AN INTEGRATED ECODESIGN METHODOLOGY FOR ELECTRICAL AND ELECTRONIC EQUIPMENT

(ELEKTRİKLİ VE ELEKTRONİK ALETLER İÇİN BÜTÜNLEŞİK BİR ÇEVRECİ TASARIM YÖNTEMİ)

by

İlke BEREKETLİ, M.S.

Thesis

Submitted in Partial Fulfillment

of the Requirements

for the Degree of

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İlke Bereketli

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Abstract

Industrial revolution has changed the production systems completely with its great contribution to the development of humanity. Nevertheless, its destructive consequences on the environment started to appear in the mid 20th century. Together with excessive production, consumerism caused several hardly reversible environmental problems, such as resource depletion, climate change, pollution, etc.. To eliminate those problems, changing the consuming habits is not enough. Sustainable, healthy and environmental production systems should be developed to go down to the core of the problems. Ecodesign is a method aiming to transform classical production systems into sustainable ones and to delete or to reduce environmental problems occurred during whole life cycle of the products, without compromising the quality, cost, functionality, aesthetics, etc. of the product. Although it is getting more popular every year, according to studies in academia and in industry, it is hard to say that its use is common among producers. The aim of this thesis is first to investigate the reasons behind the denial of ecodesign use and then to provide an integrated ecodesign methodology which fulfills the needs of the producers.

In this direction, first, a literature review is done. It shows that the researchers in general focus solely on environmental parameters in ecodesign and ignore cost and quality ones. Those studies do not exactly cover the holistic perspective of ecodesign. In this thesis, cost and quality are also considered as focus points for ecodesign.

During literature review, traditional design and ecodesign are compared for each step of design process. This comparison shows that ecodesign methods are mostly used in late stages of design process and lack in the early ones. One reason for that is these methods need detailed information about the product to do an environmental assessment, however this kind of information is not available in the early design stages. Therefore, the proposed methodology should be suitable for the use in early stages and should require less information about the product.

Secondly a survey is conducted among engineers. The results show that they find ecodesign methods complicated, expensive and hard to implement, bringing extra workload. Engineers and producers basically require simplified and cheap methods applicable with less data. Therefore the proposed integrated methodology should be simple and implementable via basic engineering knowledge.

The main steps of proposed integrated ecodesign methodology which fulfill all these requirements are as follows:

- An environmental assessment focusing on the most important environmental aspect and impact of the product should be done instead of the complicated tools which deal with all aspects (such as energy and water consumption, waste generation, etc.) and impacts (global warming, pollution, acidification, eutrophication, etc.) for the whole life cycle. The most important environmental aspect and impact should be found via the opinions of experts in the field, through Analytic Network Process (ANP), a multi criteria decision making technique which is able to deal with interdependencies among criteria and alternatives. Since there exist interdependencies among environmental aspects and impacts, the use of ANP to select the most important ones is suitable for the proposed methodology.

- A simplified environmental assessment should be done considering all life cycle phases. The most significant life cycle phase which has the highest impact on the environment, in other words, which has the lowest environmental performance, should be obtained.

- In parallel to these steps, a three phased Quality Function Deployment for Environment (QFDE) should be applied considering the requirements of all possible stakeholders (users, government, recyclers, suppliers, etc.) and parameters such as quality, aesthetics, functionality, etc.. QFDE is suitable for the use in early design stages since it does not require detailed information about the product. Weighting the stakeholders' views in QFDE is a critical issue. Fuzzy Analytic Hierarchy Process (FAHP) should be used in order to weight them. At the end of this step, the weight of the ecodesign improvement strategies should be obtained through three phases completed via decision makers' evaluation in relation matrix and the weights from FAHP.

- Regarding the results obtained from the previous steps, the environmental performance of the improvement strategies should be measured, then a Life Cycle Costing analysis should be done. At the end of this analysis, feasible ecodesign improvement strategies should be selected and applied.

The proposed simplified integrated ecodesign methodology is applied for hand blender, a member of electrical and electronic equipment (EEE) family. The reason to chose this specific product family is that they include hazardous substances which harm the environment, especially when they become waste, and also valuable metals, which cause resource depletion. Basically because of these two reasons, it is crucial to manage the ecodesign of EEE. According to the results of ANP, the most important environmental aspect is energy consumption, and its related impact is global warming potential. The results of the simplified environmental assessment show that the most significant life cycle phase of the hand blender is raw material phase. This tells that there should be an improvement in raw material selection of the product. The results of QFDE give high weights to strategies related to the use of recyclable, reusable and non-hazardous materials. Those improvement strategies are evaluated according to their environmental performance and their life cycle costs are analyzed. The final results show that all proposed ecodesign improvement strategies are feasible to apply by the producers.

Résumé

La révolution industrielle a changé les systèmes de production complètement avec sa grande contribution au développement de l'humanité. Néanmoins, ses conséquences destructrices sur l'environnement ont commencé à apparaître au milieu du 20ème siècle. La production excessive et la consommation ensemble ont causé plusieurs problèmes environnementaux difficilement réversibles, tels que l'épuisement des ressources, le changement climatique, la pollution, etc.. Pour éliminer ces problèmes, changer les habitudes de consommation n'est pas assez. Les systèmes de production durables et environnementaux doivent être développées pour descendre au cœur des problèmes. Ecoconception est une méthode qui vise à transformer les systèmes de production classiques à durables, et à supprimer les problèmes environnementaux survenus au cours du cycle de vie des produits, sans compromettant la qualité, le coût, la fonctionnalité, l'esthétique, etc. du produit. Bien que l'écoconception devienne plus populaire chaque année, il est difficile de dire que son utilisation est courante chez les producteurs. L'objectif de cette thèse est d'abord d'enquêter sur les raisons derrière le refus de l'utilisation d'écoconception et de fournir une méthodologie intégrée qui répond aux besoins des producteurs.

Dans ce sens, d'abord, une revue de la littérature est accomplie. Elle montre que les chercheurs en générale concentrent uniquement sur des paramètres environnementaux dans l'écoconception et ignorent celles du coût et de qualité. Ces études ne couvrent pas exactement le point de vue holistique de l'écoconception. Dans cette thèse, le coût et la qualité sont également considérés comme des points de discussion pour l'écoconception.

Lors de la revue de la littérature, la conception traditionnelle et écoconception sont comparées pour chaque étape du processus de conception. Cette comparaison montre que des méthodes d'écoconception sont principalement utilisés dans les stades tardifs de processus de conception et en absence dans les premiers. Une des raisons est que ces méthodes ont besoin d'informations détaillées sur le produit pour faire une évaluation

environnementale, mais ce genre d'information n'est pas disponible dans les premières étapes de conception. Par conséquent, la méthodologie proposée doit être adaptée à l'utilisation dans les stades précoces et nécessiter moins d'informations sur le produit.

Ensuite, une enquête est menée auprès des ingénieurs. Les résultats montrent qu'ils trouvent des méthodes d'écoconception complexe, coûteux et difficile à mettre en œuvre, ce qui portent la charge de travail supplémentaire. Les ingénieurs et les producteurs exigent essentiellement des méthodes simplifiées, pas cher, et applicables avec moins de données. Par conséquent, la méthodologie intégrée proposée doit être simple et réalisable par des connaissances essentielles d'ingénierie.

Les principales étapes de la méthodologie d'écoconception intégrée proposée qui remplissent toutes ces conditions sont les suivantes:

- Une évaluation environnementale en mettant l'accent sur l'aspect et l'impact environnemental le plus important du produit doit se faire à la place des outils complèxes qui traitent de tous les aspects (tels que la consommation d'eau et d'énergie, production de déchets, etc.) et les impacts (réchauffement de la planète, pollution, l'acidification, l'eutrophication, etc.) pour l'ensemble du cycle de vie. L'aspect et l'impact environnemental les plus importants doivent être trouvés via les opinions des experts dans le domaine, à travers le Processus de Réseau Analytique (PRA), une technique de décision multi critères qui est capable de traiter les interdépendances entre les critères et les alternatives. Comme il existe des interdépendances entre les aspects et impacts environnementaux, l'utilisation de PRA pour sélectionner les plus importants est adapté à la méthodologie proposée.

- Une évaluation environnementale simplifiée doit être fait en tenant compte de toutes les phases du cycle de vie. La phase la plus importante du cycle de vie qui a le plus d'impact sur l'environnement, en d'autres termes, qui a la plus faible performance environnementale, doit être obtenue.

- En parallèle à ces mesures, Développement des Fonctions Qualités pour Environnement (DFQE) à trois étapes doit être appliqué en tenant compte des besoins de tous parties prenantes possibles (les utilisateurs, les gouvernements, les recycleurs, les fournisseurs, etc.) et des paramètres tels que la qualité, l'esthétique, la fonctionnalité, etc.. DFQE est adapté pour l'utilisation dans les stades précoces de la conception car il ne nécessite pas d'informations détaillées sur le produit. Pondération des vues des parties prenantes dans DFQE est une question cruciale. Processus Hiérarchique Analytique Floue (PHAF) doit être utilisé pour les pondérer. A la fin de cette étape, les poids des stratégies d'amélioration d'écoconception doivent être obtenus par trois phases complétés par l'évaluation des décideurs dans la matrice de relation et les poids de PHAF.

- En ce qui concerne les résultats obtenus dans les étapes précédentes, la performance environnementale des stratégies d'amélioration doit être mesurée, puis une analyse des coûts de cycle de vie doit être faite. A l'issue de cette analyse, les stratégies d'amélioration en matière d'écoconception possibles doivent être choisis et appliqués.

La méthodologie d'écoconception proposée est appliquée pour mélangeur à main, un membre de la famille des équipements électriques et électroniques (EEE). La raison de choisir cette famille de produit spécifique est qu'elle contient des substances dangereuses qui nuisent à l'environnement, en particulier quand elle devient des déchets, ainsi que des métaux précieux, qui provoquent l'épuisement des ressources. A cause de ces deux raisons, il est essentiel de gérer l'écoconception des EEE. Selon les résultats de PRA, l'aspect environnemental le plus important est la consommation d'énergie et son impact lié, le potentiel de réchauffement global. Les résultats de l'évaluation l'simplifiée environnementale montre que la phase du cycle de vie la plus importante du produit est la phase de matières premières. Cela indique qu'il devrait y avoir une amélioration dans la sélection des matières premières du produit. Les résultats de DFQE donnent un poids élevé aux stratégies liées à l'utilisation de matériaux réutilisables, recyclables et non dangereux. Ces stratégies d'amélioration sont évalués en fonction de leur performance environnementale et les coûts du cycle de vie sont analysées. Les résultats finaux montrent que toutes les stratégies d'amélioration de l'écoconception proposées sont réalisables à appliquer par les producteurs.

Özet

Sanayi devrimi, üretim biçimlerini baştan aşağı değiştirip insanlığa olumlu yönde katkı sunsa da, yeni üretim biçimlerinin yıkıcı etkileri 20. yüzyılın ikinci yarısından itibaren gün yüzüne çıkmaya başladı. Aşırı ve yanlış üretim ile birlikte aşırı tüketim, doğal kaynakların tahribatı, kirlilik, iklim değişikliği gibi önüne geçilmesi zor çevresel sorunlar yarattı. Bu sorunları ortadan kaldırmak için tüketim biçimlerimizi değiştirmek yeterli değildir. Bununla birlikte sorunun kaynağına inilmeli, sağlıklı, çevreci, sürdürülebilir üretim biçimlerine yönelinmelidir. Bu amaçla ortaya çıkan çevreci tasarım, klasik üretim sistemlerini sürdürülebilir üretime dönüştüren, ürünlerin tüm yaşam döngüleri boyunca ortaya çıkardıkları çevresel sorunları yok etmeyi ya da en aza indirmeyi hedefleyen, ama bunları yaparken ürünün kalite, maliyet, işlevsellik, estetik, vb. özelliklerinden ödün vermeyen bir ürün geliştirme yöntemidir. Çevreci tasarım, popülerliğini her geçen yıl arttırsa da, yazın ve saha çalışmalarının sonuçlarına göre henüz üreticiler arasında çok yaygın olarak kullanıldığı söylenemez. Bu çalışmanın amacı, öncelikle üreticilerin neden çevreci tasarım yaklaşımını uygulamadığının araştırmasını yapmak ve elden edilen bulgulara göre üreticilerin gereksinimlerini karşılayacak bütünleşik bir çevreci tasarım yöntemi sunmaktır.

Bu doğrultuda öncelikle yazın taraması yapılmıştır. Yazın taraması, araştırmacıların çevreci tasarım konusunda genelde yalnızca çevreci parametrelere odaklandıklarını, kalite ve maliyeti görmezden geldiklerini göstermiştir. Bu çalışmalar, çevreci tasarımın bütünlüklü ürün geliştirme yaklaşımını tam olarak karşılamamaktadır. Bu tezde çevreci tasarım yöntemi geliştirilirken kalite ve maliyet de odak noktalarıdır.

Yazın taraması sırasında tasarım sürecinin her adımında, geleneksel tasarım ile çevreci tasarım karşılaştırılmıştır. Bu karşılaştırma, çevreci tasarım yöntemlerinin daha çok geç tasarım aşamalarında kullanıldığını, ilk aşamalarda bu yöntemlerin eksik olduğunu göstermiştir. Bunun bir nedeni, bu yöntemlerin, çevre değerlendirmesi yapabilmek için ürün

ile ilgili ayrıntılı bilgiyi gerektirmesidir. Oysa ürün tasarımının başlangıç aşamalarında, henüz ürüne ait ayrıntılı bilgi yoktur. Buna göre, önerilecek yöntem az ürün bilgisine dayanmalı ve tasarım sürecinin başlangıç aşamalarında kullanılmaya uygun olmalıdır.

İkinci olarak, mühendisler arasında düzenlenen anket, üreticilerin çevreci tasarım yöntemlerini genellikle zor, karmaşık ve pahalı bulduklarını, bu yöntemlerin üreticiye fazladan iş yükü getirdiğini göstermektedir. Üreticilerin ve mühendislerin çevreci tasarım için temel gereksinimleri, basitleştirilmiş, ek maliyet ve yoğun bilgi kullanımı gerektirmeyecek yöntemlerdir. Buna göre bu tezde, pahalı yazılım satın alma zorunluluğu getirmeyen, temel mühendislik bilgisiyle yürütülebilen ve fazladan iş yüküne neden olmayan bir yöntem önerilecektir.

Tüm bu beklentileri karşılayacak bütünleşik çevreci tasarım yöntemi aşağıdaki adımlardan oluşmaktadır:

- Ürünün yaşam döngüsü boyunca tüm çevresel etki (küresel ısınma, hava kirliliği, asitleşme, ötrifikasyon, vb.) ve nedenlerini (enerji, su tüketimi, atık oluşumu, vb.) hesaplayan karmaşık yöntemler yerine, bu ürün için en önemli çevresel etki ve nedene odaklanıp bunlar üzerinden çevresel değerlendirme yapılmalıdır. Ürün için en önemli çevresel etki ve neden, alanının uzman kişilerinden görüş alınarak çok ölçütlü karar verme tekniklerinden Analitik Ağ Süreci'ni (AAS) kullanarak bulunmalıdır. AAS, seçim yapılacak ölçütler ve alternatifler arasındaki bağımlılık ilişkilerini dikkate aldığından, çevresel etkiler ve nedenleri arasındaki bu bağımlılık ilişkilerini işleyebilecek en uygun teknik olarak belirlenmiştir.

- AAS'nin sonucunu temel alarak tüm yaşam döngüsü aşamalarını içeren basitleştirilmiş çevresel değerlendirme yapılmalıdır. Bu değerlendirmenin sonucunda, ürünün çevresel performansının en düşük olduğu, başka bir deyişle çevreye en çok zarar verdiği yaşam döngüsü aşaması saptanmalıdır.

- Bu çalışmalara koşut olarak, ürünle ilişki içinde olan tüm paydaşların (tüketiciler, devlet, geri dönüştürücüler, tedarikçiler, vb.) beklentilerini hesaba katacak, aynı zamanda ürünün kalite, estetik, işlevsellik vb. parametrelerini göz önünde bulunduracak üç aşamalı Çevre için Kalite Fonksiyon Göçerimi (ÇKFG) tekniği uygulanmalıdır. Bu teknik, ayrıntılı ürün bilgisi gerektirmediğinden tasarımın başlangıç aşamalarında kullanılmak için uygundur. ÇKFG'nin paydaş görüşlerinin ağırlıklandırılması önemli bir konudur. Karar vericilerin görüşlerini en sağlıklı biçimde aktarmak üzere Bulanık Analitik Hiyerarşi Süreci (BAHS) tekniği kullanılmalıdır. BAHS'den gelen ağırlıklar ve karar vericilerin ilişki matrisinde oluşturdukları değerlendirmeler ışığında üç aşamanın sonunda, ele alınan ürün için olası çevreci tasarım geliştirme stratejilerinin ağırlıkları bulunmalıdır.

- İlk üç aşama sonunda elde edilen tüm sonuçlar doğrultusunda, ele alınan ürün için geliştirme strateji alternatiflerinin çevresel performansları ölçülmeli, ardından bunların Yaşam Döngüsü Maliyetlendirme analizi yapılmalıdır. Bu analizler sonucunda üretici için en olurlu çevreci geliştirme stratejileri belirlenmeli ve uygulanmalıdır.

Bu tez çalışması kapsamında geliştirilen basitleştirilmiş bütünleşik çevreci tasarım yöntemi, elektrikli ve elektronik aletler (EEA) sınıfının bir üyesi olan el blender'ı için uygulanmıştır. Bu özel ürün sınıfının seçilmesinin nedeni, içlerinde barındırdıkları zararlı maddeler nedeniyle, özellikle atık durumuna geldiklerinde çok ciddi çevre kirliliğine yol açmaları, hem de değerli madenler nedeniyle kaynak tükenimine yol açmalarıdır. Temelde bu iki neden dolayısıyla EEAların çevreci tasarımı büyük önem taşımaktadır. El blenderı için yapılan uygulamanın AAS sonuçlarına göre, en önemli çevresel etki nedeni enerji tüketimi, buna bağlı en önemli çevresel etki küresel ısınma olarak belirlenmiştir. Ardından yapılan basitleştirilmiş çevresel değerlendirmeye göre, el blender'ının çevreye en çok zarar verdiği yaşam döngüsü aşaması hammadde aşamasıdır. Bu durum, ürünün hammadde seçiminde kesinlikle iyileştirilmeye gidilmesi gerektiğini söylemektedir. ÇKFG uygulamasının sonucunda da geri dönüştürülebilir ve zararsız hammadde ile yeniden kullanılabilir parçaların kullanımı en yüksek ağırlıklı geliştirme stratejileri olarak belirlenmiştir. Bu stratejilerin çevre ve maliyet performanslarının analizi, üreticiler için hepsinin olumlu olduğunu göstermektedir Üreticiler önerilen tüm stratejileri ürünleri için uygulayabilir.

1 Introduction

We, humans, struggle with nature, against each other or with ourselves ever since thousands years. Nevertheless this struggle has change form in the last two centuries. Once upon a time we used to seek for ways to dominate nature. Today, however, we are seeking ways to save nature from, unfortunately, ourselves.

The 20th century witnessed the breakthrough of industrialization and technology; but rapid development had significant environmental impact, bringing along an ever increasing production of waste, usage of toxic substances, depletion of valuable resources, climate change, pollution, depletion of the ozone layer, acidification, eutrophication, deforestation, etc. (Grubler et al., 1999; Bentley, 2002; Omer, 2008; Sepulveda et al., 2010).

Although the current consequences are extreme, industrialization and technology cannot be blamed in themselves for the destruction of nature. These two concepts do not necessarily require the misuse of the resources and the exploitation of the planet. Globally occurring environmental problems are mainly caused by the current mode of production, which starts as excessive production and ends up in planned obsolescence[1] and consumerism[2].

The two former ones are the key factors of over consumption, which leads to inevitable environmental degradation. The current mode of production also brings periodic financial crises on a ten year cycle or even invasions and wars. However, the discussion about these consequences is out of scope for this thesis.

Despite the severe consequences of environmental problems caused by production systems, there is no need to be hopeless and pessimistic. After all, it is always possible to create a different world. We should know that there are alternatives to live in a fair, equal,

[1] On this topic, the documentary "The Light Bulb Conspiracy" is of great interest.

[2] The book "Oburluk Çağı" by Yıldız Silier is a stimulating book about the topic.

free (not in the consumption but in the production) and green world. Of course it is not an "one day job" to transform the overall system, but people's way of life. It will take years and require hard efforts. If that's so, then will we continue to stack non-environmentally designed products without taking any caution until that day comes?. Our planet is dirty today. Then we should start cleaning the world right now, before it's too late.

The transformation of the nature into an unlivable place is certainly a global scale problem. Therefore, the solutions should also be in global scale, covering all production systems.

The environmental threats on human health and eco-system gave already rise to awareness for sustainable production and ecodesign, and push researchers to develop strategies to change the traditional objectives and way of production.

The traditional objectives of industrial production are generally accepted as increasing efficiency of the manufacturing resources and reducing the costs. Now it's a must to take into account the whole product life cycle and reduce the impacts on the environment in every phase of the industrial production in order to turn it into a sustainable one (Westkamper et al., 2000).

The main ideas of sustainable production methodology are the observation of the environmental impact of a product during its whole life cycle, determining its most environmentally influential life cycle phase, assessing these impacts and finding solutions to conduct ecodesign by interpreting the results.

Ecodesign, as a part of sustainable production, aims to develop goods and services leading to sustainability by reducing products' environmental burdens throughout the whole life cycle, while taking into account the other conventional product and customer requirements such as functionality, quality, safety, cost, manufacturability, ergonomics and aesthetics (Gurauskiene and Varzinskas, 2006).

Life cycle thinking, through which sustainable production can be reached, is a crucial approach to improve the environmental performance of the products through their whole life cycle phases. By applying proactive ecodesign strategies, product improvements can be realized and the total environmental impact of a product can be reduced (Platcheck et al., 2008) .

Although ecodesign is a crucial step in sustainable production, it is not commonly used among companies. Many studies have been conducted to find out the root of the problem and to generate solutions. However there is no common point of view in the field. Some researchers state that more methods and tools are needed, the existing ones do not satisfy the users (Jeswiet and Hauschild, 2005; Karlsson and Luttropp, 2006; Gurauskiene and Varzinskas, 2006; Lofthouse, 2006), while others claim no more methods and tools needed (Lindahl, 2003; Tingstrom, 2005).

Some of them propose to integrate the existing methods and tools to facilitate to use of ecodesign and make it spread (Tingstrom and Karlsson, 2006; Pamminger et al., 2006; Donnelly et al., 2006; Knight and Jenkins, 2009). There is a significant amount of researchers who found the solution in the integration of ecodesign into early design phases (Bhamra et al., 1999; Tingstrom, 2005; Karlsson and Luttropp, 2006; Lindahl, 2006; Kobayashi, 2006; Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010b).

There are some useful tools supporting engineers in finding suitable strategies such as ECODESIGN (Brezet et al., 1997), ECODESIGN PILOT (Wimmer and Züst, 2003), etc. However these tools do not cover the product's assessment from different aspects and focus solely on the environmental parameters by putting mostly aside the cost and quality ones. Furthermore, although they are more practical than conventional environmental assessment tools, they still require detailed information about the existing product. However, it is important to include environmental parameters into early design stages, while one does not have all the information about the product.

The disagreement among researchers and the lack of a holistic point of view show that there is still room for a further investigation about the use of ecodesign. This study aims to accomplish this task and to develop a holistic framework covering the needs and the missing points in the area.

Ecodesign has a vital importance thanks to its ability to solve the problem in the beginning phase of the production. Through ecodesign, products will be designed and produced considering the reduction or elimination of the toxic substances, with more recyclable materials and higher standardization of the components. However the point here is not to design products with higher cost and devoid of quality in order to be environmental friendly. Otherwise, the production will not be economic and efficient as it should be. People have the right to reach the most environmental products with high quality and low price. Nobody deserves poor quality products and nobody is obliged to buy unreasonably expensive products under the cover of "environmentally friendly green product". That's why this Ph.D. thesis also aims to provide a methodology to design green products respecting the notions of cost, quality and economics all together.

The proposed methodology is applied for a special product group, Electrical and Electronic Equipment (EEE). The reason to choose this specific group of product is that EEE have significant negative impacts on the environment and human health in terms of resource depletion and toxicity (Sepulveda et al., 2010). Resource depletion is caused by non-environmentally friendly and excessive production. Valuable metals, such as copper, gold, silver, etc., and different types of energy are consumed consistently and these are non-renewable resources (Widmer et al., 2005; Chancerel et al., 2009). Regarding the toxicity of EEE, hazardous components commonly found in electronic devices include lead, mercury, beryllium, barium, hexavalent chromium, cadmium, arsenic, nickel, zinc, and brominated fire retardants (BFR) in the plastics (Widmer et al., 2005; Aizawa et al., 2008). These toxic EEE, when becoming wastes, threat the environment and the human health by contaminating air, soil and water (Tsydenova and Bengtsson, 2011). Therefore it is important to analyze an EEE product to improve its environmental performance.

