction hob [58].

Environmental impacts of natural gas and electric oven was compared by Landi et al., [59] using LCA. Results of their study are shown in Figure 11. It is clear from results that electric oven had more environmental impacts as compared to gas oven in almost every environmental impact category. They also highlighted that most of the environmental impacts is generated during the use phase of the oven.

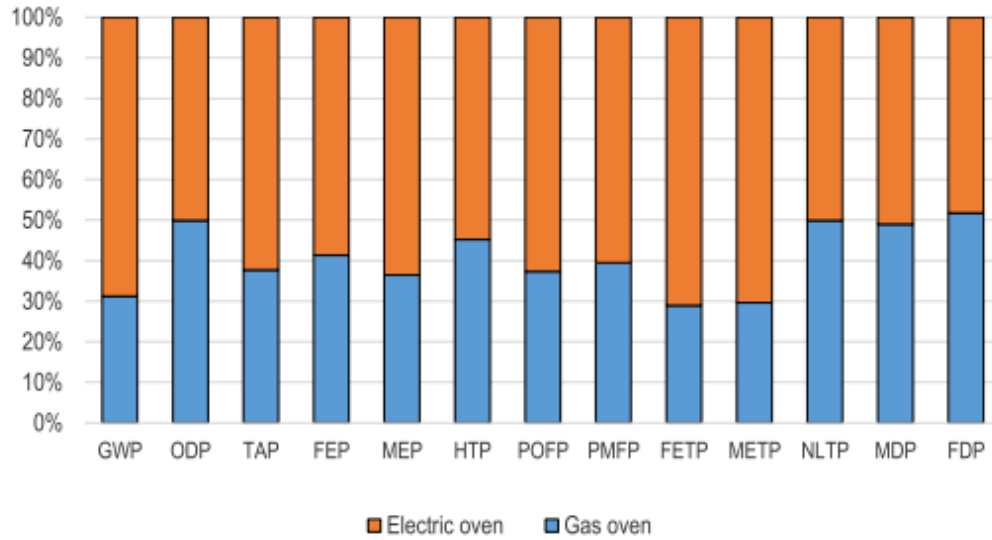


Figure 11 : Comparative environmental impact results of electric and gas oven [59].

Lozano Miralles et al., [60] conducted comparative LCA of two building heating systems: heat pump and pellets boiler. They used Eco-Indicador99 and EPS 2000 method in their study. Results are displayed in Figure 12 which shows that heat pump had more environmental impacts as compared to pellets boiler.

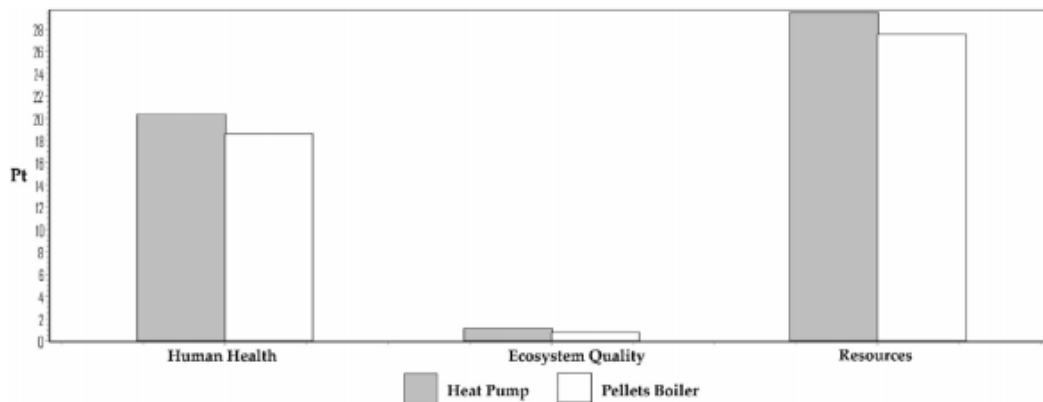


Figure 12 : Comparative environmental impact results of heat pump and boiler [60].

Hawthorne and Ameta, [61] compared the environmental impacts two blenders produced by same manufacturer. They conducted a detailed LCA to analyze the environmental

hotspots in life cycle of these blenders. They concluded that manufacturing phase of the blenders is responsible for most of the environmental impacts. They also found that the material selection for different components of blenders was an important factor that influences the environmental impact of these blenders.

Bevilacqua et al., [62] performed LCA of a cooker hood. The results of the study showed that both manufacturing and use phase contributes towards the environmental impacts of a cooker hood. They also analyzed a redesigned cooker hood and showed that by replacing one phase motor with three phase motor and halogen lamp with LED lamp significantly reduced the environmental impacts associated with a cooker hood.

R. Hischer [63] performed LCA of a field emission display (FED) television. After analyzing environmental impacts of FED, they compared its results with other display technologies like liquid crystal display (LCD), cathode ray tube (CRT) and plasma displays. Results showed that FED had better environmental performance in all environmental damage categories as shown in Figure 13.

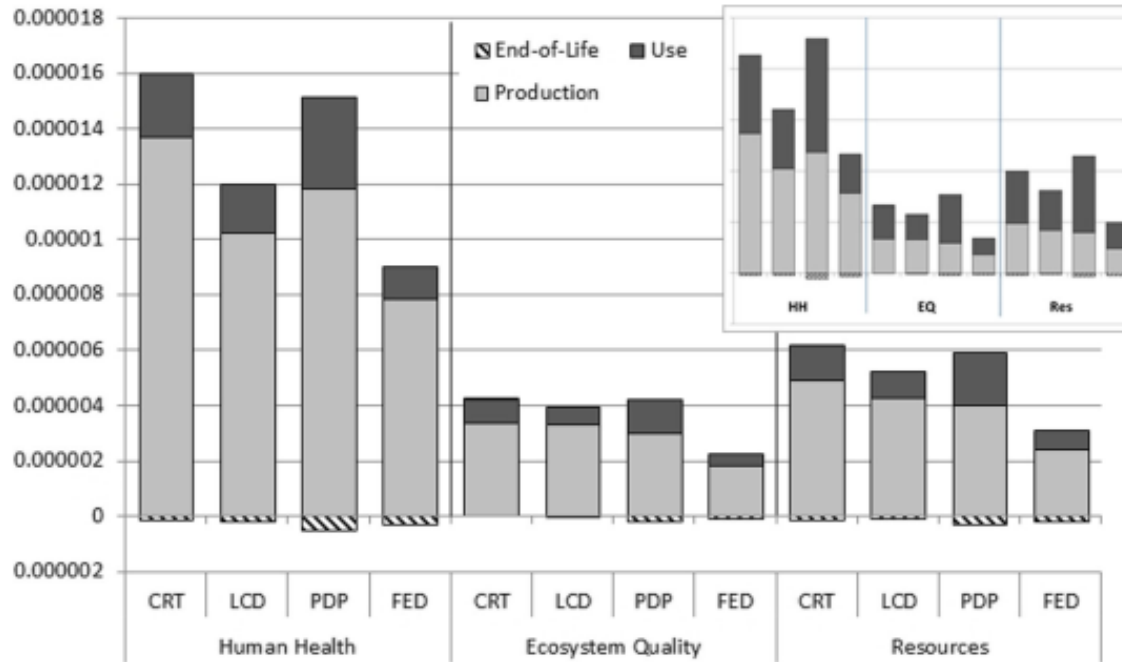


Figure 13 : Comparative environmental impact of different display technologies [63].

In addition several other researchers have conducted LCA to determine the environmental impacts of various consumer products including newspapers [64], plasma TVs [65], air conditioners [66], refrigerators [67], electronic boards of domestic hobs [68], wind turbines [69, 70] and automotive parts [71].

Literature review shows that LCA has been extensively used to study the environmental impacts of various products and processes. Researchers were able to compare products with each other and found environmental hotspots in life cycle of these products. They also used LCA to suggest improvements in product design to reduce the environmental impacts. The current study adds to the literature by incorporating the influence of price and manufacturer on environmental impacts of consumer products.

CHAPTER 3

METHODOLOGY

In this thesis, life cycle assessment is employed to analyze the environmental impacts associated with nine consumer products. These nine products belong to three categories of home appliances: irons, hand mixers and juicers. Moreover, products within each category belong to three price ranges: low, medium, and high. These products are produced by different manufacturers based in US, Europe, UAE, and China. The selected products are shown in Table 1. Expensive product is denoted by suffix 1, mid-range product by suffix 2, and low-cost product by suffix 3. So, for example, expensive iron is denoted by I1, mid-range product by I2, and low-cost iron by I3. Same nomenclature is adopted for other two products. It can also be seen from the table that the power rating of each product within the given category is same. For example, all three selected irons are rated at 1200 watts. Although the products were acquired in KSA, they are in general available in other regions of the world and their price ranges remain comparatively the same.

The LCA process consists of defining the goal and scope of the study, inventory analysis, impact assessment and interpretation of results. First two steps are discussed in detail in this chapter. Whereas the next chapter describes the last two steps.

Table 1 : Summary of price and power rating for nine consumer products

IRONS			
	I1	I2	I3
% Price	100	56	29
Rated Power (W)	1200	1200	1200
Region	American	UAE	Chinese
MIXERS			
	M1	M2	M3
% Price	100	48	28
Rated Power (W)	200	200	200
Region	European	Chinese	Chinese
JUICERS			
	J1	J2	J3
% Price	100	80	50
Rated Power (W)	25	25	25
Region	European	American	Chinese

3.1 Goal and scope

The goal of this study is to conduct LCA of nine consumer products using Simapro software. Three products of same category but of different price ranges and produced by different manufacturers are selected. The main objective of the study is to analyze the influence of price on the environmental impacts of products of same power rating. Moreover, the influence of manufacturer and their design approach on environmental impacts are studied.

3.2 Functional unit

The functional unit in LCA describes the function of the products used in the study. Functional unit helps to normalize the environmental impact results across various products. All the impacts are related to the functional unit of the products. For this study, the functional unit of iron is considered as ironing 1.0 m² of cloth daily. For hand mixer, the functional unit is to mix 1.0 liter of mixture daily and for the juicer is to produce 0.5-liter juice per day. These functional units are selected based upon the average use of these products. Functional life of all the products is assumed to be three years as this represents the warranty period provided by their respective manufacturers.