In short, the aim of this thesis can be rephrased as follows: to provide a suitable holistic methodology, which fulfills the needs of the stakeholders for product development by combining economic, quality and environmental aspects together and to derive ecodesign improvement strategies to achieve sustainable production.

To reach this aim, the outline below will be followed:

- First, the concept of ecodesign and the methods and tools used in ecodesign are presented in detail in Chapter 2.
- Secondly in Chapter 3, the leading ecodesign method, Life Cycle Assessment is presented.
- The definition and the scope of Life Cycle Costing are given in Chapter 4 to introduce the cost approach to ecodesign.
- In Chapter 5, the main object of the study, EEE is presented and the reasons behind the choice of focusing on it in this study are discussed in detail.
- After that, a literature review is provided to explore the current studies in academia, in Chapter 6.
- Later, the survey conducted among engineers experienced in ecodesign, to get their opinions about its implementation, is presented in Chapter 7.
- As the next step, with the data gathered from the first steps of the study, an integrated methodology is developed to fulfill the needs of the field and to improve the use of ecodesign. Chapter 8 is where the major contribution of the study is presented.
- The proposed methodology is applied in a case study in Chapter 9, for a product from the EEE family. The results of the application are provided and then discussed.
- Finally the thesis is concluded by presenting the possible contributions of the proposed holistic ecodesign methodology and the future directions of work in Chapter 10.

2 Ecodesign

There are many definitions of ecodesign given in the literature, showing the fact that there is still no one single definition agreed on it.

Ecodesign, Green Design (terms used in Europe) or Design for Environment (term used in the USA) (Pigosso et al., 2010) is an integrated strategy that has the goal of reducing the environmental impact of a product at the design stage. Sustainable Design, Environmental Conscious Design, Life Cycle Design or Life Cycle Engineering and also Clean Design are the names also used as a synonym. Although the phrasing may have different meanings, the concepts generally have the same objectives (Lagerstedt, 2003). It begins with research and development using environmental impact as the basis for the product, whilst procurement and quality assurance work closely with suppliers by ensuring that they meet or exceed the criteria for environmental performance.

Ecodesign is not a compliance activity, but a cross-functional strategy (Herat, 2007), which integrates multifaceted aspects of design and environmental considerations (Karlsson and Luttropp, 2006), and a systematic incorporation of environmental aspects into the product design and development for improvement of product environmental characteristics (Gurauskiene and Varzinskas, 2006).

According to a wider perspective, ecodesign is a proactive management approach that directs product development towards environmental impact reductions throughout its life cycle, without compromising other criteria such as performance, functionality, aesthetics, quality and cost (Pigosso et al., 2010).

Ecodesign's main objective is to reduce environmental loads (Karlsson and Luttropp, 2006; Gurauskiene and Varzinskas, 2006). The contribution to decrease the environmental impacts is basically the prevention (Platcheck et al., 2008).

Ecodesign aims also at improving the product's environmental performance and may be seen as a way of developing products in line with the concept of sustainable development and life cycle thinking (Pigosso et al., 2010; Gurauskiene and Varzinskas, 2006). Bruntland report statement that a sustainable future fulfils today's need without jeopardizing future generations' possibilities to reach their goals (Karlsson and Luttropp, 2006).

Ecodesign considers environmental aspects at all stages of the product development process, striving for products which cause the lowest possible environmental impact throughout the product life cycle. It requires distinct indicators which can be used as design criteria by product developers, as decision-making criteria by company managers, and as purchase criteria by consumers (users and customers) (Aoe, 2007).

Ecodesigned products have to consume as few resources as possible and to reduce impacts on the environment, to improve overall performance (Gurauskiene and Varzinskas, 2006).

Ecodesign, as a helpful, emerging tool to improve companies' environmental performance, helps organizations close the supply chain loop by addressing product functionality while simultaneously minimizing life-cycle environmental impacts. One of key aspects for ecodesign is to facilitate reuse, recycling and recovery through smart design such as easy to disassemble used products, a critical design characteristic for closed-loop supply chain management. The success of ecodesign requires internal cross-functional cooperation among the entire company and the external cooperation with other partners throughout the supply chain (Zhu et al., 2008).

Basic external drivers for implementing ecodesign are the following: compliance with both environmental legislation and requirements of standards; commitment of the company environmental policy to increase environmental efficiency giving the top priority to the pollution prevention (Gurauskiene and Varzinskas, 2006). As for requiring the environmental policy, resource depletion and the lack of landfill space are also pressing issues, making necessary the effective utilization of resources, and so ecodesign. In order to conserve scarce resources, the use of new resources at the input side must be reduced by the ecodesign methodology (Platcheck et al., 2008).

The main internal drivers are the following: reducing the costs, improving the image of the company and products and the quality of products and, making innovations (Gurauskiene and Varzinskas, 2006).

One should know the environmental problems and its causes at all stages of the life cycle of the product in order to influence the conception, the materials selection, the production, the use, the reuse, the recycling and the final disposition (Platcheck et al., 2008).

In the early ecodesign project stages new product design concepts start with a basic idea on the product function, its visual properties, lifetime, or its special features. Detailing of the product is a systematic process that requires close cooperation between all company departments involved in the product development. In its interphase this process may result in development of several product alternatives that are compared and evaluated. The final selection of the most feasible alternative is made in accordance with the company decision-making system. This model helps obtain the maximum environmental performance in the product development process with minimum costs (Gurauskiene and Varzinskas, 2006).

As a summary, ecodesign is a proactive strategy for product development which aims to reduce the environmental impacts of the product during the whole life cycle without ignoring the performance, functionality, quality, safety, ergonomics, aesthetics and cost parameters. Ecodesign facilitates 3R (Reuse, Recycle, Reduce), in this manner it supports the closed-loop supply chain approach. Ecodesign is realized just in the beginning of the life cycle of a product by design team however it requires cross-functional cooperation of the different departments in the company itself and integrates the external cooperation with stakeholders (consumers, suppliers, recyclers, etc.). For example, the consumer is the key to initiation and implementation of Ecodesign at points along the supply chain (Herat, 2007). This approach is accepted and will be followed in this thesis.

2.1 Design vs. Ecodesign

The definitions of ecodesign are given in the previous section. However to analyse the differences between traditional design process and ecodesign, it is crucial to have a deeper look.

ISO 14062:2002, "Environmental management – Integrating environmental aspects into product design and development", describes concepts and current practices relating to the integration of environmental aspects into product design and development. It gives guidelines for the integration of ecodesign into a product development process. Table 2.1 summarizes the stages of the design process, a selection of appropriate activities for ecodesign, and methods and tools used generally in product development process and adapted for ecodesign. This table is prepared by having the basic idea from Schischke et al.'s study in 2005, and the requirements of ISO 14062.

Product design and development model

A generic model of product design and development in ISO 14062 consists of six stages: planning, conceptual design, detailed design, testing/prototype, market launch, and product review. The Planning stage encompasses planning and formulation of product requirements. The Conceptual design stage realizes the product requirements. The Detailed design stage is additional actions to meet the product design specifications prior to production. The Testing/Prototype stage is to check the detailed design against environmental targets and other specifications. The environmental performance of the product such as life cycle assessment results can also be assessed at this stage. The Market launch stage is the deliverance the product to the market and the communication of information about the product's features and benefits to the customers. The Product review aims to find whether the expectations of the organization, customers etc. have been met. Feedback and criticism from customers and other stakeholders is an important information source for the organization to improve its current or future products (Lee and Park, 2005)

Before these six stages, identifying needs stage (Seo et al., 2002) can also be included in both general design and ecodesign processes, since all products should be created according to the needs of a target group.

As it is observed on Table 2.1, there are many different methods which are used in ecodesign. In the next section, it will be briefly mentioned about these methods. As for their classification according to their use, it can be said that they are mostly used in mid and late design stages and missing in the early design stages.

Another observation taken from the Table 2.1 is that ecodesign covers all the activities and approaches that traditional design has. The only difference is that ecodesign has additionally environmental concerns about product development. This proves that ecodesign is not an approach only about environment, but it also includes the traditional design parameters, concerning cost, quality, stakeholders' need, etc.

Table 2.1: Design vs. Ecodesign Table

	WHAT			**HOW**		
Design Stages	**Questions Addressed**	**Activities**		**Methods & Tools**		**Requirements of Designers**
		Traditional	**Ecodesign**	**Traditional**	**Ecodesign**	
(1) Identifying Needs	1.Who are the target users? 2.What do end-users/ consumers need? 3.What do other stake-holders need?	1.Find target audience 2.Find consumers' need 3.Find stakeholders' need (suppliers, retailers)	1.Find target audience 2.Find consumers' need 3.Find stakeholders' need (suppliers, retailers, legislations, recyclers, etc.)	1.2.Market research 3.Mandatory and voluntary requirements search	1.2.Market research 3.Mandatory and voluntary requirements search	- Information - Motivation - Coordination with customer relationships department - Coordination with legal department
(2) Planning	1.What is the product idea? 2.What are the priorities (economical, technological, ecological) for this product? 3.Is it a totally new product or a product improvement? 4.What is the overall and environmental company strategy? 5.What eco-design activities can you already base on? 6.What is the business	1.Clarify the product idea 2.Define the priorities (economical, technological) for this product 3.Define the type of the product and design: new product development or product improvement 4.Get information about the overall company strategy 5.-	1.Clarify the product idea 2.Define the priorities (economical, technological, ecological, social) for this product 3.Define the type of the product and design: environmental new product development or environmental product improvement 4.Get information about the	1.Ideation methods, brainstorming, etc. 2.4.Market research 2.4.Trend studies, 3.Patent mapping 4.Concurrent Engineering	1.Ideation methods, brainstorming, etc. 2.4.Market research 2.EQFD 2.4.Trend studies, 3.Patent mapping 4.Bench -	- Creativity - Innovation - Coordination with management departement, finance department, R&D department, manufacturing department

Continued on next page

	WHAT			HOW		
Design Stages	**Questions Addressed**	**Activities**		**Methods & Tools**		**Requirements of Designers**
		Traditional	**Ecodesign**	**Traditional**	**Ecodesign**	
(2) Planning	environment? 7.What are the internal and external drivers?	6.Consider business environment: Customer/market needs, market niches, competitors' products, 7.Define internal and external drivers	overall and environmental company strategy 5.Check the status quo & Use the cross links to environmental management systems 6.Consider business environment: Customer/market needs, market niches, competitors' products, legislation, eco-label planned... 7.Define internal and external drivers	4.Bench - marking	marking 4.5.Green Concurrent Engineering	- Information
Design	1.Is the design of the product feasible? 2.How you refine the specification? 3.Are there any demands from your supply chain partners? 4.Are ecodesign aspects included in your design? 5.Does your design cover	1.Check feasibility (technological, financial) 2.Apply guidelines, checklists, etc. to refine the specification 3.Communicate with your supply chain 4.- 5.-	1.Check feasibility (technological, financial, 2.Apply environmental guidelines and legislations (WEEE, RoHS, EuP, etc.), checklists to refine the specification 3.Communicate with your supply chain 4.Integrate ecodesign	1.Mathematical analysis tools and methods 2.Idea maps 2.TRIZ (ideas dev. Tools) 2.Strategies 2.5.Checklists 2.5.Guidelines	1.Mathematical analysis, tools and methods 2.TRIZ (ideas dev. Tools) 2.Idea maps 4.Green Concurrent Engineering	- Coordination with procurement and sales R&D dep., environmental dep. - Creativity - Ergonomics prototype

Continued on next page

	WHAT			HOW		
Design Stages	**Questions Addressed**	**Activities**		**Methods & Tools**		**Requirements of Designers**
		Traditional	**Ecodesign**	**Traditional**	**Ecodesign**	
(3) Conceptual	all life cycle stages?		aspects when drafting the specification (hard and soft criteria) 5.Consider life cycle thinking	3.Supply Chain Management approach	2.4.5 Checklists 2.5.Guidelines 2.Strategies 2.4.MET Matrix 3.Supply Chain Management approach	material technology
(4) Detailed Design	1.How to design the product in details? 2.How do you improve your product understanding? 3.Are there any alternatives for problematic materials? 4.Do you apply any specific design approaches?	1.Apply design tools and related data bases 2.Develop different product scenarios for a better product understanding 3.- 4.-	1.Apply ecodesign tools and related data bases 2.Develop product and life cycle scenarios for a better product understanding 3.Find alternatives for problematic materials 4.Design X	1.Concurrent engineering 1.QFD 2.Taguchi experimen-tation 1.2.Critical path planning	1.LCA 1.TRIZ 1.EQFD 1. Green concurrent engineering 2.Taguchi experimen-tation 1.2.Critical path planning 1.3.MET Matrix 2.3.Bench-	- Information

Continued on next page

	WHAT			HOW		
Design Stages	Questions Addressed	Activities		Methods & Tools		Requirements of Designers
		Traditional	Ecodesign	Traditional	Ecodesign	
					marking 4.Design for X methods	
(5) Testing/ prototype	1.What are the differences from former product generation? 2.Does your product fulfill the intended functions? 3.Are your targets achieved?	1.Benchmark with former product generation 2.Check your product functionality 3.Check your economical and technological targets	1.Benchmark with former product generation regarding environmental concerns 2.Check your product functionality regarding environmental concerns 3.Check your economical, technological and ecological targets	1.QFD 2.FMEA 3. Statistical Quality Control Methods	1.LCA 1.EQFD 2.FMEA 2.ERA 3.MET Matrix 3.Statistical Quality Control Methods	- Coordination with manufacturing and quality departments
(6) Market launch	1.How will the consumers be aware of the main feature of your product? 2.How will the consumers know about the related features of the product? 3.How will the consumers know about the performance and achievement of the product?	1.Raise technological awareness among consumers 2.Communicate with the consumers about related features: quality, costs 3.Communicate the performance and quality achievement of the product	1.Raise ecological, social and/or technological awareness among consumers about related features: quality, life cycles, costs 3.Communicate environmental excellence and quality achievement of your product (customer group specific)	1.2.3.Customer Relationship Management 1.2.3.PR 1.2.3.Advertisement (Website, tv ads, flyers, etc.) 1.2.3.Seminars 1.2.3.Workshops, communi - cated through sketches, graphics,animation, words and widget prototypes 2.Material Inventory List		- Market information

Continued on next page

	WHAT			HOW		
Design Stages	**Questions Addressed**	**Activities**		**Methods & Tools**		**Requirements of Designers**
		Traditional	**Ecodesign**	**Traditional**	**Ecodesign**	
				3.Environmental Product Declarations (EPD) 3.Eco-labels		
(7) Product review	1.Which arguments really counted for the customer? 2.What can be the possible further improvements? 3.Which innovations are next (internally and on the market)? 4.What are the competitors doing?	1.Evaluate success of the product 2.Identify further improvements for next product generation 3.Predict the future innovations 4.Compare your position with the competitors	1.Evaluate environmental success of the product 2.Identify further environmental improvements for next product generation 3.Predict the future environmental innovations 4.Compare your position with the competitors	1.2.Sensitivity Analysis 1.4.Surveys and feedback 2.3. Internal workshops 4.Benchmarking		- Creativity - Innovation

2.2 Ecodesign Methods

Different ecodesign methods have been developed to evaluate environmental impacts, identifying the environmental weak-points putting in evidence potential problems and conflicts and facilitating choosing from among the possible product aspects by comparing the environmental design strategies (Pigosso et al., 2010).

The methods mainly used in Ecodesign are Life Cycle Assessment (LCA), Environmental Risk Assessment (ERA), Brainstorming, Configuration Management, Quality Function Deployment (QfD), TRIZ, etc (Gurauskiene and Varzinskas, 2006; Lindahl, 2006; Sakao, 2007).

Life Cycle Assessment (LCA) is a scientific tool that could be employed for facilitating the analysis of environmental impacts over a complete product life cycle so that the so-called cradle-to-grave analysis can be achieved (Yung et al., 2009).

Brainstorming is a tool used by teams to bring out the ideas of each individual and present them in an orderly fashion to the rest of the team. The key ingredient is to provide an environment free of criticism for creative and unrestricted exploration of options or solutions[3].

British Standard 6488 : 1984 goes on to define Configuration Management as the discipline of identifying the components of a continuously evolving system for the purpose of controlling changes to these components and maintaining integrity and traceability throughout the system life-cycle (Allan, 1997).

The definition of Akao states that Quality Function Deployment (QFD) is the converting of customer demands (WHATs) into quality characteristics (QCs) (HOWs) and developing a quality plan for the finished product by systematically deploying the relationships between customer demands and the QCs, starting with the quality elements in the product plan (Prasad, 1998).

[3] www.balancedscorecard.org/Portals/0/PDF/brainstm.pdf

TRIZ, an innovation methodology, provides a systematic process to define and solve any given problems. It is different from the traditional trial and error approach which mainly relies on brainstorming and becomes unreliable with increased complexity of the inventive problem. TRIZ is the Russian acronym for the Theory of Inventive Problem Solving developed by Genrich Altshuller in Russia in 1965 (Loh et al., 2006). The core of TRIZ is to pose a contradiction and from that point to provoke inventions (Altshuller and Altov, 1996). TRIZ is a promising tool since many designers see a contradiction between EcoDesign and economic growth (Luttropp and Lagerstedt, 2006).

Environmental Risk Assessment (ERA) has become a generally used tool in the evaluation of the potential environmental risks of chemical products (Karman, 2000).

During their whole life cycle, products generate several environmental problem, principally due to their toxic and/or valuable materials. When occurred, these problems may effect the human health (cancer, several diseases, etc.), the ecosystem quality (pollution of the soil, water and the air, climate change, etc.) and the resources (depletion, etc.). Therefore LCA is chosen as a model tool in this thesis to measure the life cycle impacts. This method is accepted as the main direction of the thesis and it is analysed deeply in the next section. Nevertheless since this study is based on an integrated methodology, the other methods, such as QFD and other decision making tools, will be also used in order to do a further analysis including cost and quality parameters.

3 Life Cycle Assessment

Life cycle assessment is a methodological framework used to quantify a wide range of environmental impacts that occur over the entire life cycle of a product or process (Guinee et al., 2002). It is often referred to as a “cradle to grave” analysis (Rebitzer et al., 2004), and the assessment generally includes a quantification of the resource use and emissions associated with all of the major phases of the production chain, including the extraction and processing of raw materials, manufacturing processes, transportation at all stages, use of the product by the consumer, and recycling or disposal of the product after use (Consoli, 1993).

The concept of LCA evolved in the 1960s and there have been several efforts to develop LCA methodology since the 1970s (Curran, 1996). However, it has received much attention from individuals in environmental science fields especially since the 1990s. For this concept many names have been used, for instance eco-balancing (Germany, Switzerland, Austria and Japan), resource and environment profile analysis (USA), environmental profiling and cradl-to-grave assessment. The Society of Environmental Toxicology and Chemistry (SETAC) has been involved in increasing the awareness and understanding of the concept of LCA. In the 1990s, SETAC in North America, and the US Environmental Protection Agency (USEPA) sponsored workshops and several projects to develop and promote a consensus on a framework for conducting life cycle inventory analysis and impact assessment. Similar efforts were undertaken by SETAC Europe, other international organizations (such as the International Organization for Standardization, ISO), and LCA practitioners worldwide. As a result of these efforts, consensus has been achieved on an overall LCA framework and a well-defined inventory methodology (ISO, 1997). The method is rapidly developing into an important tool for authorities, industries, and individuals in environmental sciences (Roy et al., 2009).

There are a number of commercially available softwares for LCA. A registry of LCA tools (including software) and database providers is available from the EC (`http://lca.jrc.ec.europa.eu/`) (Finnveden et al., 2009).

The purpose of an LCA can be (1) comparison of alternative products, processes or services; (2) comparison of alternative life cycles for a certain product or service; (3) identification of parts of the life cycle where the greatest improvements can be made (Roy et al., 2009).

LCA is conducted briefly as follows: for each environmental impact taken into account in the LCA, a characterisation model is used to convert the inventory data (resources use and emitted pollutants) that contribute to this impact into potential-impact estimates. This is done by multiplying the resources used and emissions by a characterisation factor for each impact category to which it may contribute (Aubin et al., 2009)

Life cycle assessment is a standardised method (ISO14040, 2006; ISO14042, 2006). According to ISO 14040 (2006), an LCA comprises four main stages: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation of the results (see Figure 3.1).

Next subsections will present the content of these four main stages.

3.1 Goal and Scope

Goal definition and scoping is perhaps the most important component of an LCA because the study is carried out according to the statements made in this phase, which defines the purpose of the study, the expected product of the study, system boundaries, functional unit (FU) and assumptions . Goal and Scope Definition is also aimed at identifying data sources and data quality requirements.

The goal of an LCA states the intended application, the reasons for carrying out the study, the intended audience, i.e. to whom the results of the study are intended to be communicated, and whether the results are intended to be used in comparative assertions

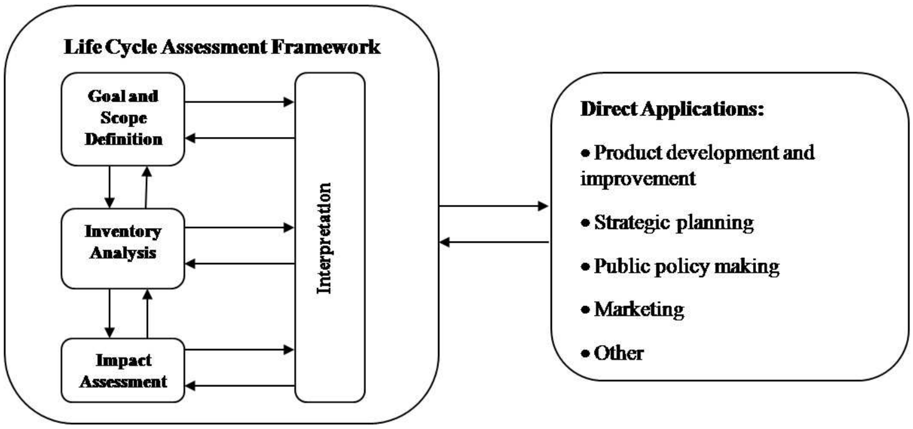

Figure 3.1: Four stages of LCA and their relation (ISO, 2006)

intended to be dis- closed to the public (ISO14040, 2006).

The scope should be sufficiently well defined to ensure that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal (ISO14040, 2006).

The scope includes the following items (ISO14040, 2006):

- the product system to be studied;
- the functions of the product system or, in the case of comparative studies, the systems;
- the functional unit; the system boundary; allocation procedures;
- impact categories selected and methodology of impact assessment, and subsequent interpretation to be used;
- data requirements;
- assumptions;
- limitations;

- initial data quality requirements;
- type of critical review, if any;
- type and format of the report required for the study.

The system boundary defines the unit processes to be included in the system (ISO14040, 2006). The system boundary of a system is often illustrated by a general input and output flow diagram. All operations that contribute to the life cycle of the product, process, or activity fall within the system boundaries.

The functional unit is the reference unit of the study and provides the basis on which alternative products or processes can be compared and analyzed (Ayer and Tyedmers, 2009).

The purpose of FU is to provide a reference unit to which the inventory data are normalized. The definition of FU depends on the environmental impact category and aims of the investigation. The functional unit is often based on the mass of the product under study. However, nutritional and economic values of products (Cederberg and Mattsson, 2000) and land area are also being used (Rebitzer et al., 2004).

3.2 Life Cycle Inventory (LCI)

This phase is the most work intensive and time consuming compared to other phases in an LCA, mainly because of data collection. The data collection can be less time consuming if good databases are available and if customers and suppliers are willing to help.

Life Cycle Inventory (LCI) consists of the collection and the detailed compilation of all the environmental inputs (material and energy) and outputs (air, water and solid emissions) at each stage of the life cycle to quantify all of the relevant inputs and outputs associated with the production of the functional unit (Ayer and Tyedmers, 2009; Roy et al., 2009).

Data on transport, extraction of raw materials, processing of materials, production of usually used products such as plastic and cardboard, and disposal can normally be found in an LCA database. Data from databases can be used for processes that are not product specific, such as general data on the production of electricity, coal or packaging. For product-specific data, site-specific data are required. The data should include all inputs and outputs from the processes. Inputs are energy (renewable and non-renewable), water, raw materials, etc. Outputs are the products and co-products, and emission (CO_2, CH_4, SO_2, NO_x and CO) to air, water and soil and solid waste generation (municipal solid waste: MSW and landfills) (Roy et al., 2009).

3.3 Life Cycle Impact Assessment (LCIA)

Life Cycle Impact Assessment (LCIA) aims at quantifying the relative importance of all the environmental burdens identified in the LCI by analysing their influence on selected environmental effects. This phase is focused on understanding and evaluating the magnitude and significance of the potential environmental impacts of the studied product system. Results of the life cycle inventory stage are grouped into categories (classification) and expressed in reference units to indicate their potential contribution to specific global environmental impacts (characterization). These two steps (classification and characterization) are mandatory steps according to ISO guidelines (ISO14040, 2006). According to ISO 14044 (2006), the general framework of an LCIA method is composed of several mandatory elements (classification and characterization) that convert LCI results into an indicator representative of each impact category and of optional elements (normalization and weighting) that lead to a single indicator comprehensive of all the impact categories using numerical factors based on value choices. Classification of the LCI results involves assigning the emissions, wastes and resources used to the impact categories chosen, e.g. CO_2, and CO_4, CO. The converted LCI results are aggregated into an indicator result, which is the final result of the mandatory part of an LCIA. Other optional steps are normalization, ranking, weighting and additional LCIA data quality analysis (Ayer and Tyedmers, 2009; Blengini and Busto, 2009; Ortiz et al., 2009) .

In this phase, the inventory results are assigned to different impact categories, based on the expected types of impacts on the environment (Roy et al., 2009). The impact categories considered are climate change, carcinogenicity, ozone layer depletion, acidification, eutrophication, eco-toxicity, human toxicity, radiation, land use, fossil fuels depletion, resource depletion, and photochemical smog. The impact categories related to the life cycle phases for EEE are deeply mentioned in Chapter 8.3.

3.4 Interpretation

Finally, the last stage of ISO 14040 is the interpretation. This stage identifies significant issues, evaluates findings to reach conclusions and formulate recommendations. The final report is the last element to complete the phases of LCA according to ISO 14040 (Ortiz et al., 2009). The results from the analysis would be used to evaluate each process to help make any decision as to which process to use. In the interpretation it is examined which process, substance and impact category is most important based on LCI and LCIA Andrae (2010).

This assessment may include both quantitative and qualitative measures of improvement, such as changes in product, process and activity design; raw material use, industrial processing, consumer use and waste management (Roy et al., 2009).

QFD is one of the appropriate tools that can be used in the interpretation step of LCA thanks to its ability to provide a means of translating customer requirements into the appropriate technical requirements for each stage of product development and production (i.e., marketing strategies, planning, product design and engineering, prototype evaluation, production process development, production, sales)" (Sullivan, 1986).

In order to formulate recommendations to the decision makers, the results obtained from the Interpretation phase can be used in QFD for Environment, an extended version of QFD. Detailed information about QFD for Environment will be provided in Chapter 8.6.

4 Life Cycle Costing

Ecodesign is based on the notion of sustainability, and sustainability can only be achieved if proposed solutions and environmental or social improvements are economically viable.

Life Cycle Costing (LCC) Analysis is an essential design process for controlling the initial and the future cost of life cycle thinking application towards sustainable production and consumption and used in companies' decision making on major investments and life cycle of products (Krozer, 2008).

The life cycle inventory of an LCA is an excellent basis for identifying and allocating all of the costs given on Figure 4.1 (Alting, 1993; Rebitzer, 2002).

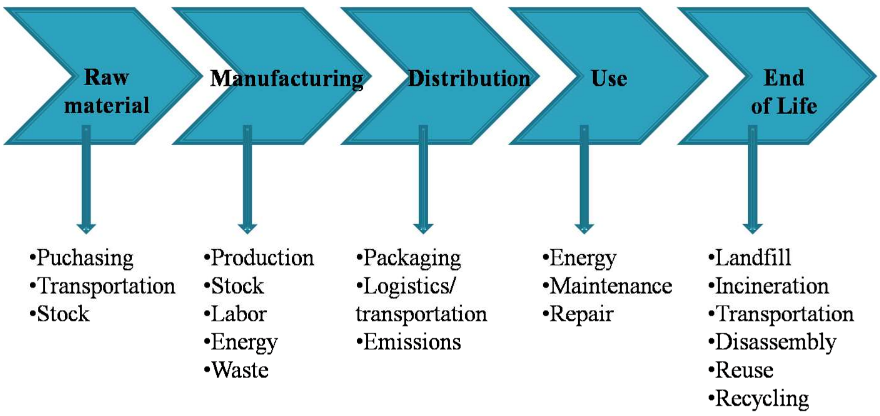

Figure 4.1: Possible life cycle cost contributions in each life cycle phase

LCA-based life cycle costing allows for an integrated environmental and economic assessment of different options, therefore enabling decision-makers to make the best overall decision, or to tackle trade-offs, if they exist, on a transparent basis. Therefore, such an approach is an essential contribution to the proliferation of life cycle management practices and corresponding sustainability metrics as advocated in the literature (Hunkeler and Biswas, 2000; Hunkeler et al., 2003).

The LCA-based LCC methodology aims to: compare life cycle costs of alternatives, detect direct and indirect (hidden) cost drivers, identify trade-offs in the life cycle of a product, utilize the full costing to identify new products, and record the improvements made by a firm in regards to a given product.

This system approach, which is relevant for both environmental and economic aspects, is illustrated in Figure 4.2 (Rebitzer et al., 2003). The principal generation (where/when they occur) as well as the pre-determination (when/where they are influenced) of costs and environmental impacts are illustrated. It also shows the relevance of addressing environmental issues and life cycle costs at the initial stages of research and development (R&D), and product planning and design. Although the R&D phase does not, itself, contribute to a great share of the overall costs and environmental impacts-generally between 5-25% of the direct product manufacturing cost which, itself, is only one segment of the total life cycle cost – it is extremely significant in determining the costs and impacts in other phases of the life cycle.

The R&D phase is key to producing a cost-efficient product with minimal environmental impact in terms of resource consumption and emissions.

Owing to widespread consciousness of global environmental problems and environmental legislative measures such as take back and recycling laws, manufacturers also have to consider reducing the cost which a user incurs during consumption and which society incurs in disassembling, recycling, and disposal. The costs incurred during production, use, and disposal are mostly committed by early design decisions. Studies reported in Dowlatshahi (1992) and by other researchers in design, suggest that the design of the product influences 70%–85% of the total cost . Design methods for minimizing the LCC of the product thus become very important and valuable. LCC analysis provides the framework for specifying the estimated total incremental costs of developing, producing, using, and disposing of a particular item (Seo et al., 2002).

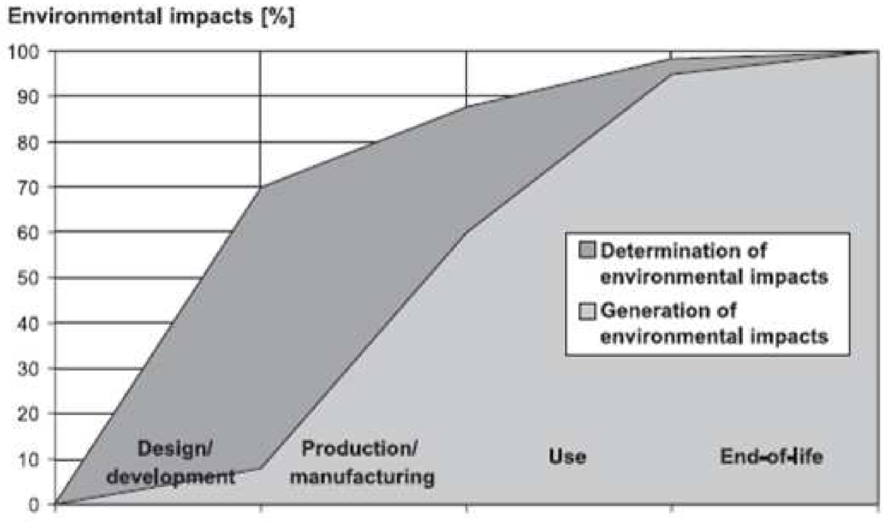

Figure 4.2: Generation and pre-determination of the costs and environmental impacts in a product life cycle (Rebitzer et al., 2003)

In addition to the costs of physical processes and their associated material and energy flows identified by the life cycle inventory analysis step of LCA (ISO 14041), expenses, such as labor costs, costs for utilizing knowledge (e.g., patents), transaction costs (e.g., information flows), and marketing expenses, have to be considered.

It has to be noted that this life cycle costing methodology is meant to be used for rough cost estimations in, for example, product development or marketing analysis. Due to its comparative and systemic nature, it is not a method that can replace traditional detailed financial cost accounting or cost management practices.

If there are high uncertainties in respect to expected costs, specifically in the future, or in regards to the discounting rate to be chosen, it is advisable to focus on the costs and assumptions that differ in the alternatives studied, and to employ sensitivity analysis on a comparative basis (Rebitzer et al., 2003).

Eco-costs can be estimated as a (Boussabaine and Kirkham, 2008):

1. Percentage of the capital cost of each element

2. Cost per unit
3. Percentage of the total cost
4. Product-related cost
5. Combination of the above.

5 Electrical and Electronic Equipment

One of the most important fields that we have to start the "cleaning" is the electrical and electronic equipment (EEE). This type of product has a significant negative impact on the environment and the human health when it becomes wastes. Because of the fast expansion of the electronic equipment sector, the number of products is getting higher and higher every year. Statistics shows us the gravity of the problem all over the world.

According to the European Commission, total amount of waste in Europe is expected to increase by about 45% between 1995 and 2020 (Hischier et al., 2005). In the former 15 European Union member countries (EU15) the amount of waste electrical and electronic equipment (WEEE, or shortly e-waste) produced varied between 3.3–3.6 kg per capita for the period 1990–1999 and has been projected as 3.9–4.3 kg per capita for the period 2000–2010 (Streicher-Porte et al., 2005). Current WEEE arising across the European Union (EU-27) amounts 8.3–9.1 millions tons per year, which corresponds to around 17 kg per capita and year (Chancerel and Rotter, 2009).

Data on WEEE from 1998 show generation of 14 kg per inhabitant and year - in total, around 6 million tonnes annually in the EU-15, or 4% of the municipal waste stream. The quantity of WEEE was estimated to be growing at 3-5% per year - more rapidly than any other waste stream and three times faster than the average. Today, each European is likely to generate between 17 and 20 kg of WEEE per year[4].

EEE are covered under 10 categories according to WEEE Directive :

1. Large household appliances
2. Small household appliances

[4] http://europa.eu/rapid/pressReleasesAction.do?reference=MEMO/06/263&format=HTML&aged=0&language=EN&guiLanguage=en

3. IT and telecommunications equipment
4. Consumer equipment
5. Lighting equipment
6. Electrical and electronic tools (with the exception of large-scale stationary industrial tools)
7. Toys, leisure and sports equipment
8. Medical devices (with the exception of all implanted and infected products)
9. Monitoring and control instruments
10. Automatic dispensers

Among this big variety of products, there are some groups, e.g. computers, mobile phones, etc., which contribute most the WEEE problem.

According to UNEP (United Nations Environment Programme), some 20 to 50 million metric tonnes of e-waste are generated worldwide every year, comprising more than 5% of all municipal solid waste. When the millions of computers purchased around the world every year (183 million in 2004) become obsolete, they leave behind lead, cadmium, mercury and other hazardous wastes. In the US alone, some 14 to 20 million PCs are thrown out every year. Developing countries are expected to triple their output of e-waste by 2010[5].

As long ago as 2003 it was estimated there were 1.3 bn mobile 'phones in use across the globe, with the total predicted to double by 2006. By April 2008 the number had reached more than 3 bn - nearly one person in two worldwide. The International Telecommunication Union suggests Africa is the world's fastest-growing mobile market, with subscribers increasing between 1998 and 2005 by 1,000%: in Nigeria the increase from 2000 to 2006 was 10,000%, a rate made possible partly by imports of second-hand mobiles from

[5] `http://www.unep.org/Documents.Multilingual/Default.asp?DocumentID=485&ArticleID=5431&l=en`

developed countries. But too often the argument that this trade is "building bridges over the digital divide" is used as an excuse to obscure and ignore the fact that these bridges double as toxic waste pipelines to some of the poorest communities and countries in the world.

In Japan, the total number of appliances discarded was estimated to be 22.87 million units in 2005, or 860,820 tonnes, based on the average weight and total quantity of type of each appliance. The number of each discarded appliance is as follows: 4936 thousand units of air conditioners, 8994 thousands units of CRT TVs, 4339 thousand units of refrigerators and 4603 thousands units of washing machines (Aizawa et al., 2008).

To summarize, the percentages of the e-wastes are as follows[6]:

- Monitors : 10%
- TVs : 10%
- Computers, phones, fax, printers : 15%
- DVD/VCD, CD players, radios, Hi-Fi appliances : 15%
- Refrigerators : 20%
- Washing machines, hoovers, ovens, air conditioners, coffee machines, etc. (Small and Large Household Appliances): 30%

As for Turkey, the president of ELECTRO World Bahadır Özbek gives the approximate quantities of e-wastes as follows[7]:

- Monitor/ TV : 56.480 tonnes
- IT/ Telecommunication: 42.360 tonnes
- Entertainment equipments: 42.360 tonnes

[6] www.exitcom.com

[7] http://www.exitcom.com.tr/basin.html

- Refrigerants: 56.480 tonnes
- Small and Large Household Appliances: 84.720 tonnes

These data give us the approximate total e-waste quantity in Turkey, which are 280.400 tonnes. According to this number, the aim is to collect 4 kg/person e-waste in year.

It is clear that this type of waste is occupying more space day by day but why will we still be interested in electrical and electronic equipments' design? That's because these equipments contain toxic materials. Regarding the toxicity of e-waste, hazardous components commonly found in electronic devices include lead, mercury, beryllium, barium , hexavalent chromium, cadmium, arsenic, nickel, zinc, and brominated fire retardants (BFR) in the plastics (Widmer et al., 2005). For example, CRTs contain lead, a well-known hazardous substance, TVs capacitors contain polychlorinated biphenyls, air conditioners contain mercury relay switches, and refrigerators contain ammonium. Glass of funnels contains more lead than glass of panels (Aizawa et al., 2008).

These toxic materials merge into soil, water and to the air while the e-wastes are landfilled or incinerated, and they threaten the environment and the human health. For example the cadmium from one mobile phone battery is enough to pollute 600,000 liters of water[8].

Non-environmentally and over production of EEEs cause another problem: resource depletion. Valuable metals, different types of energy are consumed consistently and these are non-renewable resources.

At the moment, many electrical and electronic products are being disposed of in landfill sites and millions of tonnes of materials that could be recovered and reused for new products are being lost. Recovery of these materials would reduce the need to extract more raw materials for the manufacture of new products. Another benefit of recycling is the saving of energy achieved if raw materials could be recycled instead of mined. For example, aluminum mining uses 20 times the amount of energy it takes to recycle the same amount[9].

[8] `http://news.bbc.co.uk/2/hi/technology/2603589.stm`

[9] `http://www.citizensinformation.ie/categories/environment/waste-management-and`

Furthermore, there are legal mandatory that force the producers to take care of their e-wastes. Many countries, such as EU countries (WEEE Directive, 2003), Switzerland (SWICO and SENS,1998) (Khetriwal et al., 2009), many states in USA (e.g. California, Connecticut, Maine, Rhode Island, etc.) (Davis and Herat, 2008), Japan (Electric Home Appliances Recycling Law – EHARL, 2001) (Kahhat et al., 2008), Taiwan (Waste Disposal Act Amendments, 1998), S. Korea (Recycling Law, 2006) (Terazono et al., 2006), have promulgated legislation to improve the reuse, recycling and other forms of recovery of such wastes so as to reduce disposal (Cui and Forssberg, 2003).

In 2012, Turkey has promulgated a similar version of European Union's WEEE Directive, "Atık Elektrikli ve Elektronik Eşyaların Kontrolü Yönetmeliği". It has the same scope and requirements about e-wastes' collection and treatment as WEEE Directive. This is a late, but in the end positive step forward in WEEE management. According to this regulation, consumers are responsible not to mix WEEE with other types of waste, take-back their WEEE to collection centers or to EEE stores. Retailers and distributors are responsible for take back of WEEE that consumers have returned. Producers are responsible for taking free WEEE from consumers, distributors, retailers and municipalities. Contrarily, they are not obliged to collect WEEE actively. They can accomplish their duties with accommodating special undertakings. Another duty for producers is to prepare educational campaigns to make consumers more aware on WEEE.

The importance of the topic drew the attention of the researchers and directed them to work on. The first studies on WEEE started to appear in the literature in the 1990s, though the interest in this field has been grown in 2000s. A few papers draw the scope of the notion (Schmidt, 2005; Widmer et al., 2005; Barba-Gutiérrez et al., 2008; Dimitrakakis et al., 2009; Khetriwal et al., 2009).

WEEE and its management are also examined in the papers related to reverse logistics (White et al., 2003; Nagurney and Toyasaki, 2005). The majority of these studies are about e-waste treatment strategies, especially recycling, and its technical procedures (Balart et al., 2005; Darby and Obara, 2005; Hicks et al., 2005; Hischier et al., 2005;

-recycling/waste_from_electric_and_electronic_equipment

Tange and Drohmann, 2005; Mohabuth and Miles, 2005; Streicher-Porte et al., 2005; Tasaki et al., 2006; Mohabuth et al., 2007; De Marco et al., 2008; Nnorom and Osibanjo, 2008b; Wu et al., 2008; Johansson and Luttropp, 2009; Vilaplana et al., 2009).

Another considerable research field is WEEE regulations and e-waste management applications in many countries (Kang and Schoenung, 2005; Sinha-Khetriwal et al., 2005; He et al., 2006; Peralta and Fontanos, 2006; Li et al., 2006; Lee et al., 2007; Davis and Herat, 2008; Nnorom and Osibanjo, 2008a; Yang et al., 2008; Manomaivibool, 2009).

Some of the researchers are interested in optimization of key factors or the ratios of different types of e-waste treatments (Bereketli et al., 2011; Jiang et al., 2008), and the others in the evaluation of recycling performance |citelaner2007treatment, lin2008model, and in the multi-criteria analysis based evaluation of e-waste treatment strategies or the treatment site locations by using PROMETHEE (Queiruga et al., 2008; Rousis et al., 2008).

The studies combining ecodesign and EEE will be also mentioned in Chapter 6.

6 Current situation in Academia - Literature review

Ecodesign concept appeared in the beginning of 90s, with the studies of pioneering researchers (Navinchandra, 1991; Simon and Dowie, 1993; Roy, 1994; Van Weenen, 1995; Fiksel, 1996; Brezet et al., 1997; Bhamra and Evans, 1999). All these studies aim to provide a new insight into product development by introducing environmental approach. Nevertheless interest on the topic had risen within the new millennium, when global environmental problems became more visible.

There are several papers in the literature related to ecodesign.

In 2002, van Hemel and Cramer analyzed which stimuli and barriers play a role in the success or failure of the various ecodesign solutions. As a remarkable study in the field, they concluded that internal stimuli are a stronger driving force for ecodesign than external stimuli. An ecodesign improvement option only stands as a chance, if it is supported by stimuli oher than the expected environmental benefit alone. Luttropp and Lagerstedt (2006) presented ten golden rules for ecodesign process that provide a common foundation, which can be used as a base and guidelines for development of situation specific product-design challenges. Karlsson and Luttropp (2006), Kurk and Eagan (2008), Zuidwijk and Krikke (2008), Albino et al. (2009) have also drew the baseline of the ecodesign with their studies.

Some researchers are interested in ecodesign methods and tools, either to develop, improve or criticise (Byggeth and Hochschorner, 2006; Lindahl, 2006; Lofthouse, 2006; Knight and Jenkins, 2009; Chu et al., 2009; Almeida et al., 2010; Pigosso et al., 2010), and some others in its relation with Life Cycle Assesment concept (Nielsen and Wenzel, 2002; Jeswiet and Hauschild, 2005; Sadiq et al., 2005; Scharnhorst et al., 2006). Some studies emphasized disassembly, recycling and end-of-life strategies as central issues in ecodesign (Rose et al., 2002; Johansson and Luttropp, 2009; Santini et al., 2010; Luttropp and Johansson, 2010).

There are also remarkable studies for different sectors, such as automotive (Munoz et al., 2006; Alves et al., 2010), lighting (Gottberg et al., 2006), electrical and electronic equipment (EEE) (De Langhe et al., 1998; White et al., 2003; Gurauskiene and Varzinskas, 2006; Aoe, 2007; Georgiadis and Besiou, 2008; Mathieux et al., 2008; Platcheck et al., 2008; Platcheck et al., 2008; Johansson and Luttropp, 2009; Kunnari et al., 2009; Muñoz et al., 2009; Liao et al., 2012). Most of these works are case studies, except Gurauskiene and Varzinskas (2006) and Platcheck et al. (2008) who proposed a systematic approach to conduct ecodesign for EEE.

The most interesting point about all these studies is that they mostly lack different parameters of design, such as cost, quality, functionality, etc. The researchers seem to tend to ignore these parameters while they are focusing on environmental issues. This thesis aims to fill in this gap by considering different aspects of design together, however taking environmental ones as the priority. This aim can become concrete by integrating environmental approaches with the traditional product design tools.

Among the studies focused on the methods and tools, the ones who worked on their integration with ecodesign are considered as the roots of this thesis and deserve a closer look.

As indicated in Chapter 2, among the techniques used in environmental assessment, QFD stands as a tool by having the ability to combine product design requirements with economic, social and environmental aspects. Therefore QFD is one of the most suitable product development tools to work with ecodesign. The applications of QFD have been expanded to a wide variety of areas, such as design planning, engineering, management, teamwork, timing, costing, to name a few. Nevertheless studies integrating the environmental approach into traditional QFD are relatively recent and few.

Cristofari et al. (1996) developed the Green QFD (GQFD) method to integrate life cycle analysis and QFD to evaluate products using environmental considerations. Zhang (1999) improved this tool by presenting the GQFD II that integrates life cycle assessment, life cycle costing and QFD into an efficient tool that deploys customer, environmental, and cost requirements throughout the entire product development process. Bovea and Wang (2005) applied GQFD to the furniture industrial sector to help a design team concurrently to design products according to the consumer demands and with a reduced cost and environmental impact.

Masui et al. (2003) developed a new method called QFD for Environment (QFDE) by incorporating environmental aspects (environmental voice of customers (VoC) and environmental engineering metrics (EM)) into QFD to handle the environmental and traditional product quality requirements together, intended to be used in the early stages of product design. Sakao (2007) proposed a general design methodology to effectively support environmentally conscious product design. He combined in his methodology three tools: LCA (life cycle assessment), QFDE (quality function deployment for environment), and TRIZ (theory of inventive problem solving), and applied it for a "hair dryer". He claimed that the methodology has a larger benefit than is obtained from utilizing those three tools independently. Recently, Zhang et al. (2011) proposed an improved QFDE method, with the conversion of customer requirements into technical parameters so that the customer requirements can be satisfied in the subsequent design process .

Besides these two extended methods, conventional QFD is still used among researchers to reflect the environmental product development approach. Rahimi and Weidner (2002) integrated "Design for Environment" concept into the QFD process. They redefined the traditional sequence of house of quality (HoQ) matrices to include the structuring of design objectives and alternatives based on a multi-objective decision hierarchy. Kobayashi (2005) presented a methodology and a software tool to establish an ecodesign concept of a product and its life cycle by assigning appropriate life cycle options to the components of the product. To this end, he used QFD and life cycle assessment data. Lei et al. (2007) described the extended quality function deployment in life cycle design (LCD). They defined the structure of the extended QFD for LCD. They also proposed a method to choose and adjust HoQ depending on different target products.

Although these studies are significant efforts in environmental product design, they do not provide a precise sustainability framework for the identification of the relevant improvement strategies related to part characteristics. A sustainability framework for the identification of the relevant ecodesign improvement strategies should serve as a basic conceptual structure for decision makers in conducting ecodesign with a multi-aspect approach (such as cost, quality, environmental, social aspects etc.) and should include an integrated methodology, which is able to combine the required aspects.

The novelty of this thesis among the existing studies in the literature stands on providing a holistic, integrated methodology based on QFDE and suitable decision making tools aiming at identifying and selecting the ecodesign improvement strategies to implement by considering cost and quality aspects as the constraints of the decision making problem.

Apart from the environmental assessment and life cycle thinking techniques, QFD is also combined with decision making methods. The first phase of the QFD is the house of quality (HoQ), which is the key strategic tool to determine the engineering metrics that satisfy the stakeholder requirements. Determining the relative importance of stakeholder requirements (SR) and engineering metrics (EM) is an important step of the QFD. In order to determine their relative importance, several methods are applied such as Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), TOPSIS, fuzzy set theory, etc.