3.3 System boundaries

Figure 14 shows the system boundary of this analysis. Raw material extraction, manufacturing, distribution, and use phase of the products are included in LCA. Data of recycling of consumer products in KSA is scant. Therefore, end-of-life analysis will be conducted using appropriate assumption about recycling rates of various materials.

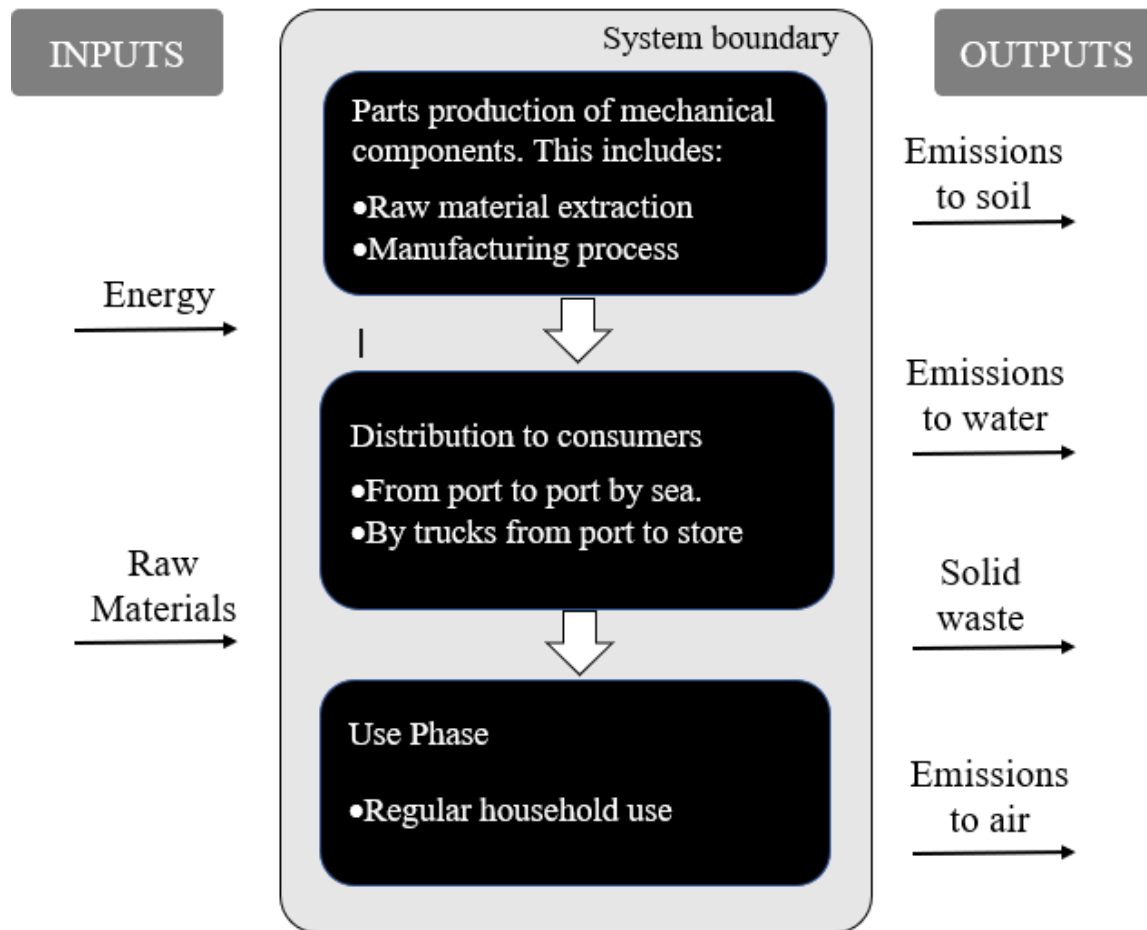


Figure 14 : System boundaries

3.4 Life cycle inventory

The life cycle inventory (LCI) is essential to conduct LCA. The process of obtaining LCI for the products used for this study is described next.

3.4.1 LCI of Irons

To compare the design and environmental impacts of irons a significant amount of inventory data is collected about materials, manufacturing processes, electrical energy consumption and transportation. First step was to measure energy consumed by each iron.

Energy meter was used to measure power consumption of three irons. It was assumed that each iron will be used for 18 minutes daily for ironing clothes. Table 2 summarizes the power consumption of three irons and it can be seen that the three irons consumed different amounts of power.

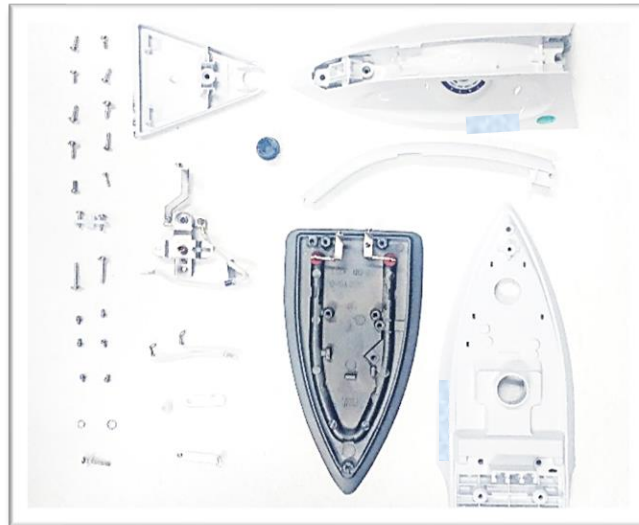
In order to collect the information about materials and manufacturing processes three irons were disassembled. Figure 15 shows the teardown picture of three irons. For weight comparison, these products were divided into subassemblies. Comparative weights of three irons and their corresponding subassemblies are shown in Figure 16. Next the weight and material of each component was determined. Moreover, manufacturing process for each component was identified using secondary data. The summary of components weights, materials and manufacturing processes are given in Table 3 and

Table 4. Comparative weight of materials used in each product is shown in Figure 17.

Table 2 : Power consumed by three irons

Irons	I1	I2	I3
Power consumed (W)	1006	991	1124
Energy used for complete life (kWh)	313.8	309.2	350.7

(a)



(b)



(c)



Figure 15 : Teardown pictures of (a) I1 (b) I2 (c) I3

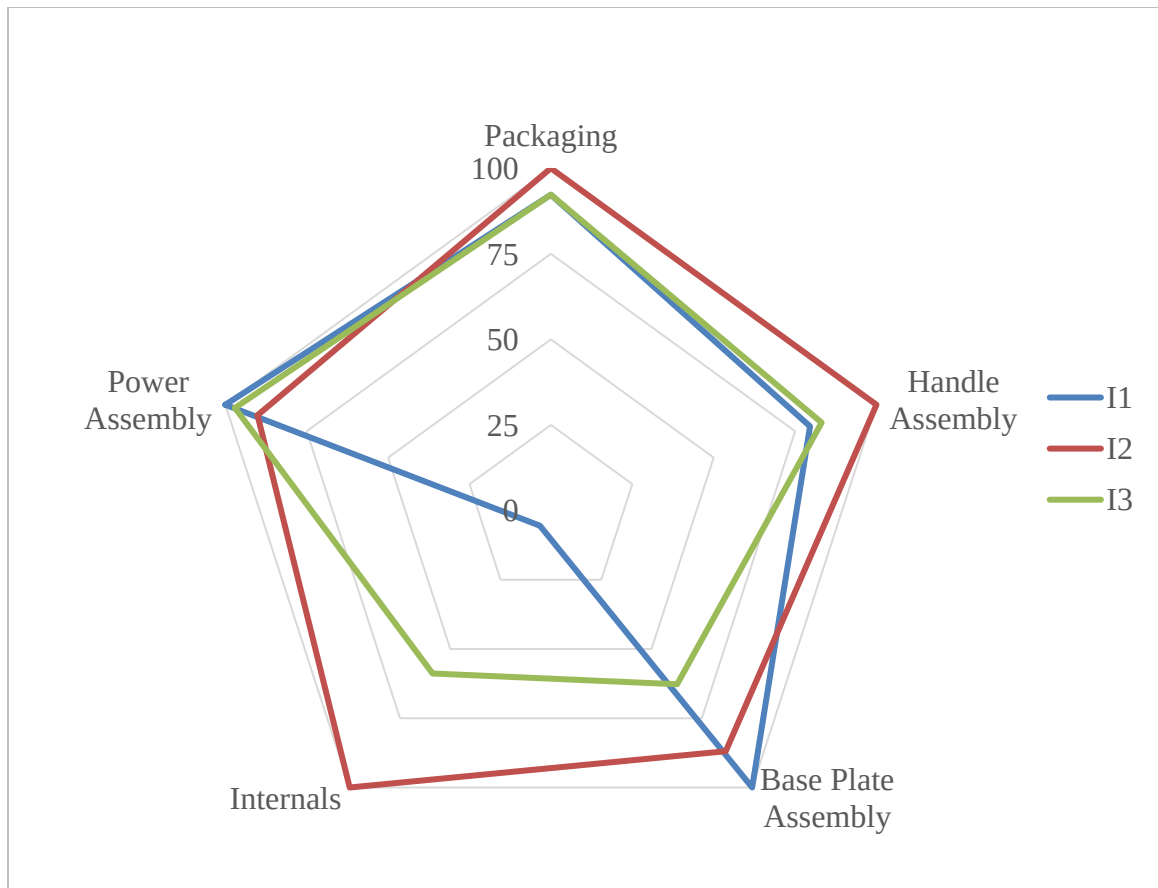


Figure 16 : Comparative weight of sub-assemblies of three irons

Table 3 : LCI of materials used in three Irons

Materials	I1 (g)	I2 (g)	I3 (g)	Simapro database
Polycarbonate	132	-	-	Polycarbonate {GLO} market for APOS, S
Polypropylene	24	-	516	Polypropylene, granulate {GLO} market for APOS, S
Printed Paper	17	17	22	Paper, newsprint {RER} market for APOS, S
Cardboard Storage	101	106	104	Cartonboard sheets, technology mix, production mix, at plant, 46% primary fiber, 54% recovered fiber, EU-27 S
Aluminum	275	207	160	Aluminum, primary, cast alloy slab from continuous casting {GLO} market for APOS, S
Steel Unalloyed	22	145	-	Steel, unalloyed {GLO} market for APOS, S
Cast Iron	-	466	-	Cast iron {GLO} market for APOS, S
Polystyrene	-	21	-	Polystyrene, expandable {GLO} market for APOS, S
Polyamide	-	190	-	Polyamide 6.6 fibers (PA 6.6), from adipic acid and hexamethylene diamine (HMDA), prod. mix, EU-27 S
Steel Chromium	2	18	23	Steel, chromium steel 18/8 {GLO} market for APOS, S
Brass	3	3	3	Brass {CH} market for brass APOS, S
Cable	158	159	174	Cable, unspecified {GLO} market for APOS, S
Copper	4	2	3	Copper {GLO} market for APOS, S
Ceramic	6	4	3	Ceramics {GLO} market for APOS, S
Steel, Low alloyed	32	13	13	Steel, low-alloyed {GLO} market for APOS, S
Polyethylene	128	3	4	Polyethylene, low density, granulate {GLO} market for APOS, S