The studies in the literature which combine QFD with decision making methods are as follows . Pal et al., 2007; Andronikidis et al., 2009; Çelik et al., 2009; Lee et al., 2010; Lin et al. 2010, they integrated decision making methods such as Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), fuzzy set theories, etc., with QFD in order to weight Stakeholder Requirements (SR) and/or Engineering Metrics (EM). However none of these integrated studies had environmental concerns.

In the field of product development, AHP combined QFD methodologies are used by many authors. Wang et al. (1998) compared the two weighting methods in QFD, AHP and prioritization matrix method, and they concluded that if time, cost and difficulty are the major concerns in product improvement, the prioritization matrix method is preferred; where accuracy is the major requirement, the AHP method would be a better choice.

Yung et al. (2006), Lin et al. (2006), Lin et al. (2008), Erkarslan and Yılmaz (2011), used AHP to prioritize customer requirements and design characteristics in QFD.

Some other studies also combined fuzzy set theory with AHP and QFD. Kwong and Bai (2003), proposed a fuzzy AHP with an extent analysis approach to determine the importance weights for the customer requirements. Nepal et al. (2010) presented a fuzzy AHP framework for prioritizing customer satisfaction attributes in target planning. Ho et al. (2012) developed an integrated approach, combining QFD, fuzzy set theory, and AHP, to evaluate and select the optimal third-party logistics service providers (3PLs). The importance of evaluating criteria is prioritized with respect to the degree of achieving the stakeholder requirements using fuzzy AHP. Li et al. (2012) presented a systematic and operational method based on the integration of a minimal deviation based method, balanced scorecard, AHP and scale method to determine the final priority ratings of customer requirements.

Currently, there are only a few studies, which aimed at integrating AHP with environmental product development techniques. Zhang et al. (1998) combined GQFD-II with AHP in order to evaluate the eco-product concepts. Madu et al. (2002) used AHP to develop priority indices for customer requirements in QFD to highlight key features that must be present in the product. They added green issues into manufacturing. Boonkanit et al. (2007) proposed a methodology for selecting products at conceptual design phase, by integrating QFD, Design for Environment (DfE) and AHP. They generated design ideas through QFD and DfE, and they used AHP not to prioritize the stakeholder requirements but to select the best design alternative at the final stage of their study.

Nevertheless, none of these studies has the aim of selecting improvement strategies by including both the fuzzy decision making systems, and the environmental approach together in product development, and providing a holistic methodology.

In this thesis, a multi aspect QFDE approach will be presented for identifying improvement strategies in sustainable product development. The proposed methodology will also fill the above mentioned gap in the literature by integrating fuzzy AHP into multi-aspect

QFDE. The new approach can improve the imprecise ranking of stakeholder requirements inherited from studies based on the conventional AHP. Furthermore, the fuzzy AHP with extent analysis is simple and easy to implement to prioritize customer requirements in the QFD process compared with the conventional AHP (Kwong and Bai, 2003).

In every step of ecodesign process, decision making methods are needed to help engineers to decide either on the significant environmental aspects and/or impacts to focus on, or the select the optimal ecodesign improvement strategies to implement. Despite of this expected cooperation, there are few and recent studies in the literature which use decision making methods integrated with ecodesign (Borchardt et al., 2009; Contreras-Miranda et al., 2010; Kengpol and Boonkanit, 2010; Remery et al., 2012; Herva et al., 2012). This indicates a gap in the field and motivates the author of this thesis to work on this subject.

7 Current situation in Industry - Survey

In this part of the study, the current situation of the use of ecodesign in industry is investigated. The analysis is based on the relevant literature review concerning mostly the problems faced by Small and Medium sized Enterprises (SME), and the survey conducted with engineers to examine their positions against ecodesign.

7.1 The challenge for SMEs and the beginners

The previous studies in the literature show that conducting a complete LCA is mostly time and cost consuming for the companies (Rebitzer et al., 2004; Le Pochat et al., 2007; Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010a). Especially for SMEs, any kind of environmental assessment is accepted to be a significant additional load on the company's shoulders since they have limited resources. Therefore they tend to ignore environmental concerns in their product development management except for some obligatory requirements of regulations (Hauschild et al., 2005).

Another obstacle standing in front of applying life cycle assessment and ecodesign techniques in product development process is the lack of knowledge, scarcity of data, lack of awareness, restrictions in specific resources for environmental issues and low levels of training (Masoni et al., 2004; Finnveden et al., 2009).

The matter of subjectivity is also a critical issue in LCIA and its interpretation. Manufacturers may choose several or only one impact category to assess their product's environmental profile according to their personal and/or corporate preference. For instance, in the case that Carbon Footprint results are needed for the communication with consumers, they would prefer to measure only the Global Warming Potential impact category and its related environmental aspect energy consumption. Although it seems to have a reasonable explanation, analyzing the environmental performance of the product requires more scientific base than a subjective preference. Thus, a decision making problem should be modeled to select the right environmental aspect and/or impact.

All these studies and arguments point the need of the companies, especially SMEs, for a simplified way to do an environmental assessment. There is clearly a need for a rapid decision or a rough first overview of a system's aspects and/or impacts in order to decide on further investigations and improvement strategies (Rebitzer et al., 2004). Especially considering the lack of data to conduct an LCA, focusing on only one environmental aspect will help manufacturers to reduce inventory requirements and work with less data.

The interest on exploring new ways to simplify the existing LCA methodology has increased among the researchers in the last decade. In 2001, Fleischer et al. proposed a methodology that lowers the requirements for data quality (accuracy) for process emissions within a simplified LCA. Kaebernick et al. (2003) presented a new simplified methodology, which calculates the product's Environmental Performance Indicator by using two sets of energy-based and material-based Impact Drivers. Hur et al. (2005) developed a simplified LCA (SLCA) method to efficiently identify EEE's significant environmental aspects for eco-design by using the environmentally responsible product assessment (ERPA) matrix method. Mourad et al., (2007) generated a simplified inventory useful for different purposes in agriculture sector. Zah et al. (2009) created a web-based questionnaire for "Sustainability Quick Check for Biofuels" in order to model a specific inventory, which increases in the end the speed of the environmental assessment. Bala et al. (2010) limited the environmental assessment to a single impact category, Global Warming Potential, and advocate, by providing two application examples, the adoption of tailor-made streamlined approaches, with reduced inventory requirements and impact assessment scope. Zabalza et al. (2009), Kellenberger and Althaus (2009) and Malmqvist et al. (2011) presented simplifications in LCA methodology to adopt a systematic approach in building sector. Ostad- Ahmad-Ghorabi and Collado-Ruiz (2011) modeled the LCA inventory information out of design parameters and also presented a parametric tool implementing this.

There also exist in the literature some studies concentrating on multi criteria decision making for a simplified environmental assessment by fuzzy logic methods (Gonzalez et al., 2002), for ranking the impact categories by using AHP with the regional scale point of view (Hermann et al., 2007), for weighting them by using a panel approach and a Multi-Criteria Decision Aid (MCDA) (Soares et al., 2006), for developing ecodesign at the conceptual design phase by integrating ANP and distance to target (DT) method (Kengpol and Boonkanit, 2010).

7.2 The motivation for the survey

Previous studies (see Chapter 6) which investigated the existing ecodesign tools and methods pose an additional workload for engineering designers during the product development process. Experiences with industry have shown that this additional workload is one reason for the denial of the use of such tools. The incompatibility and complexity of some tools with the design and product development process may be another reason (Knight and Jenkins, 2009) While many tools are optimized to deliver good results discretely along the design process, the feedback gained from the conducted ecodesign analysis sometimes cannot be implemented in a closed loop: the feedback may then be implemented in the next product concept or through a product improvement process (open loop). For example, many environmental evaluation tools require information which may not be available in the early stages of product design, when requirements are set and concepts are developed (Karlsson and Luttropp, 2006). Once the required information is available, the flexibility to change the design of the product for which the evaluation is carried out is strongly restricted (Lindahl, 2003). This may be a reason why the environmental parameter is pushed into the background in the spotlight of other design parameters such as functionality, quality, safety, ergonomics, aesthetics and cost to be optimized during the design process (Luttropp, 1999) Considering the environmental parameter through the design process is still by far not a matter of course but is rather regarded as an add-on allowing some competitive advantage.

There have been some efforts to provide ecodesign tools which can be used along the design process continuously. Lutropp and Lagerstedt (2006) differ between tools which can be used before the product specification phase and those to be used after product specification. The listing should be understood as a set of different tools suitable for different phases rather than a single tool. Lofthouse (2006) defines general requirements for ecodesign tools. Collado-Ruiz and Ostad-Ahmad-Ghorabi have proposed in 2010 an approach to compare the environmental performance of similar products already in early design stages.

In order to develop a comprehensive ecodesign approach and tool which can assist engineering designers through the entire design process, from product specification phase to prototyping, the requirements of designers regarding such tools are aimed to be covered in this part of the study. Experts from industry are surveyed and their expectations and requirements considering ecodesign tools are analyzed. The analysis serves as a first basis for the development of a comprehensive approach.

7.3 Survey

The survey is conducted in order to define the requirements of the designers to conduct ecodesign and sustainable product development of EEE.

At the end of the study it is expected to learn if designers are using ecodesign methods and tools and if they are using them, which one of these they have been using; to learn about the advantages and disadvantages of these methods and tools in designers' opinion; which requirements they need in each step of the design process, and which methods and tools they use in each step of the design process.

7.3.1 Key requirements

Key aspects surveyed within the questionnaire were information, motivation, multi-disciplinary cooperation and creative environments in different ecodesign phases and ecodesign context. These possible requirements are determined by having regard to related literature (Lofthouse, 2006). They are discussed in the following.

7.3.2 Information

Providing the right information to designers for ecodesign is not an easy mission. There is a lot of information, which has to be considered when a designer wants to develop a new electrical or electronic product. The information has to be kept up to date to be useful at all.

There are legislations, which have to be kept in mind, like the EU directives WEEE (Directive2002/96/EC, 2003), RoHS (Directive2002/95/EC, 2003), and EuP/ErP (Directive2005/32/EC, 2005; Directive2009/125/EC, 2009). And there are some additional requirements to be fulfilled, if it's an aim to get an eco-label like the EU Ecolabel (Regulation, EC), the Blue Angel[10], the Green Seal[11] or one of the many others.

The major challenge is to offer the really valuable information at the right moment, in a way the designer is not too overwhelmed with technical and scientific terms or by the large amount of text or data that has to be processed. It is rather helpful to provide it in a visual way with a possibility to find further information, when needed (Lofthouse, 2006; Ostad-Ahmad-Ghorabi et al., 2009). Many designers find it useful to find examples for well-designed sustainable products and to have some benchmark information fore hand. Some efforts in this direction have been undertaken (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010a).

The crucial parameter is time. Any tool that is to be used in the design process has to save time and should not add to workload. Any kind of guidance is helpful and crucial: to guide where, when and how to start with the ecodesign process or which parts and components to consider first.

[10] `http://www.blauer-engel.de/en/index.php`

[11] `http://www.greenseal.org/`

7.3.3 Multi-Disciplinary Cooperation

With increasing complexity of a product's function and structure, product multi-disciplinary cooperation design becomes fairly necessary (Alves et al., 2007). Multi-disciplinary cooperation is about a conversation between departments, marketing teams, distribution chains, designers, engineers and manufacturers.

Multi-disciplinary cooperative environments play an important role in idea generation and new product conceptualization. They improve the creative competencies and allow rich combinations of disconnected pools of ideas. They seem to conduce to better use of limited research capacities and the development of valuable and more radical ideas and solutions. Therefore, they are more effective in the pursuit of creativity, innovation and product development (Alves et al., 2007).

As mentioned before, ecodesign has multifaceted aspects, such as economy, ergonomics, aesthetics, quality, performance and functionality (Karlsson and Luttropp, 2006). That's why designers should be in cooperation with other disciplines to get the required data and information while designing environmentally friendly products.

7.3.4 Motivation

According to the application of ecodesign and product development in a company, the organization must assess factors regarding the company (internal) and the environment (external) (Borchardt et al., 2009). The motivation to conduct ecodesign in a company may come from internal drivers and external drivers and can also be pushed by government, business partners, regulations, citizen groups, associations or customers' needs.

Designers are personally motivated by the sense of professionalism, problem solving and opportunities to be creative in the design process (Salter and Gann, 2003). For the ecodesign process, designers need additional motivation in order to overcome the pressure on them to change their usual working way and design habits.

7.3.5 Creative Environment

Designing EEE that reduces environmental impacts will require the highest levels of creativity, the use of both traditional and advanced technologies, and the collaboration of many diverse organizations. However, preserving the environment for future generations seems like a good reason for being creative and innovative (Roy, 2000).

Within such framework, the ecodesign process is based upon creativity and innovation in productive cycles. Designers and companies focus solely on the design phase, in a completely innovative way and with the possibility to use recycled materials (di Maschio, 2011). This new environmental awareness is strictly connected with creativity and innovation. Creative design and breakthrough innovations in EEE companies are necessary for a rapid shift to an economically sustainable path (Fiksel, 2009). To reach the creative design, the designers require an adequate environment which can improve their creativity.

7.3.6 Survey Questions

Regarding the concerns presented in previous subsections the questions are prepared. See Appendix – I for the survey questions.

7.4 Presentation

The survey questionnaire is realized by 18 engineering designers/experts working in international industrial environment. The least experienced expert has only one year of background on design nevertheless the average experience years among the experts is 8 years. These people are chosen thanks to their ability to give actual valuable insight in their work.

The survey starts with the investigation of the experts' background on ecodesign and sustainable product development. According to their answers, the survey is branched in two parts, for experienced and non-experienced designers in EEE ecodesign field. For those who have already experience, the quality of their experiences, the ecodesign aspects that they focused on, the methods they used and their driving forces to apply ecodesign are asked. The designers with no experience in the field are asked why they have never used ecodesign tools and methods before and what they would need in order to use them.

Both groups of designers were asked about their personal requirements to undertake an ecodesign process in EEE sector, the priority and importance of each requirement; the possible ways to provide information, guidance and motivation, and the departments needed to cooperate in order to succeed in the ecodesign process. As the final questions of the survey, the relations between ecodesign methods and tools and the design process phases are questioned.

7.5 Results

In the survey conducted, the experts were asked 16 questions.

First the ecodesign background of the engineers are questioned to see if they are aware of the similarities and differences between traditional design and ecodesign processes. The results (See Figure 7.1) show that engineers mostly do not relate cost and quality parameters to ecodesign. They also do not think ecodesign will provide competitive advantage. These results indicate that engineers are mostly unaware of the wide perspective of ecodesign, mentioned in Chapter 2.

Most of the engineers, who answered the survey questions, have used ecodesign methods and tools or even if they have not, they have knowledge on ecodesign. Only 11% of the participants have not used ecodesign methods and tools and they do not have any background in this area (See Figure 7.2).

The experts who have applied ecodesign processes in their work mostly focused on reducing the energy consumption, materials used and the environmental impact of the product (See Figure 7.3).

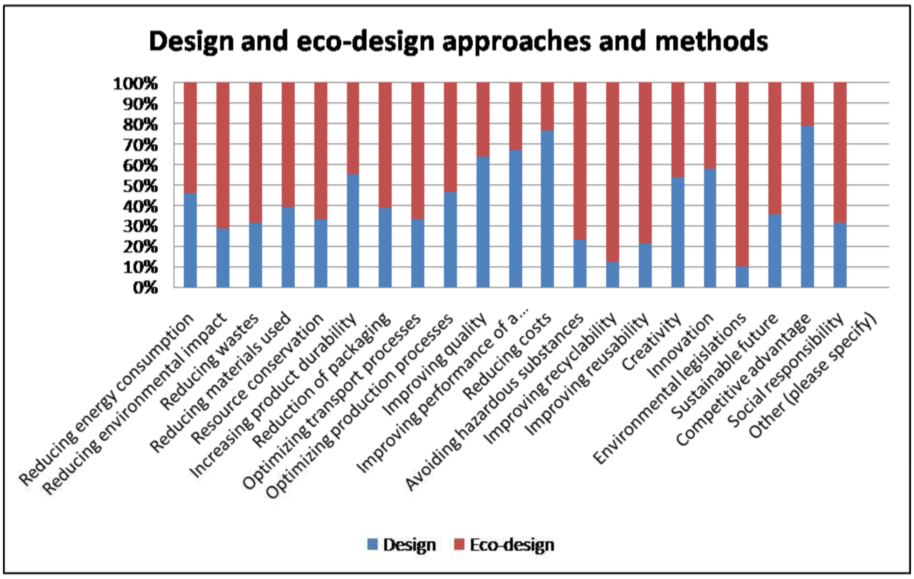

Figure 7.1: Answers to Question 1

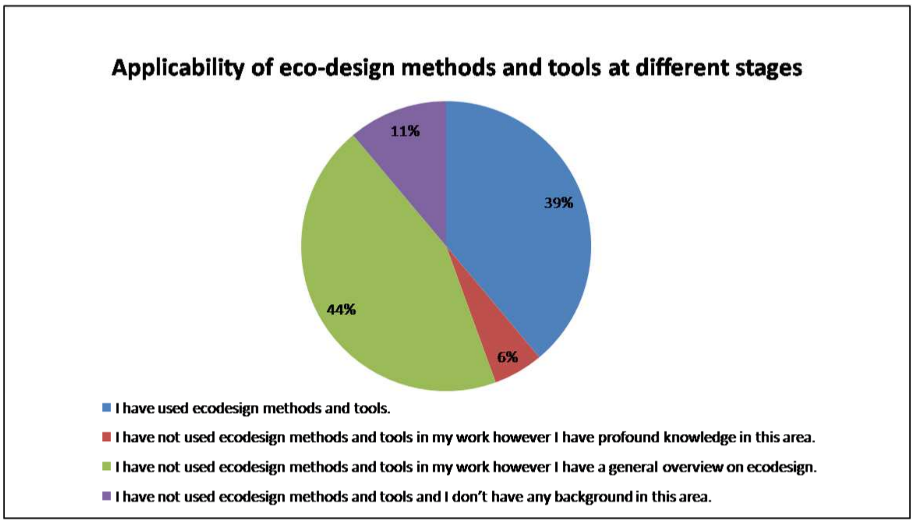

Figure 7.2: Answers to Question 2

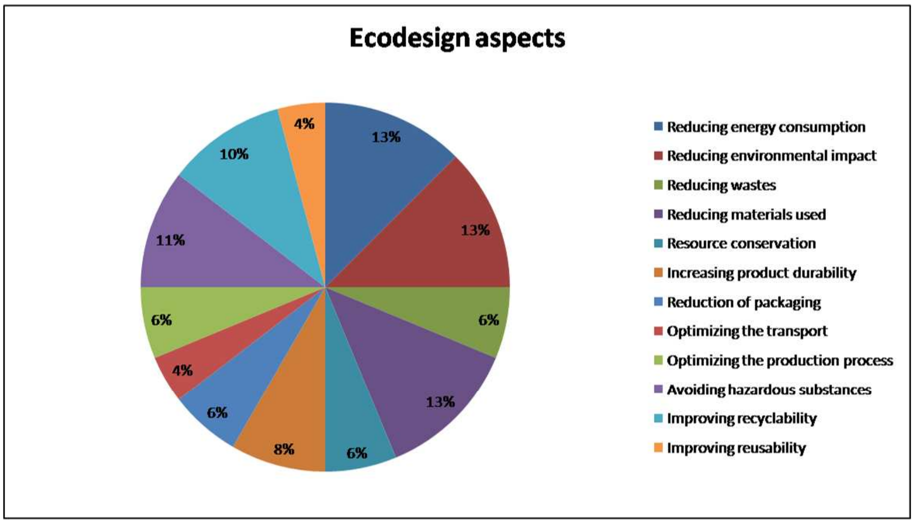

Figure 7.3: Answers to Question 3

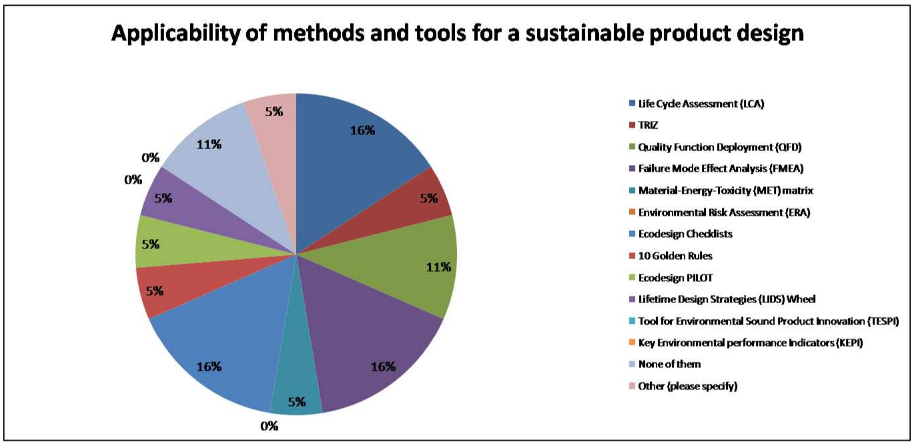

Figure 7.4: Answers to Question 4

Although they mostly used LCA (See Figure 7.4), they find it time and cost intensive (See Figure 7.5). According to their experience, FMEA and Ecodesign Checklists are the easiest methods and tools to include in ecodesign process.

The experts' answers show that there is no prominent driving force for all designers to implement ecodesign (See Figure 7.6). The answers cover a range from social responsibility to economical reasons, from legal requirements to competitive advantage. The mostly chosen alternatives are reducing energy consumption, reducing production cost, improving quality and fulfilling customers' demand.