Table 4 : LCI of processes used in three Irons

Processes	I1	I2	I3	Simapro Database
Aluminum Casting (g)	275	207	160	Casting, aluminum, lost-wax {GLO} market for APOS, S
Powder coat (cm ²)	225	225	300	Powder coat, aluminum sheet {GLO} market for APOS, S
Deep drawing (g)	22	163	23	Deep drawing, steel, auto mode {GLO} market for APOS, S
Injection molding (g)	277	197	517	Injection molding {GLO} market for APOS, S
Blow molding (g)	-	15	-	Blow molding {GLO} market for APOS, S
Extrusion of plastic sheets (g)	5	2	3	Extrusion of plastic sheets and thermoforming, inline {GLO} market for APOS, S
Hot rolling of steel (g)	32	13	13	Hot rolling, steel {GLO} market for APOS, S
Sheet rolling of copper (g)	4	2	2	Sheet rolling, copper {GLO} market for APOS, S
Contouring of brass (g)	3	3	3	Contouring, brass {GLO} market for APOS, S
Electricity (kWh)	313.8	309.1	350.6	Electricity, low voltage {SA} market for APOS, S
Ocean freighter (kg.km)	10145	9042	11434	Transport, ocean freighter, average fuel mix/US
Road transportation (kg.km)	136.9	1426	154.3	Transport, combination truck, average fuel mix/US

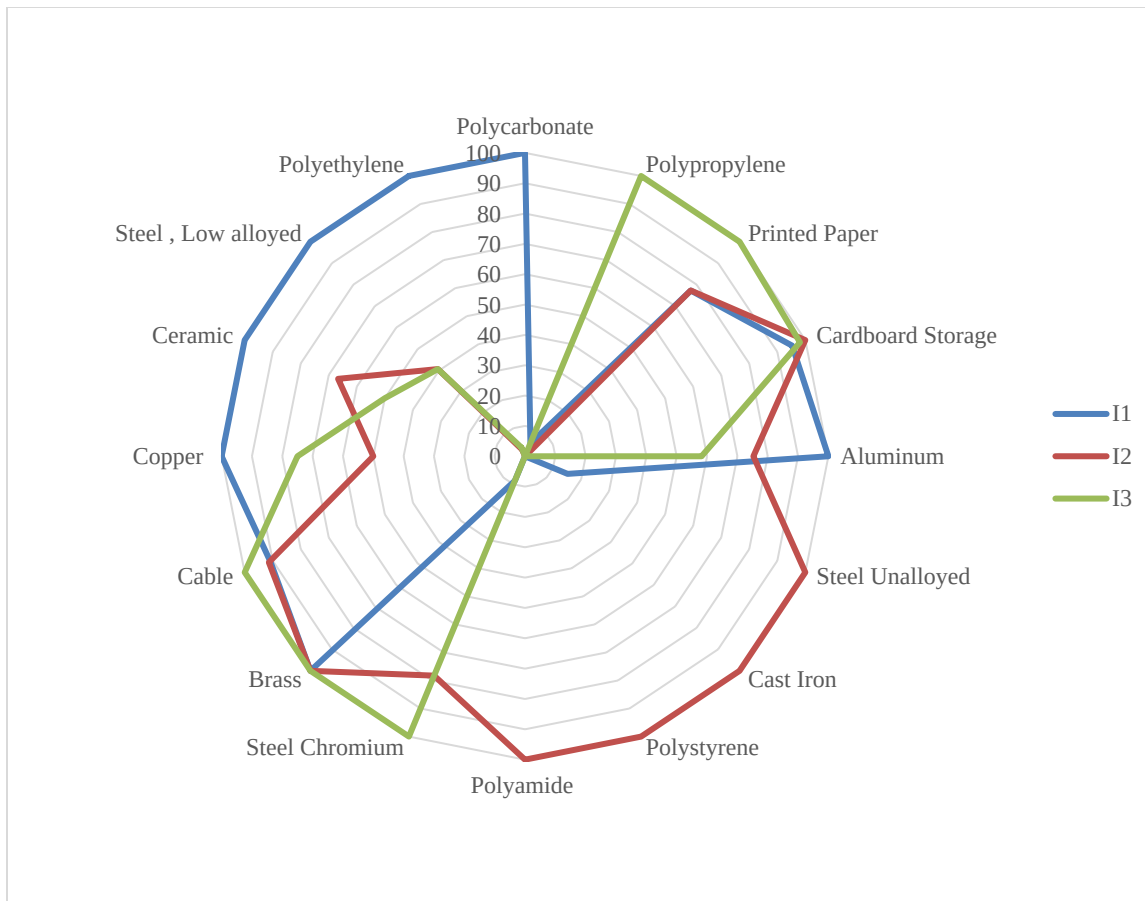


Figure 17 : Comparative weight of materials in each Iron

3.4.2 LCI of Hand Mixers

LCI of hand mixes was compiled using the similar steps as for irons. First the energy consumption of each hand mixer was measured using an energy meter. The functional unit for each hand mixer was assumed to be mixing of 1 liters of mixture. Average time for this operation was found to be 8.5 minutes. The energy consumed by each hand mixer is summarized in Table 5. It can be seen that there is a considerable difference in the energy consumed by three hand mixers. After measuring the energy consumption, hand mixers were disassembled (Figure 18) and different assemblies were weighed (Figure 19). The material and manufacturing processes used for hand mixers was determined. The summary of component weights, materials and manufacturing processes is given in Table 6 and Table 7. Comparative weight of materials used in each product is shown in Figure 20.

Table 5 : Power consumed by each hand mixers

Hand Mixers	M1	M2	M3
Power consumed (W)	64.1	82	88
Energy used for complete life (kWh)	9.9	12.7	13.7

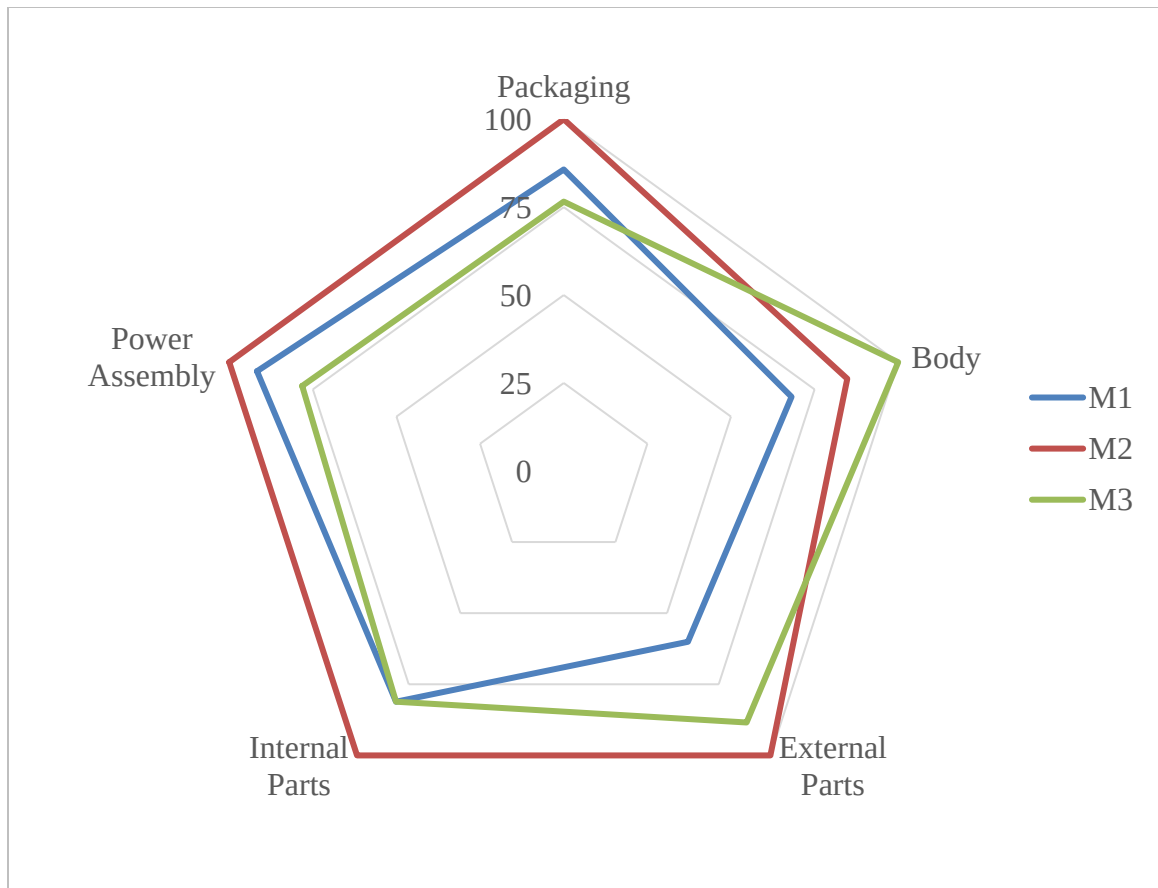


Figure 19 : Comparative weight of sub-assemblies of each hand mixer

Table 6 : LCI of materials used in each Hand Mixer

Materials	M1(g)	M2(g)	M3(g)	Simapro database
Cotton Bag	7	-	-	Textile, woven cotton {GLO} market for APOS, S
Rubber	3	2	3	Synthetic rubber {GLO} market for APOS, S
Printed Paper	26	22	20	Paper, newsprint {RER} market for APOS, S
Cast Iron	57	56	58	Cast iron {GLO} market for APOS, S
Cardboard Storage	115	144	106	Carton board sheets, technology mix, production mix, at plant, 46% primary fiber, 54% recovered fiber, EU-27 S
Polyamide	2	4	3	Polyamide 6.6 fibers (PA 6.6), from adipic acid and hexamethylene diamine (HMDA), prod. mix, EU-27 S
Steel Chromium	58	187	158	Steel, chromium steel 18/8 {GLO} market for APOS, S
ABS	250	285	318	Acrylonitrile butadiene styrene (ABS)/EU-27
Cable	100	93	99	Cable, unspecified {GLO} market for APOS, S
Steel, Low alloyed	234	256	180	Steel, low-alloyed {GLO} market for APOS, S
Copper	52	69	47	Copper {GLO} market for APOS, S
PA GF	6	10	6	Nylon 6 glass filled (PA 6 GF), production mix, at plant RER
Polyethylene	-	7	6	Polyethylene, high density, granulate, recycled {RoW} market for APOS, S