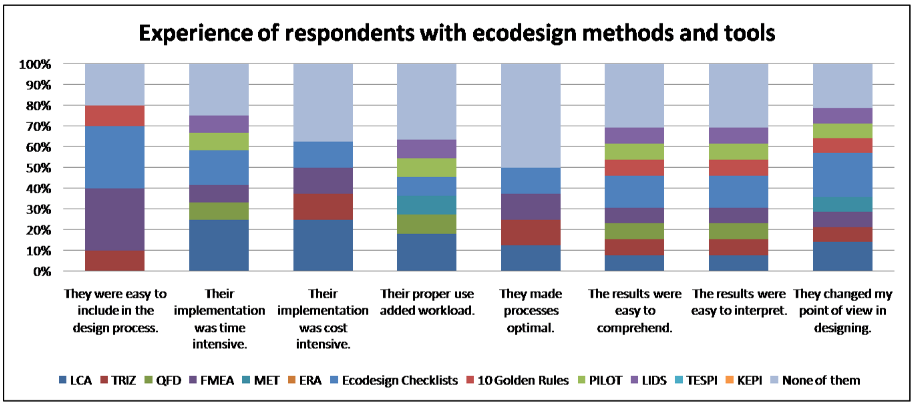

Figure 7.5: Answers to Question 5

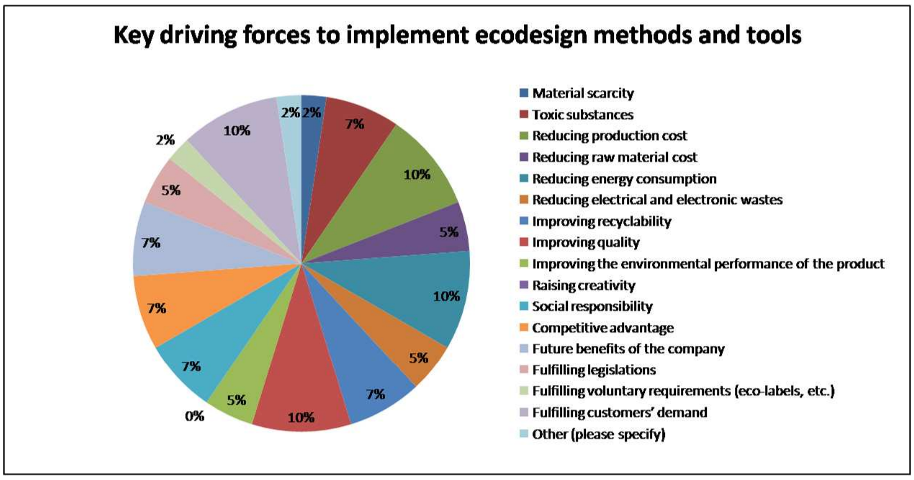

Figure 7.6: Answers to Question 6

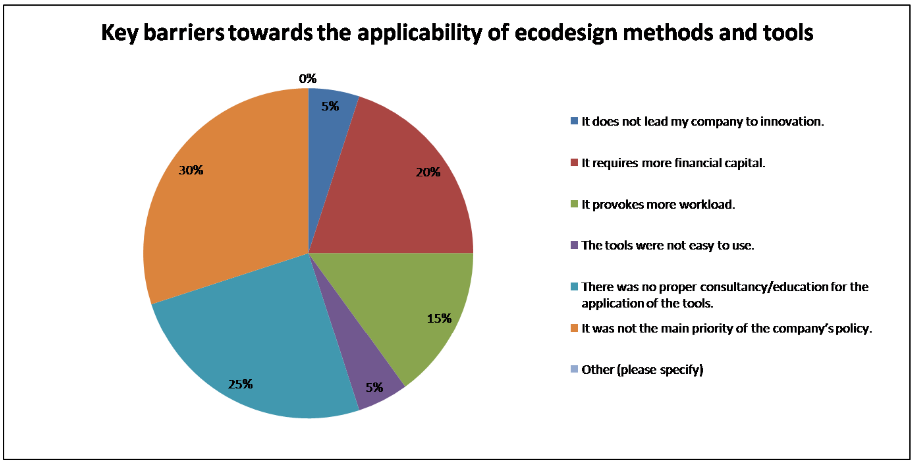

Figure 7.7: Answers to Question 7

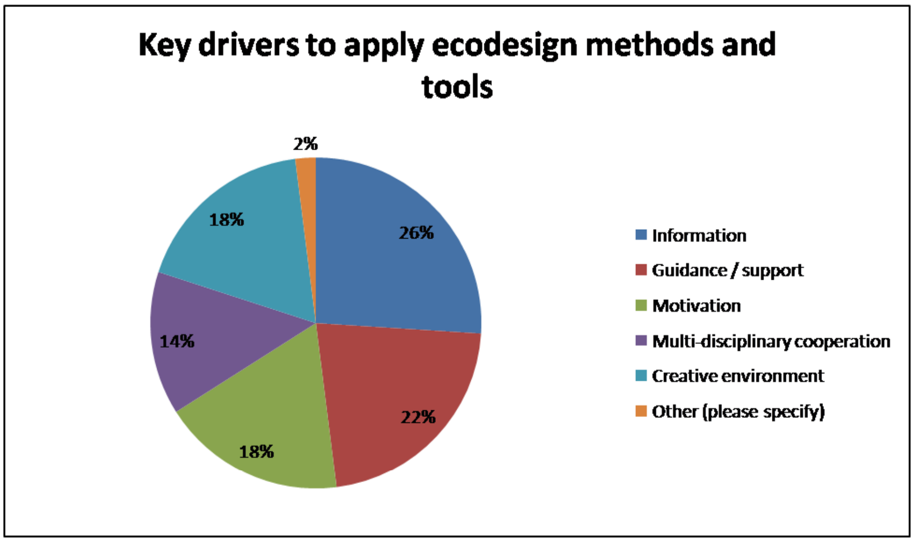

Figure 7.8: Answers to Question 8

If the engineers did not use any of the ecodesign methods and tools, the reason is mostly related to company policy which does not consider ecodesign as one of the priorities (See Figure 7.7).

Designers mostly require information and guidance/support to conduct ecodesign, with 48% (See Figure 7.8). They also approve their requirements by attaching the highest importance to information. Guidance/support follows it in the importance ranking among the requirements (See Figure 7.9).

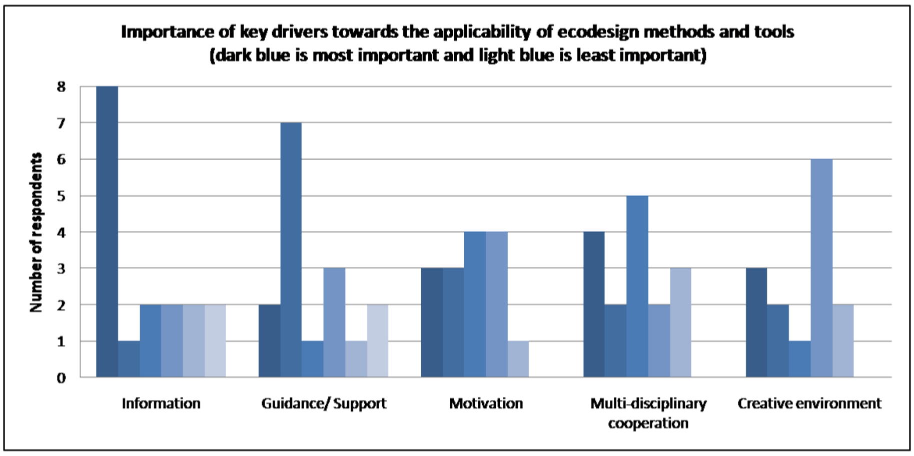

Figure 7.9: Answers to Question 9

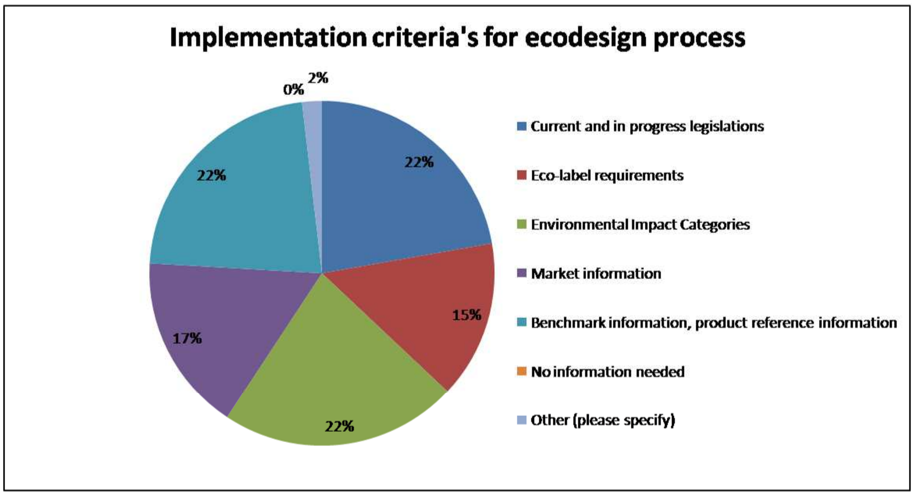

Figure 7.10: Answers to Question 11

As in the open ended question asked for their additional requirements in EEE's ecodesign, the experts answered mainly in two directions: management and financial support (See Table 7.1).

Designers would like to get information mostly about current and in progress legislations, environmental impact categories and benchmark (See Figure 7.10).

General methods and tools in design are mostly preferred by the design engineers to get the guidance/support to apply ecodesign (See Figure 7.11).

As for the motivation, financial benefits take the first place for the engineers to change

Table 7.1: Answers to Question 10

Participant #	Answer
1	Young dynamic team
2	Self responsibility
3	a feasibility study needs to be done once people are informed of tools for the effectiveness to the organisation
4	management support and financial back-up
5	funding govt aid
6	Sustainability& reliability& company vision& parters vision information& tax reduction
7	NONE
8	Access to tools and multi-disciplinary cooperation
9	Educated people
10	giving information all campany laboring
11	knowledge
12	Knowledge
13	Economical
14	NONE
15	Introduce/deliver robust products in market in time.
16	Total management participation!
17	funding allocation to research activities and projects in this area
18	NONE

their traditional design process into ecodesign (See Figure 7.12). Nevertheless, the social and moral choices are more significant in total, as the answers "Understanding my product development efforts beyond the bounders of my company" and "Taking global environmental responsibility".

As the cooperation with other departments, the most required one for being in close relations to conduct ecodesign is the production department with 23% (See Figure 7.13). Environmental department and Marketing department follow it with 16% and 15%.

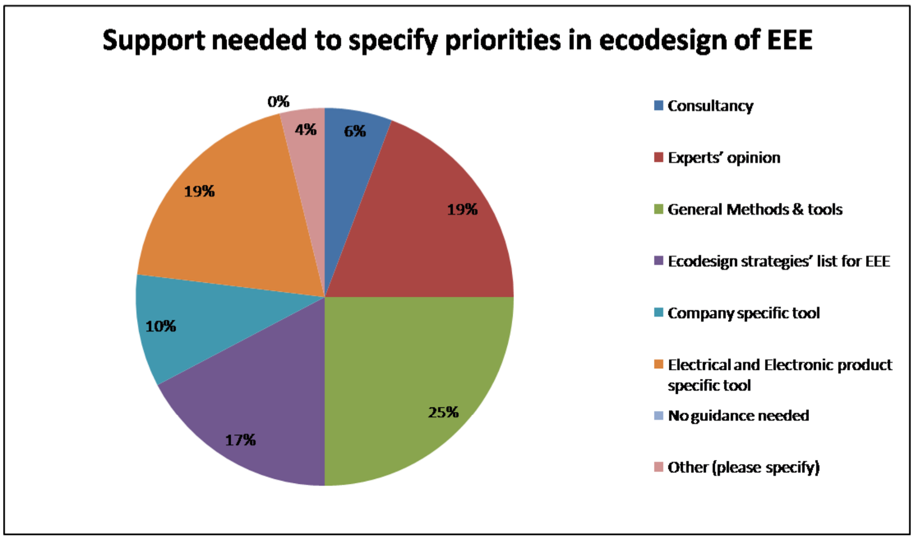

Figure 7.11: Answers to Question 12

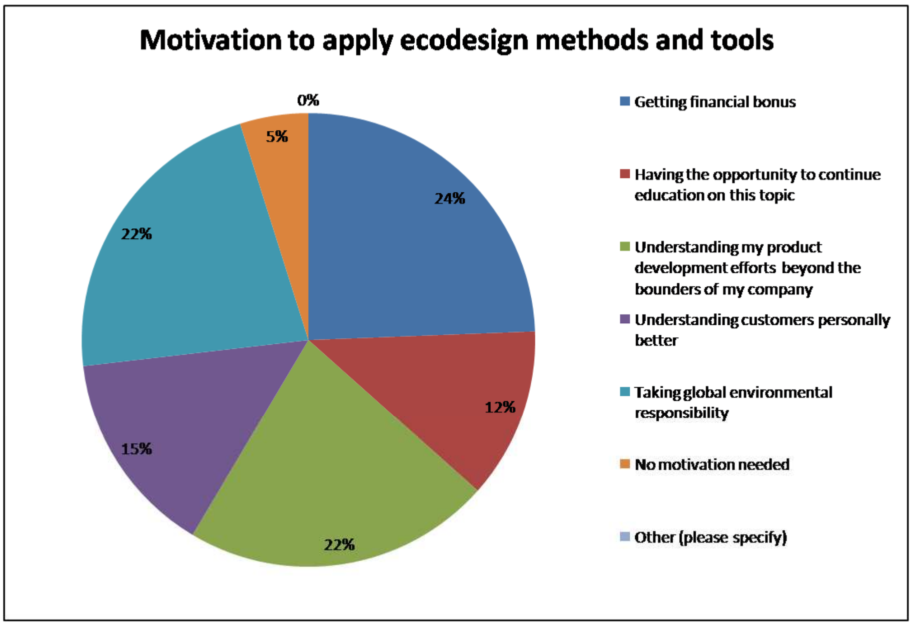

Figure 7.12: Answers to Question 13

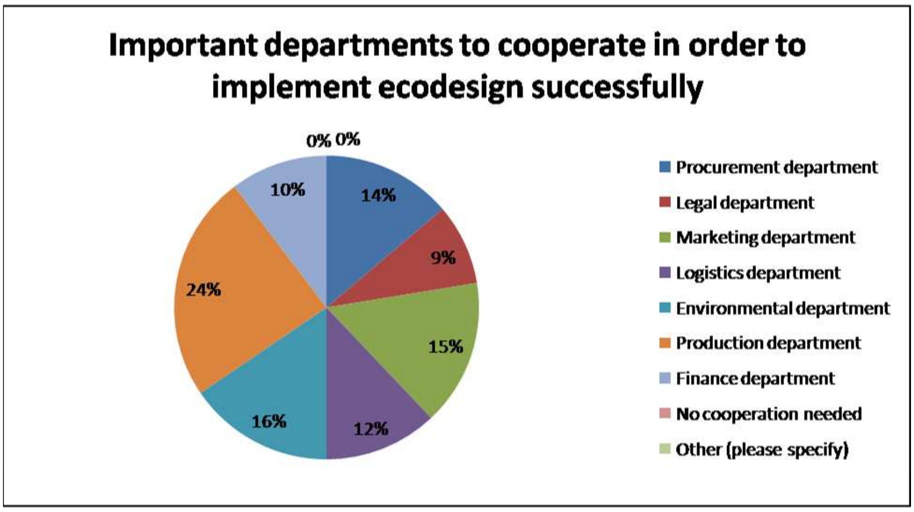

Figure 7.13: Answers to Question 14

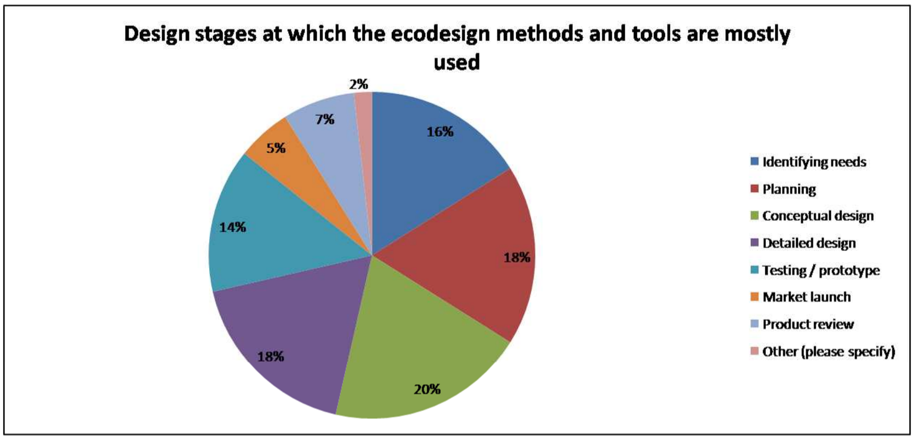

Figure 7.14: Answers to Question 15

Investigating the relations between ecodesign process and design phases was the latest part of the survey. Designers assigned ecodesign methods and tools mostly to the conceptual design and to the other early design phases (See Figure 7.14).

Finally the relations between the designers' requirements and design phases are questioned. The results for each phase can be seen on Figure 7.15.

The experts in EEE sector need to get environmental information mostly in the beginning of design process. However, their need to get guidance/support reveals mostly at the conceptual and detailed design processes, where they mostly use ecodesign methods and

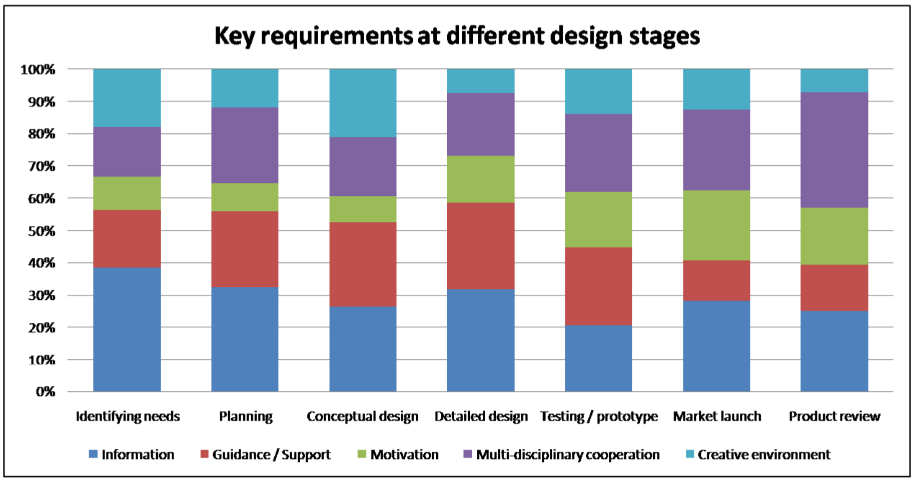

Figure 7.15: Answers to Question 16

tools (See Figure 7.15).

7.6 Discussion

Overall answers given by participant engineers to the survey prove that although they are mostly aware of ecodesign concept, they do not know its wide scope including cost and quality parameters. This result is consistent with the conclusion drawn from the Chapter 6, reflecting the tendency of some researchers focusing only on environmental parameters in their studies.

The ones who applied ecodesign in their work mostly tell that environmental assesment tools are complicated, time and cost intensive. This shows a clear requirement for a simplified ecodesign implementation approach, being consistent with the studies mentioned in the previous section.

The need for cooperation with Production and Logistics departments are obviously natural answers for designers. On the other hand, the need for cooperation with Marketing department shows that the integrated methodology should also listen to the voice of the customers.

Regarding all these observations taken from the survey, an integrated simplified ecodesign methodology, considering cost, quality and environmental parameters will be proposed in this thesis to fulfill the needs of engineers, to inform and support them in ecodesign implementation, and finally to make the use of ecodesign widespread. The results about the last two key requirements, Motivation and Creative Environment, will not be directly taken into account in this study. Providing solutions to augment the motivation of the engineers and to form a creative environment for them is not under the scope of this thesis. Nevertheless the answers of the engineers about these two key requirements open a new direction for future work.

8 Methodology

In the previous chapters it was concluded by both the literature review and the survey conducted among engineers that there was a need for the companies, specifically for SMEs, to do an environmental assessment in a simplified way, thus to provide improvement strategies for the product, considering cost, quality and environmental concerns.

With this aim, a methodology is developed to guide producers, design engineers, in other words any decision makers, in determining the optimal environmental improvement strategies step by step. The integrated methodology followed in this thesis with the efforts made in three years is seen in Figure 8.1.

8.1 Building the methodology

The integrated methodology is built in six main stages: A, B, C, D, E and F.

Stage A

The first stage forms the theoretical base of the thesis. A literature review about the latest developments in ecodesign methods and tools, the gaps in the ecodesign literature, etc. is done. Traditional design process and ecodesign process are compared to analyze better the differences. Finally, a survey is conducted among design engineers to learn about their requirements for a better ecodesign implementation. Although a base for the thesis, in the light of these efforts, is constructed, a similar approach is suggested to the decision makers before getting started with the ecodesign of their product at this stage.

The stage A, revised for the producers' requirements, includes the following steps:

A1: Do a literature review to be updated with the latest developments in the product family field.

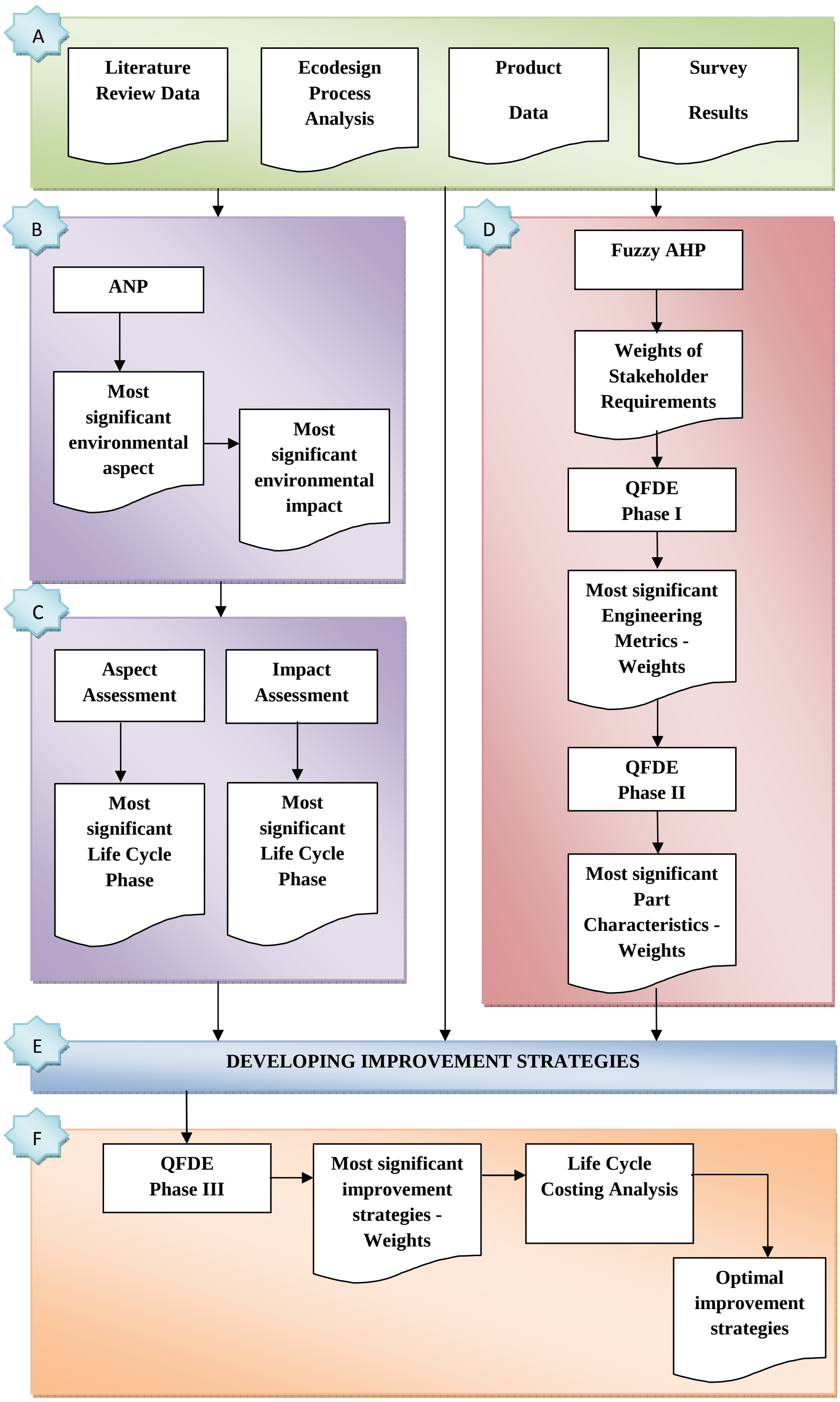

Figure 8.1: Integrated Methodology

A2: Make an analysis for the ecodesign process of the product.

A3: Gather all necessary data of the product and its components.

A4: Conduct a survey among the possible stakeholders (customers, design engineers, suppliers, recyclers, state side, etc.) and ask their wishes for an environmental product.

Stage B

The stage B forms the environmental aspect selection problem, which helps to show where to focus in a simplified Life Cycle Assessment method.

B1: Select the most significant environmental aspect by using the Analytic Network Process technique, with the help of the information collected from the previous stage.

B2: Determine the most significant environmental impact as the potential consequence of the selected aspect.

Stage C

This is the simplified environmental assessment part of the methodology. It includes the following steps:

C1: With the information collected from the literature and the stakeholders, do an aspect assessment in order to obtain the most significant life cycle phase depending on the selected aspect category

C2: With the information collected from the literature and the stakeholders, do an impact assessment in order to obtain the most significant life cycle phase depending on the selected impact category

In parallel with the stage C,

Stage D

The stage D forms the development of the product's environmental and quality specifications fitting in the early design phase. It includes the following steps:

D1: Define Voice of Customers (VoC) / Stakeholder Requirements (SR) and Engineering Metrics (EM) to build the QFDE model

D2: Conduct FAHP technique in order to weight the SR

D3: Place SR weights and relations between SR and EM in HoQ matrix and conduct the QFDE Phase I in order to get the most significant EM

D4: Place EM weights and relations between EM and part characteristics in HoQ matrix and conduct the QFDE Phase II in order to get the most significant part characteristics

Stage E

It is the improvement strategies development phase.

E1: With the gathered information from A, B, C and D stages, develop improvement strategies related to the requirements of the product.

Stage F

The last stage forms the final decision block of the methodology. It includes the following steps:

F1: Place the part characteristics weights and relations in HoQ matrix and conduct the QFDE Phase III in order to get the most significant improvement strategies and their weights.

F2: Use the weight of the improvement strategies to rank the them. Generate possible environmental actions related to those improvement strategies. Assess the changes in environmental performance of the product after the environmental actions taken. Do an LCC analysis of those actions and decide which actions to implement.

8.2 Target groups

To develop a simplified ecodesign methodology for producers, an integrated and multi stepped approach is followed. Nevertheless, it will be hard to conclude that all producers/engineers will find this six-staged methodology easy-to-use. Even in this simplified methodology, there may be some steps, which are not possible to implement in a small company. Although the proposed methodology in this thesis is developed for the use of companies, the responsibility to produce enough information and provide a theoretical support falls again on the shoulders of the scholars. Every stage of the methodology is still suggested to be conducted by the producers, if they can. Otherwise, at some stages, the scholars can take role.