Table 7 : LCI of processes used in each Hand Mixer

Processes	M1	M2	M3	Simapro Database
Injection moulding (g)	253	299	327	Injection moulding {GLO} market for APOS, S
Drawing of pipe (g)	48	176	144	Drawing of pipe, steel {GLO} market for APOS, S
Wire drawing, steel (g)	2	3	2	Wire drawing, steel {GLO} market for APOS, S
Hot rolling, steel (g)	8	9	12	Hot rolling, steel {GLO} market for APOS, S
Sheet rolling, copper (g)	3	3	3	Sheet rolling, copper {GLO} market for APOS, S
Impact extrusion of steel (g)	234	256	180	Impact extrusion of steel, cold, 1 strokes {GLO} market for APOS, S
Wire drawing, copper (g)	49	66	44	Wire drawing, copper {GLO} market for APOS, S
Weaving (g)	7	-	-	Weaving, bast fiber {GLO} market for APOS, S
Extrusion, plastic (g)	-	7	6	Extrusion, plastic film {GLO} market for APOS, S
Electricity (kWh)	9.9	12.7	13.7	Electricity, low voltage {SA} market for APOS, S
Ocean freighter (kg.km)	10323	9042	11334	Transport, ocean freighter, average fuel mix/US
Road transportation (kg.km)	139.3	1050	153	Transport, combination truck, average fuel mix/US

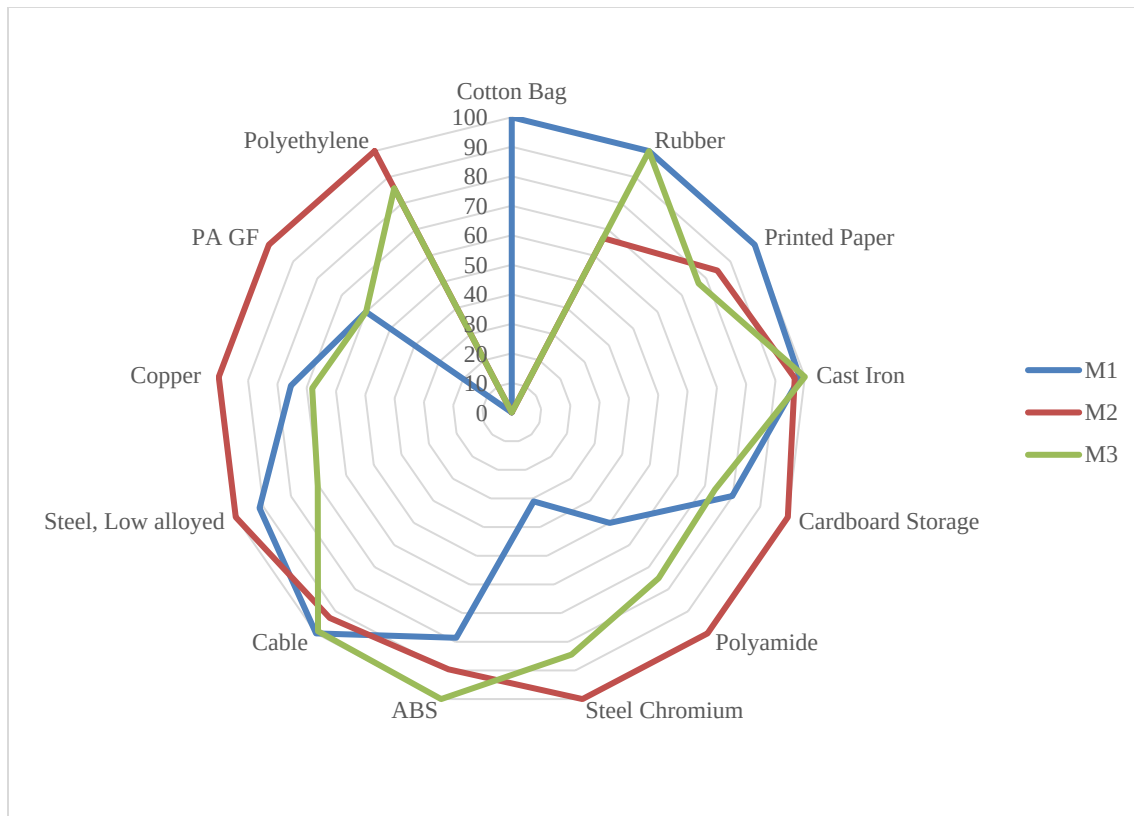


Figure 20 : Comparative weight of materials in each Hand Mixer

3.4.3 LCI of Juicers

Following the same steps, LCI of juicers was developed. First energy consumption was measured. It was assumed that each juicer will be used for extracting 0.5 liters of juice daily which corresponds to average time of three minutes. Results of energy consumption are shown in Table 8. Next the juicers were disassembled (Figure 21) and sub-assemblies of each product are weighted (Figure 22). The LCI data collected about weights, materials, and manufacturing of each component of all three juicers is summarized in Table 9 and Table 10. Comparative weight of materials used in each product is shown in Figure 23

Table 8 : Power consumed by each juicers

Juicers	J1	J2	J3
Power consumed (W)	7.5	11.5	14
Energy used for complete life (kWh)	0.4	0.6	0.7

(a)



(b)



(c)



Figure 21 : Teardown pictures of (a) J1 (b) J2 (c) J3

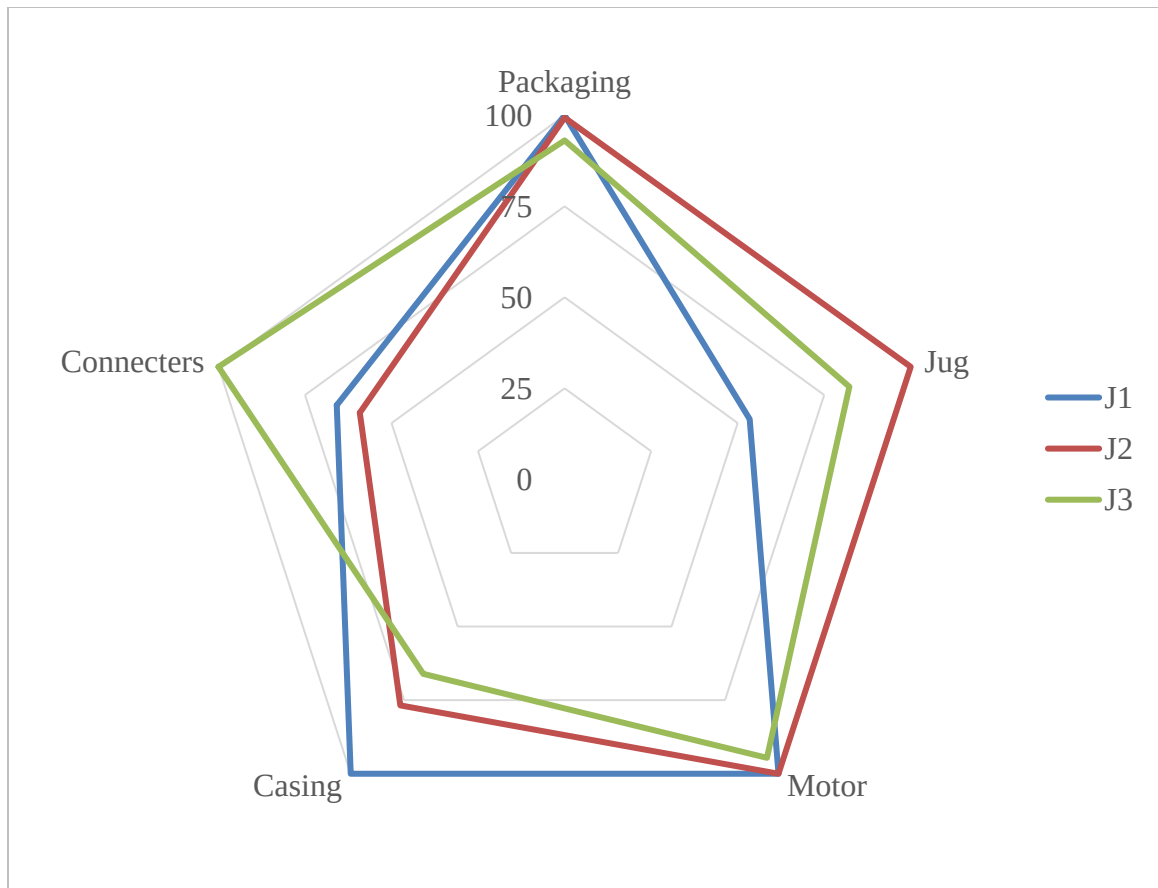


Figure 22 : Comparative weight of sub-assemblies of each juicer

Table 9 : LCI of materials used in each Juicer

Materials	J1 (g)	J2 (g)	J3 (g)	Simapro database
Polystyrene	-	-	4	Polystyrene foam slab {RoW} production APOS, S
Styrene-acrylonitrile	-	202	186	Styrene-acrylonitrile copolymer {RoW} production APOS, S
Steel Unalloyed	71	70	72	Steel, unalloyed {RoW} steel production, converter, unalloyed APOS, S
Cardboard Storage	141	116	117	Corrugated board box {GLO} market for corrugated board box APOS, S
Polyethylene	29	31	33	Polyethylene, high density, granulate, {RoW} market for polyethylene, high density, granulate,
Steel Chromium	2	13	4	Steel, chromium steel 18/8 {GLO} market for APOS, S
Rubber	-	2	-	Synthetic rubber {GLO} market for APOS, S
Polypropylene	336	542	185	Polypropylene granulate {GLO} market for APOS, S
Printed Paper	19	38	12	Printed paper {GLO} market for APOS, S
Permanent Magnet	19	18	15	Permanent magnet, for electric motor {GLO} production APOS, S
Copper	27	30	26	Copper {GLO} market for APOS, S
Cable	76	62	114	Cable, unspecified {GLO} market for APOS, S
Cast Iron	2	-	2	Cast iron {GLO} market for APOS, S

Table 10 : LCI of processes used in each Juicer

Processes	J1 (g)	J2 (g)	J3 (g)	Simapro Database
Sheet rolling, steel (g)	69	78	70	Sheet rolling, steel {GLO} market for APOS, S
Extrusion, plastic (g)	-	5	6	Extrusion, plastic film {GLO} market for APOS, S
Polymer foaming (g)	-		4	Polymer foaming {GLO} market for APOS, S
Injection moulding (g)	366	476	398	Injection moulding {GLO} market for APOS, S
Wire drawing, copper (g)	26	28	24	Wire drawing, copper {GLO} market for APOS, S
Electricity (kWh)	0.4	0.6	0.7	Electricity, high voltage {SA} production mix APOS, S
Ocean freighter (kg.km)	6843.9	8889.6	8556.2	Transport, ocean freighter, average fuel mix/US
Road Transportation (kg.km)	108.45	120	115.5	Transport, combination truck, average fuel mix/US

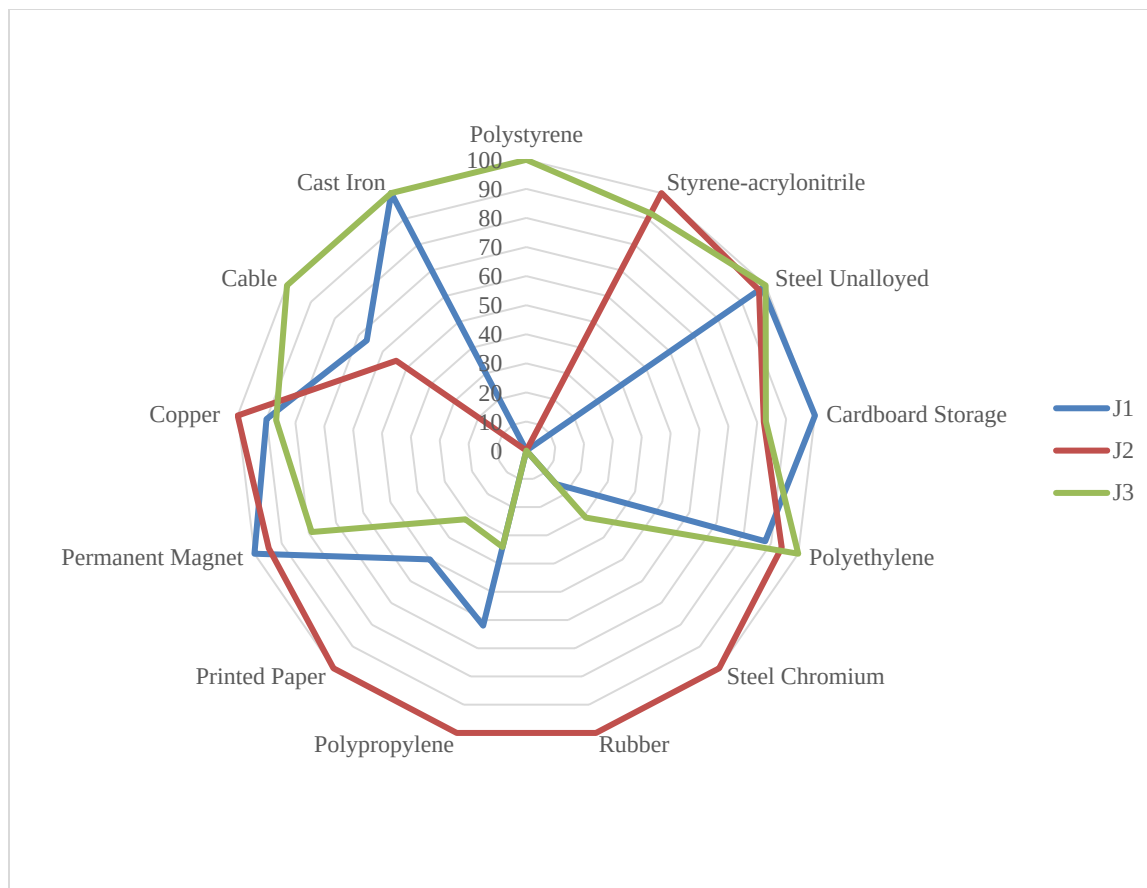


Figure 23 : Comparative weight of materials in each Juicer

The impact assessment of these products was conducted using Simapro. The results of the assessment are presented in the next chapter.

CHAPTER 4

RESULTS AND DISCUSSIONS

In this chapter, the results of LCA are presented and explained. The relationship between environmental impacts and price is discussed in detail. The results of sensitivity analysis for various end-of-life scenarios are also given.

4.1 Environmental impact assessment

After gathering life cycle inventory data, LCA model was developed in SimaPro. First, ReCiPe midpoint (H) v1.01 method was used to determine potential environmental impacts of each product. Next, ReCiPe endpoint (H) v1.01 method was employed to conduct overall assessment for these products. ReCiPe (H) midpoint impact categories included in this study are global warming, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, human carcinogenic toxicity and human non-carcinogenic toxicity.

Global warming impact category quantifies the amount (kg) of CO₂ released for the whole life cycle of a product [17]. Terrestrial acidification is the acidification potential due to emission of SO₂ during the lifecycle of a product [17]. Freshwater eutrophication impact category accounts for discharge of chemicals that contains phosphorous (P) [17]. Terrestrial ecotoxicity, human carcinogenic toxicity and human non-carcinogenic toxicity impact classifications account for toxicity effect of chemicals accumulated in human foods. The unit used for these categories is 1,4-dichlorobenzene (1,4-DCB) kg/yr. [17].

ReCiPe endpoint (H) damage categories are three: human health, ecosystem, and resource. Damage category of human health has the units of DALYs (disability adjusted life years) which represent “the years that are lost or that a person is disabled due to a disease or accident” [16]. The unit for ecosystem quality is species*year which represents “the local species loss integrated over time” [16]. The unit for resource is dollars (\$), which represents “the extra costs involved for future mineral and fossil resource extraction” [16].

4.1.1 Environmental impacts of irons

ReCiPe midpoint results for irons are shown in Figure 24. Of the selected six environmental impact categories, I3 showed the highest impacts in three categories. While, in other three categories I2 showed the highest impacts. From this, it can be inferred that I1 showed the lowest impacts. From Figure 24 it is clear that the most detrimental phase is the usage phase for all three irons. Comparison of assemblies show that base plate assembly and power assembly have comparable impacts. Moreover, internal parts have less impacts than base plate assembly and power assembly. While, other phases and assemblies like transportation, packaging and handle assembly have negligible impacts. The results of each impact category are discussed below.

- Global warming impact: In this impact category, usage phase is the most detrimental phase for all three irons. Comparison of the impacts of only the usage phase showed that I3 has highest, I1 medium, while I2 has lowest impacts during the usage phase. The large impacts internal part assembly of I2 is due to steel and cast-iron parts. Of all other assemblies only the base plate assembly contributes considerably in this impact category. Overall, from Figure 24 it can be seen that I3 showed highest impacts in this category.

- Terrestrial acidification: Like global warming impact, in this impact category most impacts are due to the usage phase of the products. In this category base plate assembly also plays significant role to determine overall impacts. From Figure 24 it is clear that I3 showed highest impacts in this category. The difference between I1 and I2 impacts is marginal.
- Water eutrophication: In this impact category usage phase, power assembly and base plate assembly show considerable impacts. For I1 and I3 internal parts showed considerable impacts but its impacts are less than usage phase, power assembly and base plate assembly. Conversely, I2 showed considerably more impacts in internal parts assembly mainly due to the use of cast iron and steel parts.
- Terrestrial ecotoxicity: In this category, like impact categories of global warming and terrestrial acidification usage phase showed highest impacts. Second most detrimental assembly is the power assembly. Only in I2 internal parts showed comparable impacts to power assembly. All other phases and assemblies were insignificant.
- Human carcinogenic toxicity: Like water eutrophication impact category, in this impact category usage phase, power assembly and base plate assembly showed substantial impacts. For I1 and I3 internal parts showed almost negligible impacts. But for I2, more impacts are observed in internal parts assembly mainly due to the use of cast iron and steel parts. Difference between I1 and I3 is marginal in this category as shown in Figure 24.

- Non-carcinogenic toxicity: In this impact category, usage phase and power assembly showed the highest impacts. Internal parts and base plate assembly showed minor impacts while packaging material, handle assembly and transportation showed almost negligible impacts.



Figure 24 : Midpoint environmental impact results of irons.

4.1.2 Environmental impacts of hand mixers

Figure 25 depicts midpoint results for hand mixers. Results showed that of selected six environmental impacts categories, M3 showed the highest impacts in two categories, while in other four categories M2 showed the highest impacts. Figure 25 depicts that both usage and manufacturing phases are important to determine environmental performance of the hand mixers. Comparison of assemblies shows that motor assembly and external parts assembly have comparable impacts, while internal parts have significantly less impacts. Remaining phases and assemblies like transportation, packaging and body assembly almost have negligible impacts. Result of each impact category is discussed below.

- **Global warming impact:** In this impact category, usage phase is the most detrimental phase for all three hand mixers. Other assemblies like motor assembly, external part and body assembly also play significant role in determining the impact of global warming. M1 showed significantly low impact in this category compared to other hand mixers, mainly due to efficient energy usage.
- **Terrestrial acidification:** Like global warming impact, in this impact category highest impacts are due to the usage phase of the products. In this category motor assembly also plays significant role to determine overall impacts. Overall, M3 showed highest impacts in this category while M1 showed lowest impacts. Efficient energy use is the reason that M1 is showing lowest impacts.
- **Water eutrophication:** Unlike other two impact categories discussed previously, in this impact category motor assembly and external parts assembly showed highest impacts. While usage phase and internal part assembly showed comparatively low

impacts. Motor assembly of M3 used material efficiently due to which it shows lowest impact in this category. From Figure 25 it is clear that difference between impacts of M1 and M2 in this category is marginal.