The methodology shown in Figure 8.1 can be assigned to different stakeholder target groups:

- Target group A: producers and/or scholars. The producers should definitely analyze their own ecodesign process and the product itself. However, the scholars can provide the theoretical base for the products/product categories' environmental behaviour in the literature. Then it's producers' responsibility to collect the necessary information from the literature.

- Target group B: producers and/or scholars. Although ANP is a less complicated tool than LCA to give an idea about the significant environmental aspects and impacts of the product, still its use requires a competency in multi criteria decision making field. In the case that the producers need, the scholars will be able to provide an easy and quick ANP solution.

- Target group C: producers and/or scholars. Environmental Product Declaration (EPD), which is a certified environmental declaration providing quantified environmental data for a product, helps producers to have an example of environmental performance for their product category. However, the problem with EEE product category is that only a very limited amount of EEE has EPD. For the majority of the EEE, there is still the need to conduct its own environmental assessment. Scholars can study different types of products and help generating new EPD, so that the producers can skip this stage.

- Target group D: producers. The stage D can be considered as the core of the simplified ecodesign methodology which should be conducted by producers for their specific product. They should work on their own product's engineering metrics, parts and the components. They should cooperate with their stakeholders to learn about their needs, wishes and expectations.

- Target group E: producers and/or scholars. Producers should generate the improvement strategies related to their own product. On the other side, the scholars can also provide potential improvement strategies in their studies.

- Target group F: producers. At this final part of the methodology, the producers should select the suitable improvement strategies for their own product, under their own constraints. They should conduct Life Cycle Costing (LCC) analysis. The generic approaches gathered from the literature will not help them to obtain their own optimal solution.

8.3 Environmental Aspects and Impacts of EEE

An environmental aspect is defined as an element of a facility's activities, products, or services that can or does interact with the environment, while an environmental impact is defined as any change to the environment, whether adverse or beneficial, resulting from a facility's activities, products, or services[12].

Confusing environmental aspects and impacts with each other is a common mistake in daily use. However the relation between these two terms is based on the fact that the aspects are the causes of impacts. For instance, energy consumption, as an environmental aspect, is the occurring reason of some of the impact categories, most importantly global warming (also known as climate change) and it is one of the most important resources

[12] http://www.epa.gov/sectors/sectorinfo/sectorprofiles/shipbuilding/module_05.pdf

needed by humanity.

Environmental aspects and impacts are influenced by each other; therefore there is interdependency among them. For example, the first impacts after emission of greenhouse gases like CO_2 and CH_4 would be the increment they cause in the atmosphere's ability to absorb infrared radiation. This impact leads to other impacts among which are an increase in the atmospheric heat content and temperature, propagating to the global marine and soil compartments causing changes in regional and global climates and sea-level rise, eventually leading to damage to several of the areas of protection: human health, natural environment, and man-made resources (Finnveden et al., 2009).

According to the existing literature, the most relevant environmental aspects and impacts of EEE family are chosen in this study (see Table 8.1 and 8.2). Every kind of EEE is energy used product, which is also under the scope of ErP Directive (Directive2009/125/EC, 2009) of European Union. Thus "energy consumption" is accepted as an environmental aspect for EEE. Sepulveda et al. (2010) stated that during the end of life phase of EEE, hazardous substances, such as lead, mercure, polybrominated diphenyl ethers, etc.. are released to water and into the air. Therefore "emissions to air", "release to water" and "hazardous and radioactive waste generation" are also selected. Plastics have become key to innovation in EEE industry, making information, communication and convenience accessible and affordable for increasing numbers of people and are used in increased amount (Tange and Drohmann, 2005; Dimitrakakis et al., 2009). EEE also contain different kinds of metals, as well as valuable ones, e.g., copper, platinum group (Morf et al., 2007; Robinson, 2009). Significant amount of water is consumed during both manufacturing phase and use phase, especially for large household appliances such as washing machine, dishwasher, etc. Therefore "raw material and water consumption" is considered as another environmental aspect for EEE. Finally, "land use" is selected due to the land occupation of the factories, warehouses, landfill and incineration for EEE. Selected environmental aspects for EEE are seen in Table 8.1. The environmental impacts are determined according to the influences of these environmental aspects on environment and human health. The impact categories relevant for EEE are shown in Table 8.2.

Table 8.1: Environmental aspects for EEE

Alternatives	Description
Energy Consumption (EC)	The amount of energy consumed during all life cycle phases of the product.
Water Consumption (WC)	The amount of water consumed during all life cycle phases of the product.
Raw Material Consumption (RMC)	The amount of raw material, such as metals, plastics, etc., consumed during all life cycle phases of the product.
Hazardous Waste Generation (HWG)	Generation of waste which poses substantial or potential threats to public health or the environment.
Radioactive Waste Generation (RWG)	Generation of waste which contains radioactive material.
Emissions to Air (EtA)	Emission of any kind of air pollutants which contain chemicals, particulate matter or biological materials, into the atmosphere.
Release to Water (RtW)	Release of hazardous water pollutants into the water.
Land Use (LU)	The occupation of the land caused by human activities in order to produce, change or maintain it.

8.4 Environmental Aspect Selection Problem

8.4.1 Methodology: ANP

Analytic Network Process (ANP) is a Multi Criteria Decision Making tool considered to be an extension of Analytic Hierarchy Process (AHP) (Saaty, 1981). Whereas AHP mod-

Table 8.2: Impact Categories for EEE

Criteria	Sub-criteria	Description
Impact on ecology	Global warming (GW)	Climate Change; which accounts for the emission of greenhouse gases;
	Ozone Layer Depletion (OLD)	Decline in the total volume of ozone; which accounts for chlorine-containing source gases (primarily CFCs and related halocarbons)
	Eco-toxicity	The potential for biological, chemical or physical stressors to affect ecosystems.
Impact on human beings	Carcinogenicity	The ability or tendency to produce cancer; which accounts for any substance radionuclide or radiation, some physical, chemical and biological substances.
	Human Toxicity (HT)	The potential to affect human health; which addresses a wide range of toxic substances.
Pollution and Contamination	Acidification	The loss of nutrient bases (calcium, magnesium and potassium) through the process of leaching and their replacement by acidic elements; which accounts for the emissions of NOx, SOx and ammonia
	Eutrophication	Enrichment of nutrient content to an extent that increases the primary productivity of the waterbody; which accounts for nitrogen (N) and phosphorus (P)
	Radiation	The stream of particles, such as electrons or alpha particles.
	Photochemical Smog (PS)	The chemical reaction of sunlight, nitrogen oxides (NOx) and volatile organic compounds (VOCs) in the atmosphere, which leaves airborne particles (called particulate matter) and ground-level ozone; which accounts for the exhaust of fossil fuel-burning engines in cars, trucks, coal power plants, and industrial manufacturing factories.
Resource Depletion	Fossil Fuels Depletion (FFD)	The exhaustion of the fossil fuels due to large amount of use for producing energy, such as electricity, heating, etc.
	Raw Material Depletion (RMD)	The exhaustion of raw materials; which accounts for overconsumption/excessive or unnecessary use of resources, pollution and abuse of resources, etc.
	Water Depletion (WD)	The exhaustion of water resources due to large amount of use and pollution.
Impacts on landscape & cultural heritage	Deforestation	The removal of a forest by cutting the trees for industrial, agricultural and/or urbanization purposes.
	Depletion of coral reefs	The exhaustion of coral reefs which accounts for coral mining, climate change, oil and industrial pollution, etc.
	Depletion of glaciers	The exhaustion of glaciers due to climate change, ozone layer depletion and human intervention.
	Decrease in agricultural fields	Loss of agricultural fertile fields due to land misuse, soil pollution, urbanization, etc.

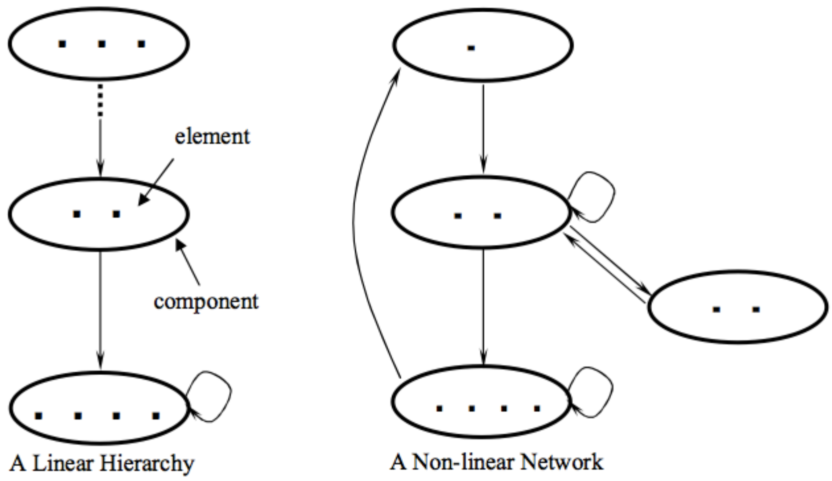

Figure 8.2: Structural difference between linear and non linear network

els a decision making framework using a unidirectional hierarchical relationship among decision levels, ANP allows for more complex interrelationships among the decision levels and components (Sarkis, 1998). In many real life decision problems, the hierarchy becomes more like a network (See Figure 8.2., where a loop means an inner dependence). Therefore, AHP is a weak method in determining interrelationships among factors. In the ANP, there is an associated network of influences among the elements and clusters. The ANP allows both interaction and feedback, within clusters of elements (inner dependence) and between clusters (outer dependence), with respect to an underlying control criterion. Therefore, ANP is a more powerful technique in modeling complex decision environments than AHP because it can be used to model very sophisticated decisions involving a variety of interactions and dependencies that exist in real life problems. It is implemented in conjunction with the use of Super Decisions software and it has been applied to a large variety of decisions such as marketing, medical, political, military, social, and forecasting and prediction, and many others (Saaty, 2005).

ANP's stepwise algorithm for the selection problem used in this study is stated by Saaty (2005) as following:

Step 1: Describe the decision problem in detail with goal, criteria and sub-criteria.

Step 2: Determine the general network of components / clusters and the elements within the clusters.

Step 3: Determine all inter and inner-dependencies that exist in the decision problem and the clusters of the general feedback system.

Step 4: Build the supermatrix by performing the pairwise comparisons, prioritization and define the weights of the criteria and the sub-criteria while considering the interdependencies between them.

Step 5: Perform pairwise comparison on clusters.

Step 6: Rate the alternatives according all the criteria and sub-criteria.

Step 7: Find the weighted supermatrix, compute and find the limit supermatrix from which the overall score for the alternatives is retrieved.

Step 8: Make the final decision as to choose the best alternative or to obtain the final ranking of the alternatives.

8.5 Simplified Environmental Assessment

In this part of the study, the environmental performance of the product hand blender is assessed in a simplified way.

The aim of this study is to propose a simplified methodology which guides producers step by step in determining the possible environmental improvement strategies. To do that, one needs to know the most problematic life cycle phase of a product according to its impact and aspect assessment. However developing improvement strategies respond only to the requirements of the most problematic life cycle phase is not enough to provide a holistic sustainable product development approach. The requirements of different stakeholders and the related engineering metrics also take an important role in determining the improvement strategies to achieve a product with a better environmental performance, which does not ignore the cost and quality concerns. Therefore, two assessment processes in parallel are proposed and presented in the next sections.

8.5.1 Environmental aspect measuring: energy consumption

For each life cycle phase, the environmental aspect measuring is done according to the energy consumption amount of the product during its whole lifetime. For the raw material phase, the energy consumptions in MJ/kg for the each raw material used in hand blender are calculated. The sum gives the total amount of energy consumed in the production of the raw materials. At the manufacturing phase, the manufacturing processes for each raw material to produce the hand blender are in focus and their energy consumptions are calculated. The calculations for the distribution phase consist of the energy consumed for the packaging and the transport of the hand blender.

The calculation of the energy consumption for the use phase is based on the data relevant for Turkey, which is defined in the range 10,59-11,62 MJ/kWh to produce 1 kWh electricity (Acaroglu, 2001). In this study, in order to prevent the ambiguity of this range, the equivalent energy level is accepted to be 11 MJ/kWh for Turkey's electricity consumption. There is no stand by mode for the hand blender. The electricity consumed is only considered for the use mode. Nonetheless, the energy consumption at the use phase is not only covered by the electricity. The dishwater wasted during cleaning the product is also included in the calculations. Finally for the end of life (EoL) phase, according to the different EoL treatment strategies of the producer for each material, the total energy consumption is calculated.

8.5.2 Environmental impact measuring: global warming potential

Global Warming Potential (GWP) is defined as the cumulative radiative forcing effects of a gas over a specified time horizon resulting from the emission of a unit mass of gas relative to a reference gas. The GWP-weighted emissions of direct greenhouse gases are presented in terms of equivalent emissions of carbon dioxide (CO_2), using units of teragrams of carbon dioxide equivalents (Tg CO_2-eq.) (EPA Glossary) [13].

Conversion: Tg = 109 kg = 106 metric tons = 1 million metric tons

The molecular weight of carbon is 12, and the molecular weight of oxygen is 16; therefore, the molecular weight of CO_2 is 44 (i.e., 12+[16 x 2]), as compared to 12 for carbon alone. Thus, carbon comprises 12/44ths of carbon dioxide by weight.

Carbon dioxide equivalents, CO_2-eq is a metric measure used to compare the emissions from various greenhouse gases based upon their global warming potential (GWP). Carbon dioxide equivalents are commonly expressed as "million metric tons of carbon dioxide equivalents (MMT CO_2Eq)". The carbon dioxide equivalent for a gas is derived by multiplying the tons of the gas by the associated GWP. The use of carbon equivalents (MMTCE) is declining (EPA Glossary) [14].

MMT CO_2Eq = (million metric tons of a gas) * (GWP of the gas)

The GWP (CO_2-eq g)/unit data needed for the calculation of the global warming impact is taken from the commercial LCA database ECOINVENT (http://www.ecoinvent.org/database/) and Wimmer et al. due to the lack of relevant data for Turkey (Wimmer et al., 2004).

8.6 QFD for Environment

To achieve sustainability, it is necessary to achieve improvements in economic, social and environmental areas. Quality Function Deployment for Environment (QFDE), as the extended version of the well known method QFD has a large application area within the sustainability framework, such as sustainable product development, improvement analysis and design process. In this study in order to design effectively a sustainable product, the QFDE approach is used as it is a commonly used tool for the environmentally conscious

[13] http://www.epa.gov/climatechange/glossary.html#CO2Equivalent

[14] http://www.epa.gov/climatechange/glossary.html#GWP

design process.

QFD is "a method for developing a design quality aimed at satisfying the consumer and then translating the consumers' demands into design targets and major quality assurance points to be used throughout the production stage" (Akao, 2004). The complex relationships between customer requirements and technical attributes, and the correlation between different technical attributes, can be illustrated in a typical "House of Quality" (HoQ) matrix. HoQ serves to link the Voice of Customer (VoC) to engineering metrics (EM).

QFD for Environment (QFDE) is a method developed by Masui et al. (2003). It introduces environmental aspects (environmental VoC and environmental EM) into QFD to handle the environmental and traditional product quality requirements together, and it is intended to be used in the early stages of product design.

The major advantages of the QFDE framework are summarized as follows. Unlike traditional QFD, to improve the product design process, not only the end users but also business-to-business (B2B) customers, recyclers, the government and the environment itself are considered to be stakeholders in QFDE. In this multi aspect method, SR weights play an important role since they significantly affect the target values set for the engineering metrics; hence it's crucial to give a realistic approach. Various methods have been attempted to determine the importance weights. The simplest method to prioritize customer requirements is based on a point scoring scale, such as one to five or one to ten (Griffin and Hauser, 1993). However, this method cannot effectively capture human perception (Kwong and Bai, 2003). Furthermore, the judgments of the decision makers are more difficult to assess with the precise quantitative forms due to the vagueness and uncertainty existing in the early stage of new product development (Zhang and Chu, 2009). In early stages of product development, the decision makers have limited information about the relationship between different SR and EM. As being a convenient tool for integrating the fuzzy theory application, QFDE helps the product development/design team to overcome the vagueness and uncertainty faced in SR weighting. Finally, various technical attributes and environmental concerns can be prioritized such that the product development team can concentrate their limited resources on critical issues to develop customer-oriented environmentally friendly products (Kuo et al., 2009).

A typical QFD system usually has four interlinked phases, where four matrices that integrate the customer requirements, design specifications, product or part characteristics, manufacturing processes, and production requirements are used. The matrices explicitly relate the data produced in one phase of the process to the decisions that must be made at the next process phase (Griffin and Hauser, 1993). Product planning is the first matrix. Customers' desires, in customers' own words (VoC - WHATs), are determined and translated into technical description (EM - HOWs) or proposed performance characteristics of the product. The second QFD matrix relates potential product features to the delivery of performance characteristics. Process characteristics and production requirements are related to engineering and marketing characteristics with the third and fourth matrices (Temponi et al., 1999). Four-Phases of QFD are illustrated in Figure 8.3 and summarized as follows (Chan and Wu, 1998):

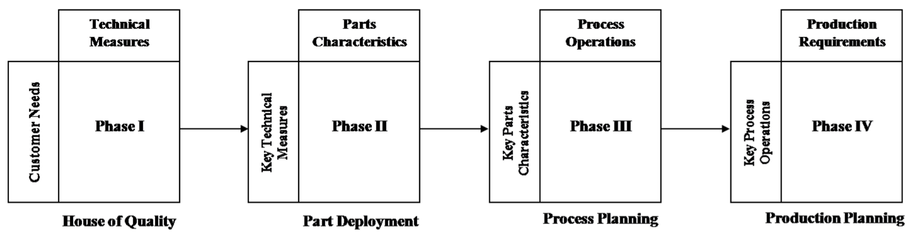

Figure 8.3: Quality Function Deployment: the four interlinked phases

QFDE is also carried out in four phases. Phases I and II allow the user to identify environmentally significant components (component parts and devices) of the product. Phases III and IV allow the user to choose the most environmentally friendly design from alternative design proposals.

In this study, the improvement strategies presented to ameliorate the environmental performance of the product will be accepted as the production requirements. Since these strategies are mostly related to part characteristics, they will be interlinked to them in traditional phase III instead of "process operations". Hence, the traditional phase III will be merged with the phase IV and in total, the QFDE method will be conducted in only three phases.

8.6.1 Basic concepts of Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a theory of measurement through pairwise comparisons and relies on the judgments of experts to derive priority scales. It is these scales that measure intangibles in relative terms. The comparisons are made using a scale of absolute judgments that represents, how much more, one element dominates another with respect to a given attribute. Since the judgments may be inconsistent, a way to measure inconsistency is of concern to the AHP method, in order to, if possible, obtain better consistency and improve the judgments (Saaty, 1981).

The multi-attribute problem is structured in a hierarchic skeleton. In a typical hierarchy, the highest level reflects the general goal of the decision maker. The elements affecting the decision are called criteria and they are represented in intermediary levels. The criteria can be divided in sub-criteria for an additional refining. The criteria can be either objective or subjective. Once the criteria are defined, they should be evaluated for their relative contribution to the goal, or to the following upper level. The lowest level in the hierarchy contains the options of the decision, which are called the alternatives.

In the conventional AHP, the pairwise comparisons for each level with respect to the goal are conducted using a nine-point scale proposed by (Saaty, 2008) (see Table 8.3).

The relative priorities for the criteria and the alternatives for the subjective criteria are obtained from the pairwise comparison matrices of the FAHP method using the extension principle. Subjective criteria ratings for the alternatives obtained in the previous step and objective criteria values are collected in a decision matrix. Finally the weights of the alternatives are found.

In this study, the FAHP method is used for determining the weights for SR, because, in the early stage of the product development process the weight determination problem primarily depends on subjective judgment of the decision makers.

Table 8.3: Fundamental Comparison Scale

Intensity of Importance	**Verbal Definition**	**Explanation**
1	Equally important	Two decision elements have equal influence on the superior decision element.
3	Moderately more important	One decision element has moderately more influence than the other.
5	Strongly or essentially more important	One decision element has strongly more influence than the other.
7	Very strong or demonstrated importance	One decision element has very strongly more influence than the other.
9	Extremely more important	One decision element has extremely more influence than the other.
2, 4, 6, 8	Intermediate values of judgment	

8.6.2 The construction of fuzzy judgment

To make abstraction mathematically meaningful, it is necessary to have enough a priori information about the studied object to make it possible to assess (Zadeh et al., 1996). Designers and engineers would like to predict as many attributes and features of the final product as possible during the design process. However, a major problem in early design stages is that many of the attributes of the final product are not exactly known (Hellenbrand et al., 2010). Since the focus of the QFD is on the early stage of new product design or redesign process, most of the input parameters are therefore highly subjective in nature (Kim et al., 2007). In view of this, a method or approach that is capable to systematically analyze and accurately quantify those subjective experiences and judgments of the QFD team is highly required (Raharjo et al., 2008).

According to Zadeh (1965), when it is very difficult for conventional quantification to define the complex situations, the notion of a linguistic variable, whose values are words or sentences, is necessary. The conventional AHP method is incapable of handling the uncertainty and vagueness involved in the mapping of one's preference to an exact number or ratio (Zadeh, 1965). The major difficulty with classical AHP is its inability in mapping human judgments.

In this thesis, to assess the relative importance of the criteria and to evaluate the alternatives, the FAHP approach is introduced, with the use of Triangular Fuzzy Numbers for the pairwise comparison scale of FAHP according to the method of Chang's (1996) fuzzy extent analysis by applying the correct normalization formula given later by (Wang et al., 2008).

The extent analysis method and the principles for the comparison of fuzzy numbers are employed to obtain estimates for the weight vectors for individual levels of a hierarchy of customer requirements (Chang, 1996). The extent analysis method is used to consider the extent of an object to be satisfied for the goal, that is, satisfied extent. (Kwong and Bai, 2003)

The steps of Chang's extent analysis can be given as follows (Chang, 1996):

The first task of the fuzzy AHP method is to decide on the relative importance of each pair of factors in the same hierarchy. By using triangular fuzzy numbers, via pairwise comparison, the fuzzy evaluation matrix $A = (\tilde{a}_{ij})_{n \times m}$, is constructed. Where $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ for $i, j = 1, 2, \ldots, n$ and $i \neq j$, and l and u stand for the lower and upper value of the support of $\tilde{a}_{ij}$ respectively, and m for the model value. The triangular number is denoted by (l, m, u).

First, by fuzzy arithmetic operations, we take the sum of each row (RS_i) of the fuzzy comparison matrix.

$$\begin{aligned}\mathrm{RS}_i &= \sum_{j=1}^{n} \tilde{a}_{ij} \\ &= \left(\sum_{j=1}^{n} \ell_{ij}, \sum_{j=1}^{n} m_{ij}, \sum_{j=1}^{n} u_{ij}\right), i = 1, 2, \ldots, n \end{aligned} \tag{8.1}$$

$$\begin{aligned}\tilde{S}_i &= \frac{\mathrm{RS}_i}{\sum_{j=1}^{n} \mathrm{RS}_j} \\ &= \left(\frac{\sum\limits_{j=1}^{n} \ell_{ij}}{\sum\limits_{j=1}^{n} \ell_{ij} + \sum\limits_{k=1, k\neq i}^{n} \sum\limits_{j=1}^{n} u_{kj}}, \frac{\sum\limits_{j=1}^{n} m_{ij}}{\sum\limits_{k=1}^{n} \sum\limits_{j=1}^{n} m_{kj}}, \frac{\sum\limits_{j=1}^{n} u_{ij}}{\sum\limits_{j=1}^{n} u_{ij} + \sum\limits_{k=1, k\neq i}^{n} \sum\limits_{j=1}^{n} \ell_{kj}} \right) \end{aligned} \tag{8.2}$$

for $i = 1, 2, \ldots, n$

$$V\left(\tilde{S}_i \geq \tilde{S}_j\right) = \begin{cases} 1 & \text{if } m_i \geq m_j \\ \frac{u_i - \ell_j}{(u_i - m_i) + (u_j - m_j)} & \text{if } \ell_j \leq u_i \text{ for } i, j = 1, 2, \ldots, n \text{ with } i \neq j \\ 0 & \text{otherwise} \end{cases} \tag{8.3}$$

$$\begin{aligned} V(M \geq M_1, M_2, \ldots, M_K) &= V\left((M \geq M_1) \wedge (M \geq M_2) \wedge \cdots \wedge (M \geq M_K)\right) \\ &= \min_{i=1,2,\ldots,n} V(M \geq M_i) \end{aligned} \tag{8.4}$$

$$d(A_i) = \min_{i=1,2,\ldots,n j\neq i} V(S_i \geq S_j) \tag{8.5}$$

$$W' = \left(d'(A_1), d'(A_2), \ldots, d'(A_n)\right)^T \tag{8.6}$$

$$W = (d(A_1), d(A_2), \ldots, d(A_n))^T \tag{8.7}$$

These steps are conducted for the comparison matrix of the criteria with respect to the goal and for each comparison matrix of the alternatives with respect to each criterion, and the normalized weight vectors are obtained. These normalized weight vectors provide the final global weight vector, by multiplying the weight coefficients of the elements of the criteria (the higher levels) with the ones of the alternatives until the top of the hierarchy is reached. The result is the global weight vector of the attributes where each element stands as the weight of the each alternative of the decision making problem.

8.6.3 Measurement of Consistency

Pairwise comparison is used to generate the matrix of relative rankings for each level of the hierarchy. After all the matrices were built, participants calculate the eigenvectors or the relative weights (the degree of relative importance amongst the elements), global weight vector, and the maximum eigenvalue (λ_{max}) for each matrix. Then, participants use eigenvectors and maximum eigenvalue (λ_{max}) to measure consistency, making sure that the pairwise comparison matrix provides a completely consistent evaluation. The consistency is calculated in the following way.

E is the eigenvector of comparison matrix A , representing the relative weights of n elements in level k. .

1. Calculate the maximum eigenvalue (λ_{max}) for each matrix of order n by the formulae:

$$\lambda_{max} = \frac{1}{n} \sum_{j=1}^{n} \frac{(AE_i)}{E_i} \tag{8.8}$$

Table 8.4: Random consistency index values

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0,58	0,9	1,12	1,24	1,32	1,41	1,45	1,49

2. Compute the consistency index (CI) for each matrix of order n by the formulae:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{8.9}$$

3. Calculate the consistency ratio (CR) using the formulae:

$$CR = \frac{CI}{RI} \tag{8.10}$$

RI is known as random consistency index obtained from a large number of simulation runs and varies depending upon the order of matrix. Table 8.4 shows the value of the random consistency index (RI).

A value of CR < 0,1 is typically considered acceptable, larger values require the decision maker to reduce inconsistencies in reviewing judgments.

8.7 Life Cycle Costing Analysis

As described in Chapter 4, LCC aims to provide the changes in cost regarding all life cycle phases of the product. It does not require a complicated finance analysis, but only a simple calculation of the changes in product. Therefore it is suitable to include into the simplified methodology.

At the end of the integrated methodology, after determining the possible improvement strategies, LCC analysis will be used to make the final decision about which strategy to implement. This will be the last step of the methodology.

The results for each life cycle phase will be given on a table to clearly show the changes in cost.

9 Case study

In this part of the study, the proposed methodology to identify the improvement strategies will be applied for the product “hand blender”.

9.1 Description of the product: Hand Blender

A hand blender is a kitchen appliance to blend ingredients or puree food in the container in which they are being prepared. It is included in the small household appliances EEE family. The shape, style and subcomponents of the hand blender can be seen in Figure 9.1 and 9.2. The exemplary product is disassembled. All parts are weighted and energy consumption levels are measured. General information about the product is given on Table 9.1.

Figure 9.1: Hand Blender with its parts - I

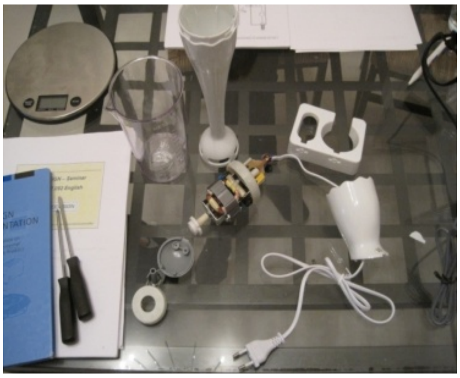

Figure 9.2: Hand Blender with its parts - II

Table 9.1: General Information of the hand blender

Environmental Parameters - general information	
Product	Hand blender
Weight	0,85 kg (including packaging)
Volume	354x120x102 mm (=4,33 dm^3)
Supply part's environmental performance	Cable, Hanging loose, Mixing beaker
Lifetime	4 years
Functionality	Mixing food to soups
Functional Unit	Blending one liter of soup for one minute.
Power	170 W (max. 180 W)
Environmental Parameters - life cycle information	
Material used	Blender: 190g Copper, 120g PP, 220g stainless steel; 10g printed circuit board Mixing beaker: 70g PS; Wall mounting: 30g PP, 2g stainless steel; Packaging: 10g LDPE (LDPE), 170g cardboard;
	Continued on next page

Table 9.1 – continued from previous page

	All together: 190g Copper, 220g stainless steel, 10g printed circuit board, 150g PP, 30g PVC, 70g PS, 10g LDPE, 170g cardboard
Problematic materials	PVC in cables hanging loop, PCB
Manufacture	
Problematic technology	Injection molding (housing 120g PP, wall mounting 30g PP, mixing beaker 70g PS) Extrusion (packaging 10g LDPE (LDPE), cable 30g PVC) Stranded Cable (20 g Copper) Coiling Engine (170 g Copper) Cutting (220 g steel) Cutting and gluing (170 g cardboard)
Distribution	
Packaging	Single use cardboard box
Transportation	25000 km by transoceanic ship 1400 km by 40 t truck 20 km by van
Product use	
Energy consumption	Blending vegetables and fruits to make soups or shakes. 400 uses in lifetime (2 uses a week, 1 min) equals 1,15 kWh
Waste	dishwater (200 l)
Noise and vibrations	approx. 85 dB
Emissions	None
Maintenance	Cleaning with water after use
Reparability	Not useful
End of life	

Continued on next page

Table 9.1 – continued from previous page

Fasteners and joints	snap fit and screws
Time for disassembly	2 min
Reusability	Reuse of parts is not possible (0 %)
Recyclability	Rate: 65 % of total weight
Incineration	Rate: 28 % of total weight
Landfill	Rate: 7 % of total weight
Information about realistic scenarios	
User doesn't take product to disposal collection point	Rate of landfill increases to 100 % of total weight

9.2 Building the model for ANP

Step 1: The first step is to define the decision problem, then the model to be evaluated is constructed. The main objective of the problem is to evaluate the environmental aspects of an electrical and electronic product. The environmental aspects defined as the alternatives of this evaluation model are selected in Chapter 8.3 as follows: Energy consumption, water consumption, raw material consumption, hazardous waste generation, radioactive waste generation, emissions to air, release to water, land use (ISO14001, 2004; Guinee et al., 2002)

For the proposed environmental aspect evaluation model, 5 main impact categories are determined as criteria according to the general acceptance abovementioned in Chapter 8.3, for the protection areas in LCA: impact on human beings, impact on ecology, resource depletion, pollution/contamination/wastes, and impacts on landscape and cultural heritage. These 5 main categories, representing the clusters in the model, can be divided into sub-criteria which are formed by detailed environmental impact categories (see Chapter 8.3): global warming, carcinogenicity, ozone layer depletion, acidification, eutrophication, eco-toxicity, human toxicity, radiation, fossil fuels depletion, raw material depletion, water depletion and photochemical smog (Guinee et al., 2002; Roy et al., 2009), deforestation (depletion of forests), depletion of glaciers, depletion of coral reefs, and decrease in agricultural fields.

Step 2 & 3: Given this model, the relevant criteria and alternatives are structured in the form of a simple network by the decision makers. Interdependencies are represented by the arrows among the clusters (outer dependence) and a looped arc within the same cluster (inner dependence). The direction of the arc signifies dependence. Arcs emanate from a controlling attribute to other attributes that may influence it. All the relations among criteria and sub-criteria, and the network of the model can be seen in Figure 9.3.

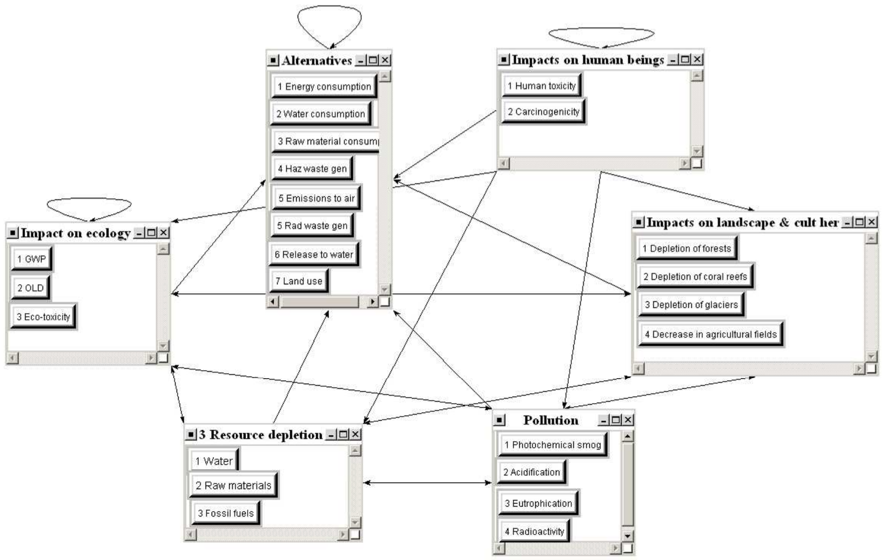

Figure 9.3: ANP network scheme of the decision problem

9.2.1 Pairwise matrices, weights and supermatrix formation

In this step of the ANP methodology, comparison sets between clusters and elements are set. To build the comparison matrices, clusters and their elements are compared with respect to a control criterion. To reflect interdependencies in this simple network model, pairwise comparisons among all the clusters/elements/alternatives are performed and these relationships are evaluated.

As for the evaluation of the alternatives and criteria, the fundamental comparison scale (1 to 9) is used (see Table 8.3) (Saaty, 2008).

The ANP method is able to handle interdependencies among elements through the calculation of composite weights as developed in a supermatrix. After completing all the pairwise comparisons, the derived priorities of the unweighted supermatrix are obtained for each control criterion. Then, using the cluster weights matrix, the priorities of all factors in each cluster are weighted. The weighted supermatrix, each of whose columns sums to one, is known as a column stochastic matrix. The weighted supermatrix is then raised to limit powers to obtain the final priorities of all elements in the limit matrix. Then

Table 9.2: Pairwise comparison matrix for Carcinogenicity

Carcinogenicity	**HWG**	**RWG**	**EtA**	**RtW**	**Weights**
HWG	1	1/5	1/4	1/3	0,069
RWG	5	1	3	5	0,557
EtA	4	1/3	1	2	0,236
RtW	3	1/5	1/2	1	0,139

the results are synthesized through addition for the entire control criterion. These synthesized results of these priorities are normalized to select the highest priority alternative. The supermatrix and its powers are the fundamental tools needed to lay out the functions of the ANP (Saaty, 2003).

Step 4, 5 & 6: In this study, in order to reflect the priorities of EEE, comparison matrices are completed by experts who have experience in the EEE field. The experts' opinions are used to fill in the pairwise comparison matrices for both criteria and alternatives and then the supermatrix is built according to these pairwise comparison matrices by using the Super Decisions software (`http://www.superdecisions.com/`).

Among the several comparison matrices completed by decision makers, the four representative ones for the comparison between sub-criteria elements (Table 9.2 and 9.3), clusters (Table 9.4), and alternatives (Table 9.5) are given as examples.

As an example, Table 9.2 shows the pairwise comparison matrix for the alternatives with respect to the "carcinogenicity" criterion. In comparing the four connected environmental aspect (Hazardous Waste Generation, Radioactive Waste Generation, Emissions to Air, Release to Water) based on carcinogenicity, the experts are asked which environmental aspect is more significant under carcinogenicity criterion. Radioactive Waste Generation appears superior to the other three alternatives according to the carcinogenicity criterion.

The pairwise comparison matrix for Human Toxicity in Impact on Ecology cluster is given on Table 9.3.

Table 9.3: Pairwise comparison matrix for Human Toxicity

Human toxicity	OLD	Eco toxicity	Weights
OLD	1	1/5	0,167
Eco toxicity	5	1	0,883

Table 9.4: Pairwise comparison matrix for Resource Depletion

Resource depletion	Pollution	Impact on ecology	Impacts on landscape & cultural heritage	Alternatives	Weights
Pollution	1	1/3	5	1/5	0,131
Impact on ecology	3	1	5	1/4	0,236
Impacts on landscape & cultural heritage	1/5	1/5	1	1/7	0,047
Alternatives	5	4	7	1	0,585

Table 9.5: Pairwise comparison matrix for Hazardous Waste generation

HWG	Emission to air	Release to water	Weights
Emissions to air	1	3	0,75
Release to water	1/3	1	0,25

The pairwise cluster comparison matrix for Resource Depletion is given on Table 9.4.

The pairwise comparison matrix for Hazardous Waste Generation in Alternatives cluster is given on Table 9.5.

Table 9.6: Cluster priorities

	Alternatives	Impact on human beings	Resource depletion	Impact on ecology	Impacts on landscape & cultural heritage	Pollution
Alternatives	1,000000	0,167580	0,58539	0,194509	0,457610	0,57407
Impact on human beings	0,000000	0,436035	0,00000	0,000000	0,000000	0,00000
Resource depletion	0,000000	0,036640	0,00000	0,035925	0,042541	0,09151
Impact on ecology	0,000000	0,172068	0,23572	0,356823	0,325994	0,28208
Impacts on landscape & cultural heritage	0,000000	0,033732	0,04757	0,219269	0,000000	0,05233
Pollution	0,000000	0,153945	0,13131	0,193474	0,173855	0,00000

9.2.2 Results and Discussion

Step 7: Given the comparison matrices, the Super Decisions software computed the unweighted, weighted and limit supermatrices. The synthesized results and the priorities are provided. The cluster priorities, the weighted and limit supermatrices are seen on Table 9.6 to 9.10.

The values in the cluster priorities matrix show how much a cluster influences other clusters. For example, the cluster of “Impacts on ecology” influences the cluster of “Impacts on human beings” (0,1721). As another example, the cluster of “Impacts on human beings” influences itself as well (0,436) since this cluster is inner dependent.

Table 9.7: Weighted Supermatrix

	Alternatives								Impact on human beings		Resource depletion		
	EC	WC	RMC	HWG	EtA	RWG	RtW	LU	HT	C	WD	RMD	FFD
Energy consumption	0,00	0,00	0,00	0,00	1,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00
Water consumption	0,00	0,00	0,00	0,00	0,00	0,00	1,00	0,00	0,00	0,00	0,614629	0,00	0,00
Raw material consumption	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,924846	0,00
Haz waste gen	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,014276	0,012001	0,00	0,00	0,00
Emissions to air	0,00	0,00	0,00	0,75	0,00	0,875	0,00	0,00	0,034157	0,040981	0,00	0,00	0,00
Rad waste gen	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,084989	0,096802	0,00	0,00	0,00
Release to water	0,00	0,00	0,00	0,25	0,00	0,125	0,00	0,00	0,034157	0,02417	0,00	0,00	0,00
Land use	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Human toxicity	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,452619	0,00	0,00	0,00
Carcinogenicity	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,436035	0,00	0,00	0,00	0,00
Water	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,03664	0,00	0,00	0,00	0,00
Raw materials	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Fossil fuels	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
GWP	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,076548	0,123747	0,00	0,00
OLD	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,028678	0,076548	0,00	0,00	0,00
Eco-toxicity	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,14339	0,025516	0,123747	0,00	0,00
Depletion of forests	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,033732	0,035015	0,00	0,018787	0,00
Depletion of coral reefs	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Depletion of glaciers	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Decrease in agricultural fields	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,056367	0,00
Photochemical smog	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,019243	0,045142	0,00	0,00	0,00
Acidification	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,019243	0,01077	0,068938	0,00	0,00
Eutrophication	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0	0,019243	0,010771	0,068938	0,00	0,00
Radioactivity	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,096216	0,093116	0,00	0,00	0,00

Table 9.8: Weighted Supermatrix Continued

	Impact on ecology			Impacts on landscape & cultural heritage				Pollution			
	GWP	**OLD**	**Eco-T**	**DoF**	**DoCR**	**DoG**	**DiAF**	**PS**	**A**	**E**	**R**
EC	0,267087	0,083524	0,00	0,00	0,00	0,154515	0,00	0,204277	0,00	0,00	0,00
WC	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
RMC	0,00	0,00	0,00	0,029903	0,00	0,00	0,00	0,036883	0,00	0,00	0,00
HWG	0,00	0,047039	0,048396	0,00	0,059758	0,00	0,05247	0,089933	0,111754	0,111754	0,00
EtA	0,128402	0,370771	0,039932	0,046544	0,00	0,359553	0	0,435069	0,00	0,00	0,00
RWG	0,00	0,00	0,04306	0,07959	0,00	0,00	0,07814	0,033473	0,00	0,00	0,670524
RtW	0,00	0,00	0,070368	0,00	0,418184	0,00	0,07049	0,00	0,55877	0,55877	0,00
LU	0,037038	0,00	0,00	0,301573	0,00	0,039841	0,25651	0,00	0,00	0,00	0,00
HT	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
C	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
W	0,079887	0,00	0,00	0,042541	0,00	0,00	0,042541	0,00	0,00	0,00	0,00
RM	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
FF	0,00	0,00	0,00	0,00	0,00	0,051493	0,00	0,127473	0,00	0,00	0,00
GWP	0,00	0,00	0,00	0,065199	0,056746	0,394597	0,00	0,00	0,00	0,00	0,00
OLD	0,00	0,00	0,37012	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,329476
Eco-T	0,00	0,00	0,00	0,260795	0,283732	0,00	0,325994	0,00	0,329476	0,329476	0,00
DoF	0,406321	0,00	0,11372	0,00	0,00	0,00	0,00	0,072893	0,00	0,00	0,00
DoCR	0,00	0,00	0,11372	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
DoG	0,081264	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
DiAF	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
PS	0,00	0,374	0,028669	0,086928	0,00	0,00	0,00	0,00	0,00	0,00	0,00
A	0,00	0,00	0,086007	0,00	0,045391	0,00	0,044904	0,00	0,00	0,00	0,00
E	0,00	0,00	0,086007	0,00	0,136188	0,00	0,018208	0,00	0,00	0,00	0,00
R	0,00	0,124666	0,00	0,086928	0,00	0,00	0,110743	0,00	0,00	0,00	0,00

Table 9.9: Limit Supermatrix

	Alternatives								Impact on human beings		Resource depletion		
	EC	**WC**	**RMC**	**HWG**	**EtA**	**RWG**	**RtW**	**LU**	**HT**	**C**	**WD**	**RMD**	**FFD**
Energy consumption	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,421	0,421	0,428	0,428	0,000
Water consumption	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,118	0,118	0,120	0,120	0,000
Raw material consumption	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,004	0,004	0,004	0,004	0,000
Haz waste gen	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,019	0,019	0,019	0,019	0,000
Emissions to air	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,165	0,165	0,164	0,164	0,000
Rad waste gen	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,031	0,031	0,030	0,030	0,000
Release to water	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,050	0,050	0,051	0,051	0,000
Land use	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,013	0,013	0,013	0,013	0,000
Human toxicity	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,002	0,002	0,000	0,000	0,000
Carcinogenicity	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,002	0,002	0,000	0,000	0,000
Water	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,003	0,003	0,003	0,003	0,000
Raw materials	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Fossil fuels	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,010	0,010	0,010	0,010	0,000
GWP	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,006	0,006	0,005	0,005	0,000
OLD	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,035	0,035	0,034	0,034	0,000
Eco-toxicity	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,029	0,029	0,028	0,028	0,000
Depletion of forests	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,019	0,019	0,018	0,018	0,000
Depletion of coral reefs	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,007	0,007	0,007	0,007	0,000
Depletion of glaciers	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,001	0,001	0,001	0,001	0,000
Decrease in agricultural fields	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Photochemical smog	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,035	0,035	0,035	0,035	0,000
Acidification	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,007	0,007	0,007	0,007	0,000
Eutrophication	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,008	0,008	0,008	0,008	0,000
Radioactivity	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,014	0,014	0,014	0,014	0,000

Table 9.10: Limit Supermatrix Continued

	Impact on ecology			Impacts on landscape & cultural heritage				Pollution			
	GWP	**OLD**	**Eco-T**	**DoF**	**DoCR**	**DoG**	**DiAF**	**PS**	**A**	**E**	**R**
Energy consumption	0,428	0,428	0,428	0,428	0,428	0,428	0,428	0,428	0,428	0,428	0,428
Water consumption	0,120	0,120	0,120	0,120	0,120	0,120	0,120	0,120	0,120	0,120	0,120
Raw material consumption	0,004	0,004	0,004	0,004	0,004	0,004	0,004	0,004	0,004	0,004	0,004
Haz waste gen	0,019	0,019	0,019	0,019	0,019	0,019	0,019	0,019	0,019	0,019	0,019
Emissions to air	0,164	0,164	0,164	0,164	0,164	0,164	0,164	0,164	0,164	0,164	0,164
Rad waste gen	0,030	0,030	0,030	0,030	0,030	0,030	0,030	0,030	0,030	0,030	0,030
Release to water	0,051	0,051	0,051	0,051	0,051	0,051	0,051	0,051	0,051	0,051	0,051
Land use	0,013	0,014	0,015	0,016	0,017	0,018	0,019	0,020	0,021	0,022	0,023
Human toxicity	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Carcinogenicity	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Water	0,003	0,003	0,003	0,003	0,003	0,003	0,003	0,003	0,003	0,003	0,003
Raw materials	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Fossil fuels	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010	0,010
GWP	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005
OLD	0,034	0,034	0,034	0,034	0,034	0,034	0,034	0,034	0,034	0,034	0,034
Eco-toxicity	0,028	0,028	0,028	0,028	0,028	0,028	0,028	0,028	0,028	0,028	0,028
Depletion of forests	0,018	0,018	0,018	0,018	0,018	0,018	0,018	0,018	0,018	0,018	0,018
Depletion of coral reefs	0,007	0,007	0,007	0,007	0,007	0,007	0,007	0,007	0,007	0,007	0,007
Depletion of glaciers	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001
Decrease in agricultural fields	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Photochemical smog	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035
Acidification	0,007	0,007	0,007	0,007	0,007	0,007	0,007	0,007	0,007	0,007	0,007
Eutrophication	0,008	0,008	0,008	0,008	0,008	0,008	0,008	0,008	0,008	0,008	0,008
Radioactivity	0,014	0,014	0,014	0,014	0,014	0,014	0,014	0,014	0,014	0,014	0,014

Table 9.11: Results for Alternatives

Name	Ideals	Normals
Energy consumption	1,000000	0,516441
Water consumption	0,281170	0,145208
Raw material consumption	0,009886	0,005106
Hazardous waste gen.	0,044313	0,022885
Emissions to air	0,382636	0,197609
Radioactive waste gen.	0,069289	0,035784
Release to water	0,118016	0,060948
Land use	0,031020	0,016020

The weighted supermatrix has zero values when there is no influence. For example, Photochemical Smog does not influence Fossil Fuel Depletion. On the other hand, it influences Human Toxicity (0,019) and Carcinogenicity (0,045). Every component is weighted with its corresponding cluster matrix weight in this way. Then, the limit matrix is obtained by raising the weighted supermatrix to powers by multiplying it by itself. When every column is the same, the limit matrix has been reached and the matrix multiplication process is halted (Saaty, 2003). The limit matrix for the selection problem is shown in Table 9.9 and 9.10. The synthesized results of the priorities are extracted and obtained for the alternatives from the limit matrix.

Step 8: Finally, the overall results in the environmental aspect selection model of ANP are synthesized and shown in Table 9.11.

The overall results given in Table 9.11 show that the best alternative as the most significant environmental aspect for the EEE family is “energy consumption”. Keeping in mind that EEE are generally considered as “use phase intensive” products in the life cycle thinking approach (Wimmer et al., 2004), which signifies that the impacts during use dominate the overall environmental impact of the product (Wimmer and Züst, 2003), we can conclude that the result is reasonable enough to focus on it and to apply LCA in a simpler way. According to this result, assessing only the impacts related to the energy consumption would be enough to have a rough overview about the product’s environmental performance.

"Emissions to air" is found as the second best alternative signifying mostly the importance of the end-of-life waste treatment strategies, which produce hazardous gases while, for example, the EEE are incinerated.

Selecting the right environmental aspect with the use of ANP gives consistent results with a full LCA. We can conclude that the best alternative result is reasonable enough to focus on it. The proposed decision making methodology in this paper, as a simplified LCA technique, can be applied by SMEs and beginners in the environmental management field to complete their assessment in a shorter period, with less cost.

9.3 Simplified Aspect-Impact Assessment

9.3.1 Environmental aspect measuring: energy consumption

As indicated in Chapter 8.5.1, the energy consumption levels are calculated for each of life cycle phases of the hand blender. Each life cycle phase's calculations can be seen on Tables 9.12 to 9.16. The overall results are presented in Figure 9.4.