- Terrestrial ecotoxicity: In this impact category, like impact categories of water eutrophication, motor assembly and external parts assembly showed highest impacts. Second most significant phase is the usage phase. Motor assembly of M3 has lowest impacts while usage phase of M1 has lowest impacts.
- Human carcinogenic toxicity: Similar to terrestrial ecotoxicity impact category, in this impact category motor assembly and external parts assembly showed highest impacts. Second most significant phase is usage phase. Motor assembly of M3 has lowest impact while usage phase of M1 has lowest impact. Also, external part assembly of M1 showed lowest impact. From Figure 25 it is clear that in this impact category M2 showed highest impacts while M1 showed lowest impacts.
- Non-carcinogenic toxicity: In this impact category, motor assembly and external parts assembly showed highest impacts. Packaging material, handle assembly and transportation showed almost negligible impacts.

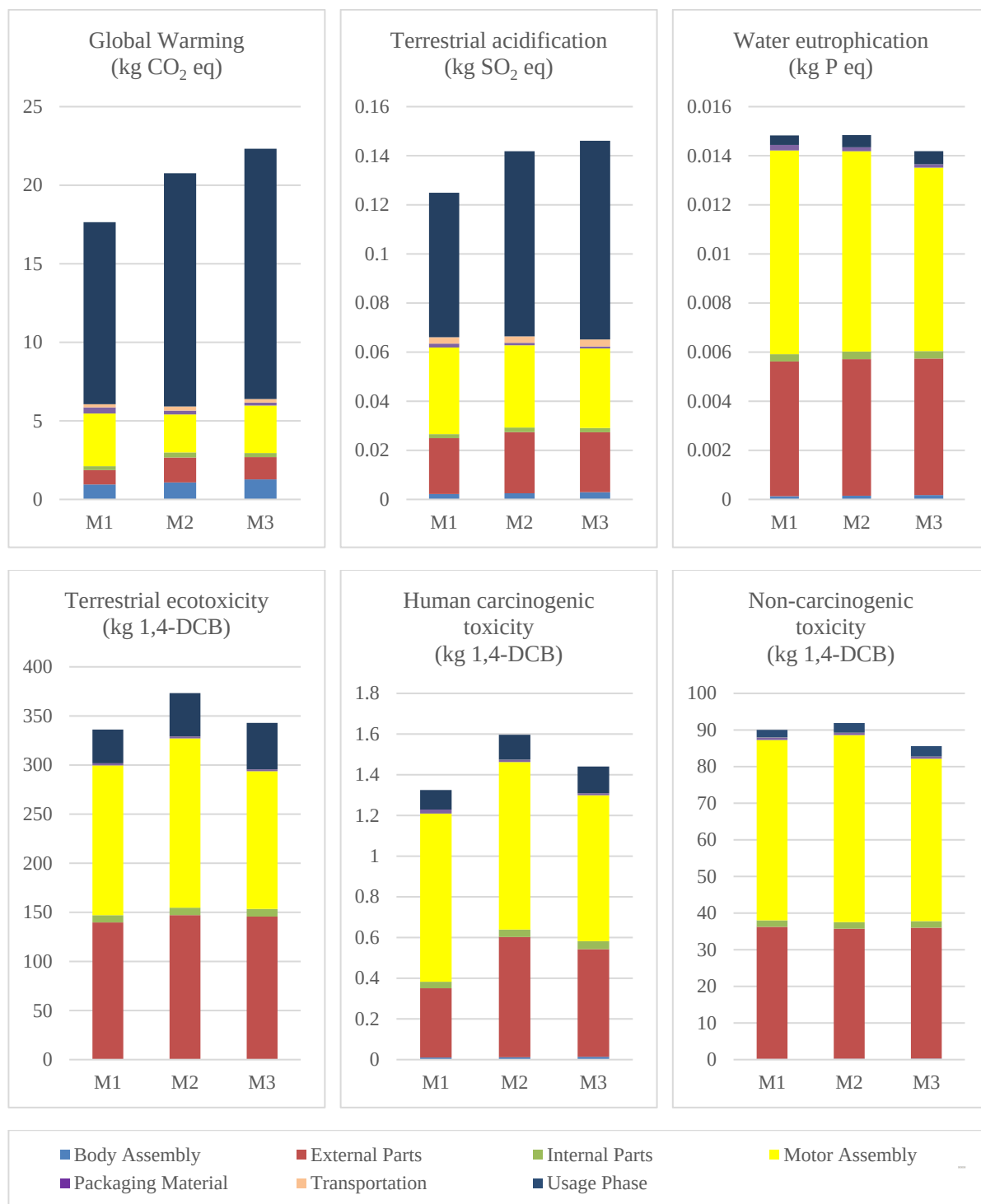


Figure 25 : Midpoint environmental impact results of hand mixers.

4.1.3 Environmental impacts of juicers

ReCiPe midpoint results of juicers are displayed in Figure 26. It shows that J1 juicer is more environment friendly than J2 and J3 in several environmental categories. Result of each impact category is discussed below.

- **Global warming impact:** In this impact category, all parts excepts for packaging contributes considerably toward environmental impacts. It is clear from results that motor assembly of J1 has more environmental impacts than motor assembly of J2 and J3. However, for all other assemblies J1 has lowest impacts. Due to which total global warming impacts of J1 juicer are lowest.
- **Terrestrial acidification:** The main contributor to this category is casing assembly which is mainly composed of polypropylene, copper switches and cable. In this impact category J3 has maximum value, while a marginal difference in observed between J1 and J2.
- **Water eutrophication:** In this impact category motor assembly and casing assembly contributes significantly towards environmental impacts. It is clear from the results that J3 showed highest impacts in this category while J2 showed the lowest impacts.
- **Terrestrial ecotoxicity:** Similar to other impact categories J3 showed highest impacts in this category. Comparing J1 and J2 a marginal difference can be observed between them. Comparison of sub-assemblies showed that, motor assembly and casing assembly has the highest impacts in all three juicers.

- Human carcinogenic toxicity: In this impact category, like other categories motor assembly and casing assembly has the highest impacts for all three products. Comparison of results showed that J3 has highest impacts. A marginal difference can be observed between J1 and J2.
- Non-carcinogenic toxicity: Sub-assemblies of motor assembly and casing assembly have the highest impacts in this impact category for all three Juicers. Similar to other categories J3 showed highest impacts in this impact category.

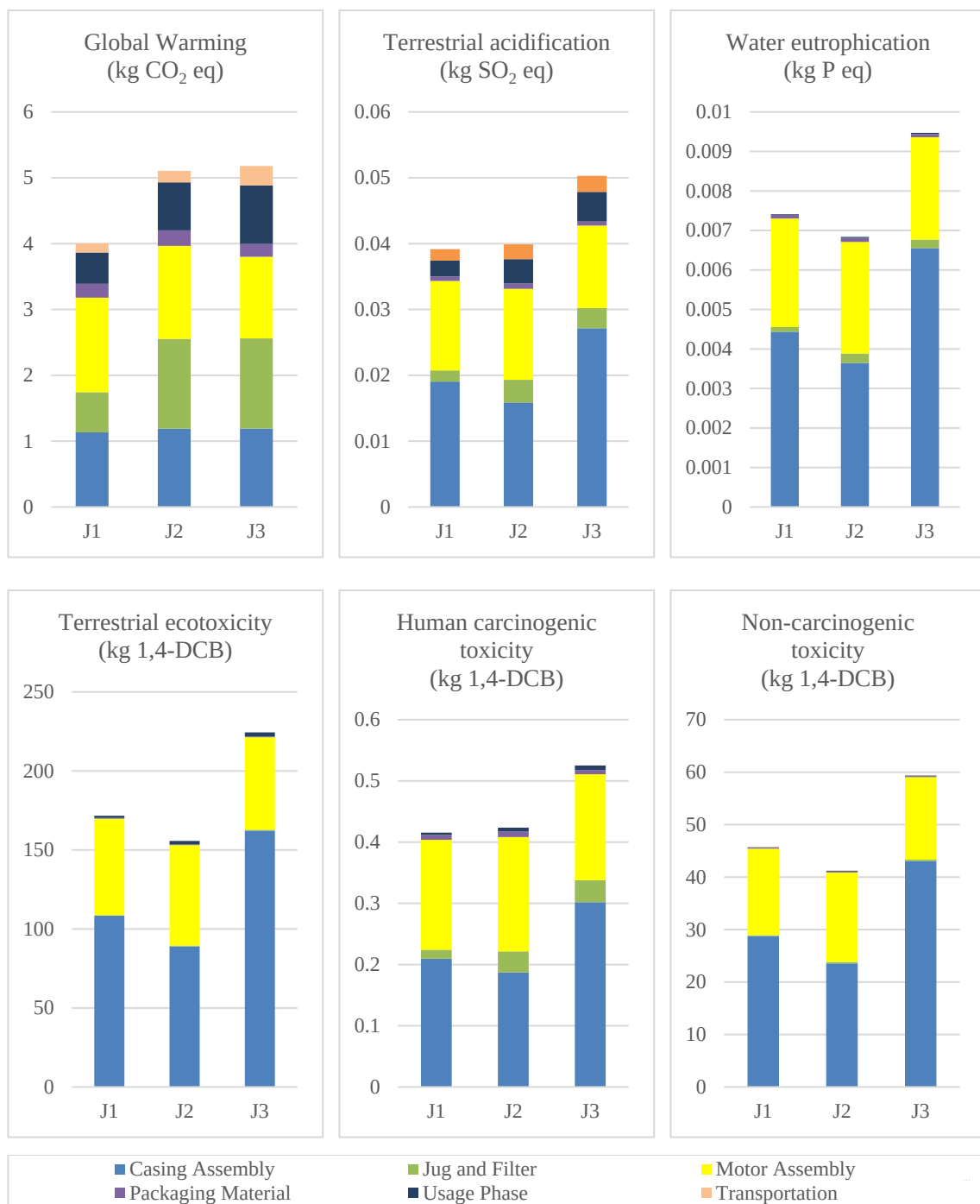


Figure 26 : Midpoint environmental impacts results of juicers.

4.1.4 Endpoint damage categories results of all nine consumer products

Figure 27 shows endpoint damage categories of human health, ecosystem, and resource for all nine products. In case of irons, I3 overall has larger impacts as compared to I1 and I2. In case of hand mixers, M1 has the lowest environmental impacts in all damage categories due to its compact design and efficient motor. On the other hand, M3 has the highest impacts in all three damage categories. In case of juicers, J1 has the lowest environmental impacts while J3 has the highest impacts. The difference between J1 and J2 in damage categories of human health and ecosystems is marginal. Again, compact design and efficient motor of J1 is responsible for low environmental impacts. Figure 28 compares the environmental impacts of use phase with environmental impacts of manufacturing phase. It can be seen that for irons the use phase is most damaging to the environment whereas for juicers the manufacturing phase is the most damaging. For hand mixers both use and manufacturing phases are equally responsible for environmental impacts.

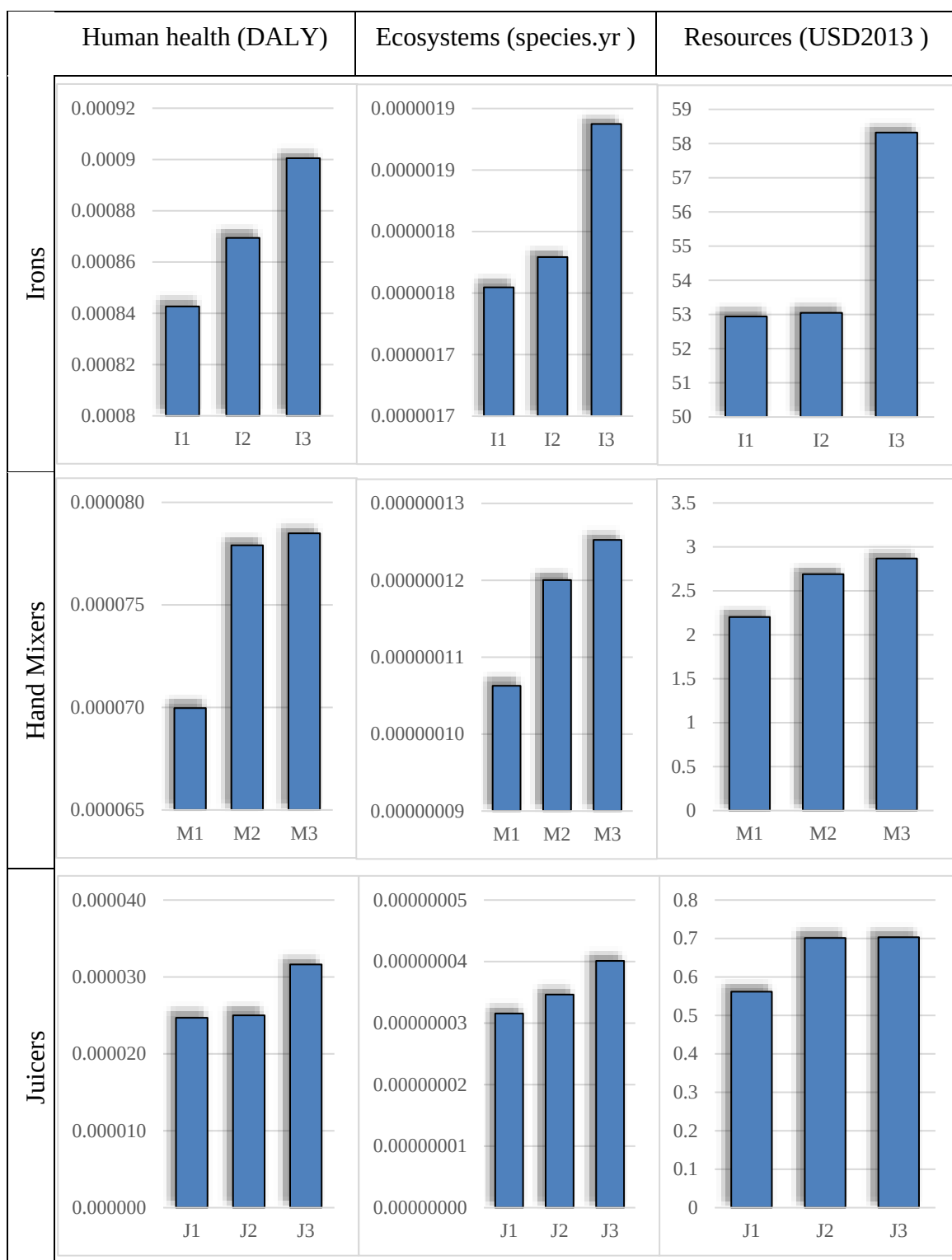


Figure 27 : Endpoint Damage categories for all three products

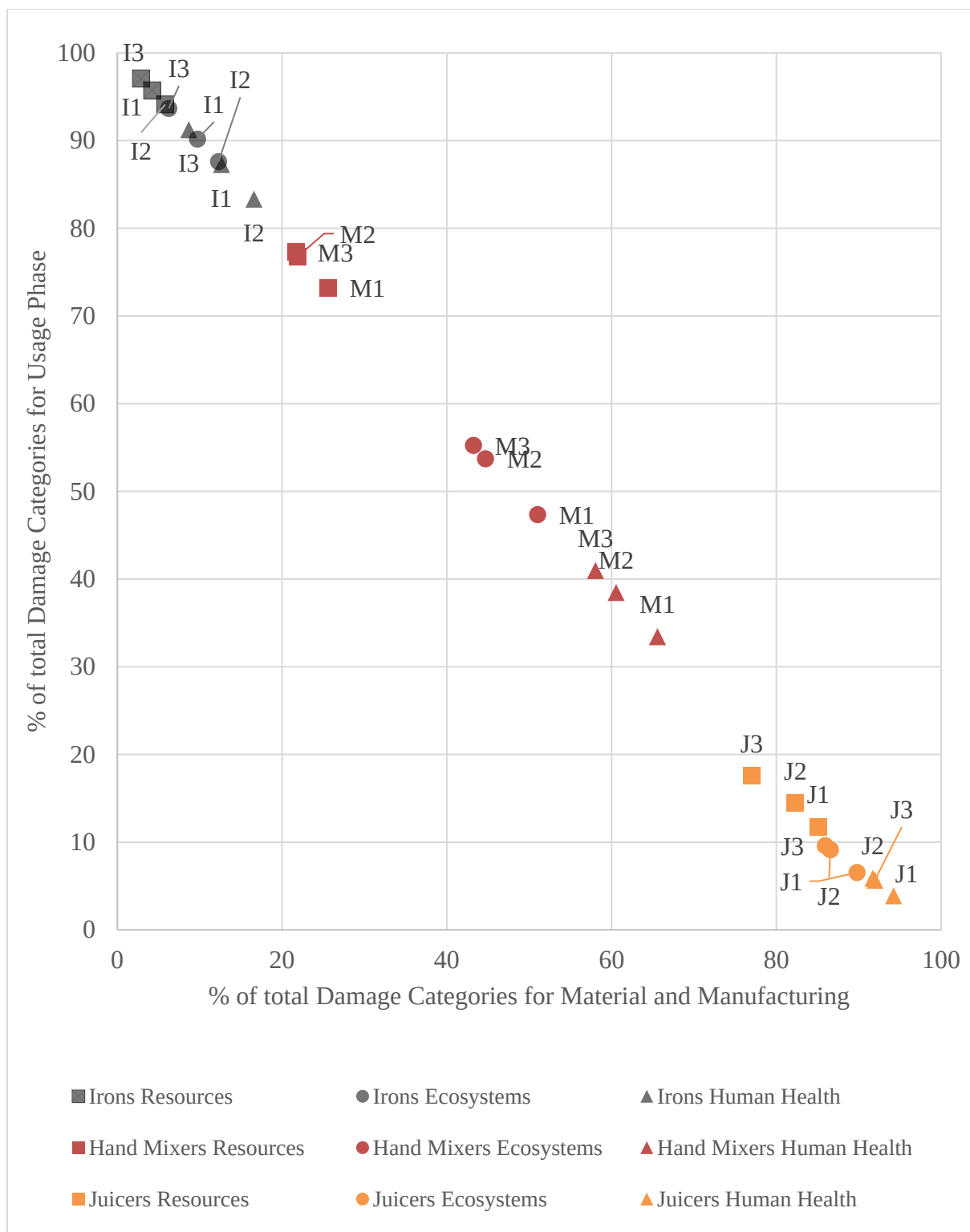


Figure 28 : Comparison of Endpoint damage categories of usage phase and material/manufacturing phase of all three consumer products.

4.2 Relationship of price and environmental impact

Table 11 shows the comparison of end point damage categories of all consumer products used in this thesis. It can be inferred from the table that in all three consumer products low-priced products are the most damaging to the environment. It also important to note that even though expensive products are performing better than low cost products, the impacts of mid-range products are not very different than expensive products.

Table 11 : Comparison of Endpoint damage categories of all the products

Damage Categories	Values			% Differences		
	I1	I2	I3	I1	I2	I3
Human Health (DALY)	0.000843	0.000869	0.000901	93.58	96.55	100
Ecosystems (species.yr)	1.75×10^{-06}	1.78×10^{-06}	1.89×10^{-06}	92.97	94.27	100
Resources (USD2013)	52.94205	53.04689	58.32323	90.77	90.95	100
	M1	M2	M3	M1	M2	M3
Human Health (DALY)	7.00×10^{-05}	7.79×10^{-05}	7.85×10^{-05}	89.14	99.26	100
Ecosystems (species.yr)	1.06×10^{-07}	1.20×10^{-07}	1.25×10^{-07}	84.85	95.83	100
Resources (USD2013)	2.202287	2.689526	2.868421	76.78	93.76	100
	J1	J2	J3	J1	J2	J3
Human Health (DALY)	2.47×10^{-05}	2.50×10^{-05}	3.16×10^{-05}	78.07	79.07	100
Ecosystems (species.yr)	3.16×10^{-08}	3.46×10^{-08}	4.01×10^{-08}	78.69	86.36	100
Resources (USD2013)	0.561735	0.701369	0.703269	79.87	99.73	100

In case of irons, the expensive iron is showing 6%, 7%, and 9% less impacts than low cost iron in three end point categories of human health, ecosystems, and resources. The medium priced iron shows 4%, 6%, and 9% less impacts than the low cost iron. This shows that both high and medium price iron is performing better than the low cost iron. This clearly depicts that expensive iron is more environment friendly as compared to the low cost iron. In case of hand mixers, the expensive hand mixer is depicting 11%, 15%, and 24% lower impacts in end point categories as compared to the low-cost hand mixer. This clearly depicts the superiority of expensive hand mixer in terms of environmental performance. However, it is interesting to note that the mid-priced hand mixer is only 1%, 4%, and 6% better than the low-cost hand mixer in three end point categories. It indicates that expensive hand mixer is using a much better approach in design to reduce the environmental impacts. For juicers, again the expensive juicer J1 is performing much better than low cost juicer. It is showing about 20% lower impacts in all three end point categories. The medium-priced juicer is closer to low cost juicer in three end point categories. It can be inferred from this comparison that expensive products are using better parts and a better design approach to reduce the environmental impacts.

4.3 Environmental impact comparison of similar products from different manufacturers

The environmental impacts produced by the three different irons manufactured by different manufacturers show a significant difference. The manufacturer of I1 iron is an American company, for I2 it is a UAE based company and for I3 it is a Chinese company. Considering the end point damage categories I1 is performing the best and I3 is performing the worst. Impacts of I2 is in between the two but more closer to I1. It can be inferred that Chinese

iron is using a design approach that results in more damage to the environment. The environmental impacts of different hand mixers manufactured by different manufacturers also show a significant difference. The manufacturer of M1 hand mixer is a European company. M2 and M3 both are manufactured in China. M1 shows significantly lower impacts in end point impact categories than M2 and M3. This is in part driven by use of efficient motor and optimal design. The manufacturer of J1 is a European company, for J2 it is an American company and for J3 it is a Chinese company. For all end-point categories J3 showed highest impacts and it can be inferred that this juicer is most detrimental to the environment. J1 has lower impacts than J3, and J2 impacts are in the middle. Again, it can be inferred that country of origin of these products is influencing the environmental impacts. In general, American and European companies are relying on more efficient power assemblies and optimal design to reduce environmental impacts.

4.4 End-Of-Life results of all three consumer products

End-of-life treatment of consumer products is the responsibility of local governments and waste management authorities. Due to lack of reliable data, end-of-life treatments were not included in the calculations. However, using appropriate assumptions, three end-of-life scenarios are presented in this section. This will help to evaluate that how recycling effects the environmental impacts of the consumer products considered for this study. Three scenarios developed for end-of-life treatment of the products are:

Scenario 1: It is assumed that after use all the products are dumped in a landfill with no recycling or reuse.

Scenario 2: It assumed that 25% of materials are recycled and remaining 75% goes in the landfill.

Scenario 3: It is assumed that 50% of materials are recycled and remaining 50% go to a landfill.

Figure 29 shows comparative ReCiPe endpoint damage category results for three end-of-life scenarios. It can be seen that by increasing the amount of material for recycling, the impacts are decreasing. It is depicted in the results that the base scenarios show marginally lower impacts than scenario 1. Scenarios 2 and 3 show lower impacts than base scenario due to increase in the amount of recyclability.

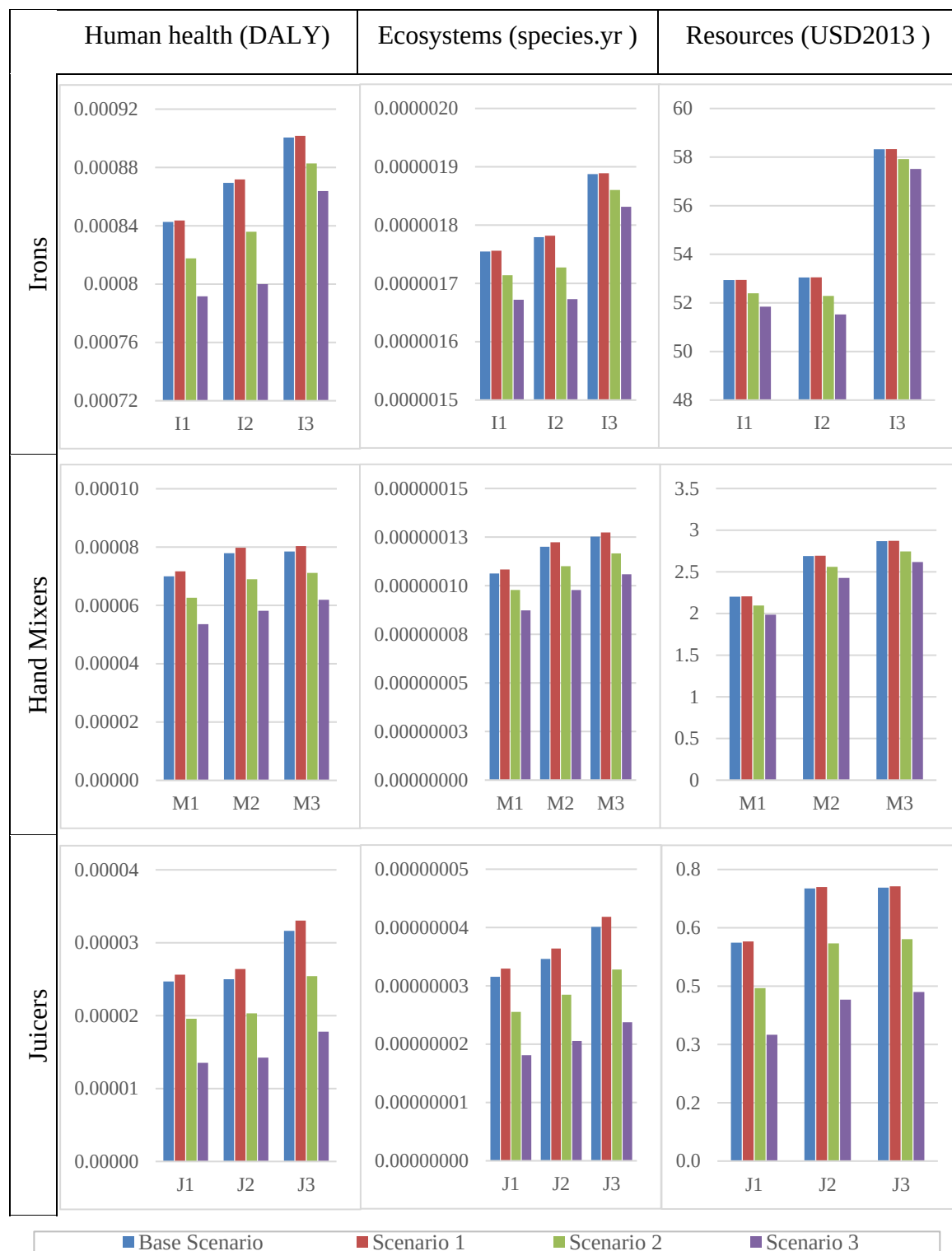


Figure 29 : Endpoint results of End-of-Life Scenarios of all three products

CHAPTER 5

CONCLUSIONS

5.1 Summary

In this thesis, a holistic approach was adopted to compare environmental impacts of nine consumer products. Domestic consumer products consist of a wide variety of devices and machines helping in various actions. The manufacturing of domestic consumer products has high importance nowadays. Increase in popularity of domestic consumer products has caused an increase in environmental impacts associated with these consumer products. Due to impending issues related to climate change, the manufacturers and designers of these consumer products are trying to optimize their products for better environmental performance.

In this thesis, LCA is used for assessment of sustainable design of consumer products. LCA is one of the most frequently used technique employed by researchers for assessment of sustainable design. In this study, comparison of sustainable design of different consumer products was conducted using two approaches. First approach was to compare sustainable design of consumer products and check whether price have any correlation with environmental impacts of these products. Second approach was to compare similar consumer products designed and manufactured by different manufacturers.

Nine products were acquired for this study. These products included three irons, three hand mixers, and three juicers designed, produced, and distributed by different manufacturers.

In addition, these products belonged to three different price ranges low, medium, and high. Energy consumption of these products were measured and then products were disassembled to generate a detailed list of components, materials, and processes used to manufacture them. SimaPro, was used to calculate environmental impacts.

The results of the study showed that there is a difference in environmental performance of products based upon their price and manufacturer. It is important to make customers aware of these differences so that they can make more informed choices while buying these products.

5.2 Contribution

Two main contributions of this thesis are as follows:

Studied the influence of price on environmental impacts of diverse consumer products.

First contribution of this research is to study the influence of price on the environmental performance of consumer products. The products selected for this study belonged to three different price ranges: low, medium, and high. Results of the study showed that in general the low-priced products have higher environmental impacts than expensive products.

Studied the environmental impacts of similar products designed and made by different manufacturers

Second contribution of this research is to show the influence of design on the environmental impact of consumer products. Different manufacturers employed different design strategies that led to difference in environmental performance of these products.

5.3 Limitations of the study

LCA studies are always limited by the richness of the data available for analysis. As more details about materials, manufacturing, and transportation become available, LCA becomes more robust. This study relied on collection of data about materials and manufacturing processes through teardown of the products. Specific limitations to this study are summarized below:

- As this study is performed independently from manufacturers of the products, the inventory data is obtained solely from disassembling of the products. Generic manufacturing processes are considered for the manufacturing of the products. This study can be immensely improved if performed in collaboration with the manufacturing firms of the products.
- The environmental impacts of raw material extraction are included in the study, but transportations associated with these raw materials to the main manufacturing plants was ignored due to unavailability of data.
- End of life analysis was based upon assumptions about percentage of recycling of various materials. Study can be improved by using actual data about recycling of these products in KSA.

5.4 Recommendations for future studies

This study can be further extended to include a variety of consumer products so that the relationship between price and environmental impacts can be studied in a much broader scope. One limitation of this study was that there was no access to manufacturers of consumer products. In future by including manufacturers in this study can help to analyze

the design and manufacturing process in detail. This can provide further insights that can lead to more environment friendly design of these products. Design strategies of various manufacturers can be extracted, and a guideline can be compiled that can help to share best practices for designing sustainable consumer products. This work can further be enhanced to provide guidelines for environmental labelling of consumer products. This can help customers to consider price and environmental impacts simultaneously while purchasing these products.

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Publications

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2. Masood, H., Shaukat, M. M., Is expensive more environment friendly? Comparative LCA of home appliances from different price ranges, journal of Cleaner Production, Under preparation.