Table 9.12: Energy consumption for the raw material phase

Material	**Weight**	**Energy consumption**	**Total**
	[g]	**[MJ/kg]**	**[MJ]**
Copper	190,00	102,00	19,38
Stainless steel	220,00	80,00	17,60
PP	150,00	78,00	11,70
PS	70,00	96,00	6,72
PVC	30,00	101,00	3,03
PCB	10,00	3500,00	35,00
		Total	93,43

The results show us that the most environmentally problematic phase of hand blender is "Use of Raw Material Phase". Although EEE are generally consuming big amount of electricity (or batteries, any kind of power source, etc.) and are expected to be "Use Phase Intensive" products (Wimmer et al., 2004), according to the results of the energy consumption analysis, hand blender is included in "Raw Materials Phase Intensive" prod-

Table 9.13: Energy consumption for the manufacturing phase

Process	Material	Weight	Energy consumption	Total
		[g]	[MJ/kg]	[MJ]
Machining, bending, stamping	**Copper**	190,00	27,00	5,13
	Stainless steel	220,00		5,94
Injection molding	**PP**	150,00	29,00	4,35
	PS	70,00		2,03
Extrusion plastic pipes	**PVC**	30,00	23,00	0,69
Extrusion plastic film	**LDPE**	10,00	14,00	0,14
			Total	18,28

Table 9.14: Energy consumption for the distribution phase

Product Weight	0,85	[kg]	
Packaging	**Weight**	**Energy Consumption**	**Total**
	[g]	**[MJ/kg]**	**[MJ]**
LDPE	10,00	98,00	0,98
Cardboard	170,00	28,00	4,76
Transport	**Distance [km]**	**Energy consumption [MJ/ton km]**	**[MJ]**
Transoceanic freight ship	25000,00	0,17	3,61
Truck	1400,00	2,70	3,21
Van	20,00	5,60	0,10
		Total	12,76

Table 9.15: Energy consumption for the use phase

	Power	Time/use	Uses in Lifecycle	Electricity in Turkey	Total
	[W]	[s]	[1]	[MJ/kWh]	[MJ]
Energy cons.: Use	170,00	60,00	400,00	11	12,47
Energy cons.: Stand by	0,00				0,00
	[l]	[MJ/m^3]			
Water	0,50	6,70	400,00		1,34
				Total	13,81

Table 9.16: Energy consumption for the end of life phase

Material	Weight	Type of EoL	Energy consumption	Total
	[g]		**[MJ/kg]**	**[MJ]**
copper	190,00	recycling	-10,00	-1,90
stainless steel	220,00	recycling	-8,80	-1,94
PP	150,00	incineration	-39,00	-5,85
PS	70,00	incineration	-48,00	-3,36
PVC	30,00	incineration	-50,50	-1,52
PCB	10,00	landfill	0,00	0,00
LDPE	10,00	incineration	-49,00	-0,49
Cardboard	170,00	recycling	-32,00	-5,44
			Total	-20,49

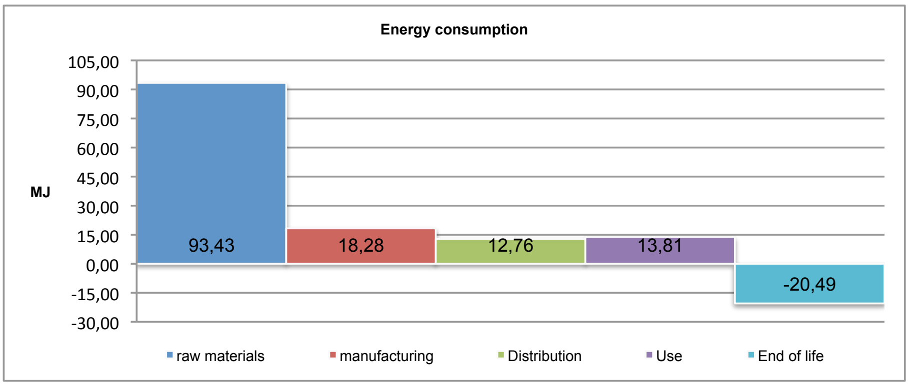

Figure 9.4: Energy Consumption levels for each life cycle phase

ucts family. This is the inevitable consequence of infrequent and short time period use of the product.

9.3.2 Environmental impact measuring: global warming potential

As indicated in Chapter 8.5.2, the global warming potential levels are calculated for each of life cycle phases of the hand blender.

As it is seen on Table 9.17 and Figure 9.5, the global warming potential warming impact of each life cycle phases has the same tendency with the energy consumption calculations. Again by observing the results, it can be concluded that the most environmentally problematic phase of the hand blender is “Use of Raw Material Phase”, with 3416,049 g CO_2-eq.

Table 9.17: Global Warming Potential changes after all improvements

RAW MATERIALS	**Parameter**	**Category**	**Unit of materials**	**GWP (CO2-eq g) / unit**	**Amount of materials**	**Total GWP (CO2-eq g)**
Copper	CO2	Air	kg	2038.5	0.19	387.315
Stainless Steel	CO2	Air	kg	3650	0.22	803
PCB	CO2	Air	kg	155840	0.01	1558.4
PP	CO2	Air	kg	1800	0.15	270
PVC	CO2	Air	kg	1972.8	0.03	59.184
PS	CO2	Air	kg	3400	0.07	238
LDPE	CO2	Air	kg	2076	0.01	20.76
Cardboard	CO2	Air	kg	467	0.17	79.39
						3416.049
MANUFACTURING	**Parameter**	**Category**	**Unit of process**	**GWP (CO2-eq g) / unit**	**Amount of processed materials**	**Total GWP (CO2-eq g)**
Injection Molding	CO2	Air	kg	1335	0.22	293.7
Extrusion for plastic film (PVC)	CO2	Air	kg	526	0.03	15.78
Extrusion for plastic pipe (cable)	CO2	Air	kg	378	0.01	3.78
						313.26
TRANSPORTATION	**Parameter**	**Category**	**Unit of transp.**	**GWP (CO2-eq g) / unit**	**Distance (km)**	**Total GWP (CO2-eq g)**
40 t truck (1 t-km)	CO2	Air	ton-km	93	1400	110.67
USE	**Parameter**	**Category**	**Unit of energy use**	**GWP (CO2-eq g) / unit**	**Consumption**	**Total GWP (CO2-eq g)**
Electricty	CO2	Air	kWh	290	1.15	333.5
END of LIFE	**Parameter**	**Category**	**Unit of process**	**GWP (CO2-eq g) / unit**	**Amount of processed waste**	**Total GWP (CO2-eq g)**
Recycling (1 kg waste)	CO2	Air	kg	-200	0.5525	-110.5
Landfill	CO2	Air	kg	19	0.0595	1.1305
Incineration	CO2	Air	kg	3.56	0.238	0.84728
						-108.52222
					TOTAL GWP (CO2-eq g)	**4064.95678**

Figure 9.5: GWP levels for each life cycle phase

The first suggestion to the producers, which can be generated at a first glance for the development of EEE ecodesign strategies, should be keeping in mind that each product has its own properties and behaviours during different phases of its lifetime. General acceptances for the product family do not always fit with the environmental performance of a single product.

Secondly, the environmental aspect and impact assessments of the hand blender show that the raw materials with the highest energy consumption should be changed with the lower ones in order to improve the environmental performance during hand blender's whole lifetime. The results of the assessments give us a focus point, raw material phase, nevertheless they do not provide a holistic approach covering the cost and quality requirements of the product. Therefore we need to conduct in parallel another technique to reach the sustainable product development.

9.4 QFDE Application

The product does not produce any waste during the use phase. Therefore "use waste" will not be considered as an Engineering Metric in QFDE application.

The lists of stakeholder requirements and product and environmental engineering metrics which are collected from the relevant literature (Masui et al., 2003; Wimmer et al., 2004;

Sakao, 2007; Vinodh and Rathod, 2010) and by the decision makers of our study are as follows:

Stakeholder Requirements (SR):

- *Cheap*: price of the product (Cost)
- *Easy to use*: using the product with fewer buttons, clear instructions, etc. (Quality)
- *Energy saving*: consuming less energy in the use phase (Environment, Cost)
- *Durable*: having robustness and long lifetime. (Quality, Environment)
- *Lightweight*: use of non-heavy materials (Quality)
- *Easy to maintain*: maintenance without requiring expert knowledge (Quality)
- *Easy to repair*: repair possible on site by user (Quality)
- *Quiet*: less noise while operating (Quality)
- *Ergonomic hold*: the shape of the handle, the button, the size, etc. (Quality)
- *Reliable*: service support, warranty period (Quality)
- *Visually attractive (Aesthetic appearance)*: color, shape, size, etc. (Quality)
- *Easy to clean*: use of cleanable, rust-free surface materials, easily separable knife part (Quality)
- *Safe to use*: related to leakage, burning of boiled water, etc. (Quality)
- *Easy to reuse*: use of reusable parts and components (Environment, Cost)
- *Easy to recycle*: use of recyclable materials (Environment, Cost)
- *Easy to disassemble*: use of fasteners and joints, avoiding adhesives (Environment)
- *Free of hazardous substances*: absence of toxic, hazardous substances and materials (Environment)

- *Less material use*: reducing the number of different types of materials used in the product (Environment)
- *Environmentally safe*: being harmless to the living environment in any of the product life cycle phases (Environment)
- *Less transportation*: optimizing the transportation routes and lots, reducing oil consumption and CO_2 emission (Environment, Cost)

Engineering Metrics (EM):

- *Weight*: product and environment related parameter
- *Volume*: product and environment related parameter
- *Supply parts environmental performance*: environment related parameter
- *Lifetime*: product and environment related parameter
- *Functionality*: product related parameter
- *Materials used*: product and environment related parameter
- *Production technology*: product related parameter
- *Production waste*: environment related parameter
- *Packaging*: product and environment related parameter
- *Transportation*: environment related parameter
- *Usability*: product related parameter
- *Energy Consumption*: product and environment related parameter
- *Waste (End of Life)*: environment related parameter
- *Noise and vibration*: product related parameter
- *Emissions in use*: environment related parameter

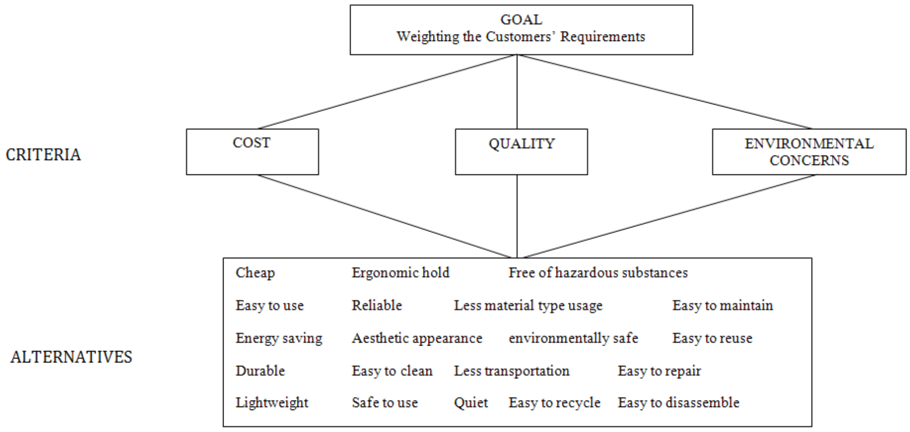

Figure 9.6: Hierarchy of the weighting problem

- *Maintenance*: product related parameter
- *Reparability*: product related parameter
- *Fasteners and joints*: product and environment related parameter
- *Time for disassembly*: product and environment related parameter
- *Rate of reusability*: environment related parameter
- *Rate of recyclability*: environment related parameter

9.4.1 Weighting SR with FAHP

The goal of the decision making problem in this section is to weight the stakeholders' requirements. The second level represents the three criteria; cost, quality and environmental concerns. They are accepted as criteria to weight the SR, which are the alternatives (A_i) of the prioritization in the third level. The hierarchy of this decision problem is given in Figure 9.6.

The triangular fuzzy conversion scale of the linguistic values in the weighting set used by decision makers is shown in Table 9.18. From a number of scales that have been proposed in the literature, the one that seems to correspond better to the original preferences scale of the crisp AHP in Table 8.3 is used.

Table 9.18: The triangular fuzzy conversion scale

Equally important	(1,1,2)	Equally to moderately	(1,2,3)
Moderately more important	(2,3,4)	Moderately to strongly	(3,4,5)
Strongly more important	(4,5,6)	Strongly to very strongly	(5,6,7)
Very strongly more important	(6,7,8)	Very strongly to extremely	(7,8,9)
Extremely more important	(8,9,9)		

Table 9.19: Comparison matrix for criteria

	Quality	**Environmental Concerns**	**Cost**
Quality	(1,1,1)	(1,2,3)	(1/3,1/2,1)
Environmental Concerns	(1/3,1/2,1)	(1,1,1)	(1/3,1/2,1)
Cost	(1,2,3)	(1,2,3)	(1,1,1)

The pairwise comparison matrices are formed by three decision makers, via a consensus decision making process. These decision makers, chosen from the three stakeholder groups as end users, government, and B2B customers (in our case a recycler), filled in 4 pairwise comparison matrices in total: One for the criteria with respect to the goal, which is shown here in Table 9.19. Then, there are three comparison matrices for the twenty alternatives with respect to the three criteria (cost, quality, environmental concerns), which are all from the first level. Only one of these three matrices comparing the alternatives with respect to environmental concerns are shown on Table 9.20.

Table 9.20: Comparison matrix for the alternatives with respect to environmental concerns

	Cheap	Easy to use	Energy saving	Durable	Lightweight	Easy to maintain	Easy to repair	Quiet	Ergonomic hold	Reliable	Vis. Att.-Aesth.	Easy to clean	Safe to use	Easy to reuse	Easy to recycle	Easy to dissassemble	Free of haz. substances	Less material type usage	Env. safe	Less transportation
Cheap	(1,1,1)	(1/2,1,1)	(1/9,1/9,1/8)	(1/8,1/7,1/6)	(1/3,1/2,1)	(1/3,1/2,1)	(1/4,1/3,1/2)	(1/3,1/2,1)	(1/2,1/2,1)	(1/3,1/2,1)	(1/2,1,1)	(1/3,1/2,1)	(1/2,1,1)	(1/9,1/9,1/8)	(1/9,1/9,1/8)	(1/8,1/7,1/6)	(1/9,1/9,1/8)	(1/9,1/8,1/7)	(1/9,1/9,1/8)	(1/9,1/8,1/7)
Easy to use	(1,1,2)	(1,1,1)	(1/9,1/9,1/8)	(1/8,1/7,1/6)	(1/3,1/2,1)	(1/3,1/2,1)	(1/4,1/3,1/2)	(1/3,1/2,1)	(1/2,1/2,1)	(1/3,1/2,1)	(1/2,1,1)	(1/3,1/2,1)	(1/2,1,1)	(1/9,1/9,1/8)	(1/9,1/9,1/8)	(1/8,1/7,1/6)	(1/9,1/9,1/8)	(1/9,1/8,1/7)	(1/9,1/9,1/8)	(1/9,1/8,1/7)
Energy saving	(8,9,9)	(8,9,9)	(1,1,1)	(1/8,1/7,1/6)	(6,7,8)	(5,6,7)	(4,5,6)	(6,7,8)	(8,9,9)	(6,7,8)	(8,9,9)	(7,8,9)	(7,8,9)	(1/3,1/2,1)	(1/3,1/2,1)	(2,3,4)	(1/2,1,1)	(1/3,1/2,1)	(1/2,1,1)	(1/3,1/2,1)
Durable	(6,7,8)	(6,7,8)	(1/6,1/5,1/4)	(1,1,1)	(4,5,6)	(2,3,4)	(1,2,3)	(4,5,6)	(7,8,9)	(3,4,5)	(8,9,9)	(4,5,6)	(6,7,8)	(1/4,1/3,1/2)	(1/4,1/3,1/2)	(1/2,1,1)	(1/3,1/2,1)	(1/4,1/3,1/2)	(1/3,1/2,1)	(1/4,1/3,1/2)
Lightweight	(1,2,3)	(1,2,3)	(1/8,1/7,1/6)	(1/6,1/5,1/4)	(1,1,1)	(1/4,1/3,1/2)	(1/5,1/4,1/3)	(1/2,1,1)	(2,3,4)	(1/3,1/2,1)	(4,5,6)	(1/3,1/2,1)	(1,2,3)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1/6,1/5,1/4)	(1/8,1/7,1/6)	(1/7,1/6,1/5)	(1/8,1/7,1/6)	(1/8,1/7,1/6)
Easy to maintain	(1,2,3)	(1,2,3)	(1/7,1/6,1/5)	(1/4,1/3,1/2)	(2,3,4)	(1,1,1)	(1/3,1/2,1)	(1/2,1,1)	(4,5,6)	(1,2,3)	(4,5,6)	(1/2,1,1)	(2,3,4)	(1/6,1/5,1/4)	(1/6,1/5,1/4)	(1/2,1,1)	(1/6,1/5,1/4)	(1/6,1/5,1/4)	(1/6,1/5,1/4)	(1/6,1/5,1/4)
Easy to repair	(2,3,4)	(2,3,4)	(1/6,1/5,1/4)	(1/3,1/2,1)	(3,4,5)	(1,2,3)	(1,1,1)	(1,2,3)	(5,6,7)	(2,3,4)	(1/2,1,1)	(1,2,3)	(3,4,5)	(1/5,1/4,1/3)	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(1/5,1/4,1/3)	(1/5,1/4,1/3)	(1/5,1/4,1/3)	(1/5,1/4,1/3)
Quiet	(1,2,3)	(1,2,3)	(1/8,1/7,1/6)	(1/6,1/5,1/4)	(1,1,2)	(1,1,2)	(1/3,1/2,1)	(1,1,1)	(1,2,3)	(1/2,1,1)	(4,5,6)	(1/3,1/2,1)	(1,2,3)	(1/7,1/6,1/5)	(1/7,1/6,1/5)	(1/6,1/5,1/4)	(1/7,1/6,1/5)	(1/7,1/6,1/5)	(1/7,1/6,1/5)	(1/7,1/6,1/5)
Ergonomic hold	(1,1,2)	(1,1,2)	(1/9,1/9,1/8)	(1/9,1/8,1/7)	(1/4,1/3,1/2)	(1/6,1/5,1/4)	(1/7,1/6,1/5)	(1/3,1/2,1)	(1,1,1)	(1/4,1/3,1/2)	(1/2,1,1)	(1/4,1/3,1/2)	(1/3,1/2,1)	(1/9,1/8,1/7)	(1/9,1/8,1/7)	(1/7,1/6,1/5)	(1/9,1/8,1/7)	(1/9,1/8,1/7)	(1/9,1/8,1/7)	(1/9,1/8,1/7)
Reliable	(1,2,3)	(1,2,3)	(1/8,1/7,1/6)	(1/5,1/4,1/3)	(1,2,3)	(1/3,1/2,1)	(1/4,1/3,1/2)	(1,1,2)	(2,3,4)	(1,1,1)	(4,5,6)	(1/2,1,1)	(1,2,3)	(1/7,1/6,1/5)	(1/7,1/6,1/5)	(1/5,1/4,1/3)	(1/7,1/6,1/5)	(1/7,1/6,1/5)	(1/7,1/6,1/5)	(1/7,1/6,1/5)
Vis. Att.-Aesth.	(1,1,2)	(1,1,2)	(1/9,1/9,1/8)	(1/9,1/9,1/8)	(1/6,1/5,1/4)	(1/6,1/5,1/4)	(1/7,1/6,1/5)	(1/6,1/5,1/4)	(1,1,2)	(1/6,1/5,1/4)	(1,1,1)	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(1/9,1/9,1/8)	(1/9,1/9,1/8)	(1/8,1/7,1/6)	(1/9,1/9,1/8)	(1/9,1/9,1/8)	(1/9,1/9,1/8)	(1/9,1/9,1/8)
Easy to clean	(1,2,3)	(1,2,3)	(1/9,1/8,1/7)	(1/6,1/5,1/4)	(1,2,3)	(1,1,2)	(1/3,1/2,1)	(1,2,3)	(2,3,4)	(1,1,2)	(3,4,5)	(1,1,1)	(2,3,4)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1/6,1/5,1/4)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1/8,1/7,1/6)
Safe to use	(1,1,2)	(1,1,2)	(1/9,1/8,1/7)	(1/8,1/7,1/6)	(1/3,1/2,1)	(1/4,1/3,1/2)	(1/5,1/4,1/3)	(1/3,1/2,1)	(1,2,3)	(1/3,1/2,1)	(2,3,4)	(1/4,1/3,1/2)	(1,1,1)	(1/9,1/8,1/7)	(1/9,1/8,1/7)	(1/8,1/7,1/6)	(1/9,1/8,1/7)	(1/9,1/8,1/7)	(1/9,1/8,1/7)	(1/9,1/8,1/7)
Easy to reuse	(8,9,9)	(8,9,9)	(1,2,3)	(2,3,4)	(6,7,8)	(4,5,6)	(3,4,5)	(5,6,7)	(7,8,9)	(5,6,7)	(8,9,9)	(6,7,8)	(7,8,9)	(1,1,1)	(1/2,1,1)	(2,3,4)	(1/4,1/3,1/2)	(1,2,3)	(1/4,1/3,1/2)	(1/2,1,1)
Easy to recycle	(8,9,9)	(8,9,9)	(1,2,3)	(2,3,4)	(6,7,8)	(4,5,6)	(3,4,5)	(5,6,7)	(7,8,9)	(5,6,7)	(8,9,9)	(6,7,8)	(7,8,9)	(1,1,2)	(1,1,1)	(2,3,4)	(1/4,1/3,1/2)	(1,2,3)	(1/4,1/3,1/2)	(1/2,1,1)
Easy to diss.	(6,7,8)	(6,7,8)	(1/4,1/3,1/2)	(1,1,2)	(4,5,6)	(3,4,5)	(2,3,4)	(4,5,6)	(5,6,7)	(3,4,5)	(6,7,8)	(4,5,6)	(6,7,8)	(1/4,1/3,1/2)	(1/4,1/3,1/2)	(1,1,1)	(1/6,1/5,1/4)	(1/2,1,1)	(1/5,1/4,1/3)	(1/4,1/3,1/2)
Free of haz. substances	(8,9,9)	(8,9,9)	(1,1,2)	(1,2,3)	(6,7,8)	(4,5,6)	(3,4,5)	(5,6,7)	(7,8,9)	(5,6,7)	(8,9,9)	(6,7,8)	(7,8,9)	(2,3,4)	(2,3,4)	(4,5,6)	(1,1,1)	(2,3,4)	(1,2,3)	(1,2,3)
Less mat. use	(7,8,9)	(7,8,9)	(1,2,3)	(2,3,4)	(5,6,7)	(4,5,6)	(3,4,5)	(5,6,7)	(7,8,9)	(5,6,7)	(8,9,9)	(6,7,8)	(7,8,9)	(1/3,1/2,1)	(1/3,1/2,1)	(1,1,2)	(1/4,1/3,1/2)	(1,1,1)	(1/3,1/2,1)	(1/3,1/2,1)
Env. safe	(8,9,9)	(8,9,9)	(1,1,2)	(1,2,3)	(6,7,8)	(4,5,6)	(3,4,5)	(5,6,7)	(7,8,9)	(5,6,7)	(8,9,9)	(6,7,8)	(7,8,9)	(2,3,4)	(2,3,4)	(3,4,5)	(1/3,1/2,1)	(1,2,3)	(1,1,1)	(1,2,3)
Less transp.	(7,8,9)	(7,8,9)	(1,2,3)	(2,3,4)	(6,7,8)	(4,5,6)	(3,4,5)	(5,6,7)	(7,8,9)	(5,6,7)	(8,9,9)	(6,7,8)	(7,8,9)	(1,1,2)	(1,1,2)	(2,3,4)	(1/3,1/2,1)	(1,2,3)	(1/3,1/2,1)	(1,1,1)

Table 9.21: Crisp Matrix of pairwise comparison values for Criteria

CRISP MATRIX	**Quality**	**Environmental concerns**	**Quality**
Quality	1	2	0,556
Environmental concerns	0,556	1	0,347
Cost	2	3	1

Table 9.22: Normalized Matrix of pairwise comparison values for Criteria

NORMALIZED MATRIX	**Quality**	**Environmental concerns**	**Quality**
Quality	0,281	0,333	0,292
Environmental concerns	0,156	0,167	0,182
Cost	0,563	0,5	0,526

Table 9.23: Eigenvector of the comparison matrix for Criteria

EIGENVECTOR		**Normalized**
E1	0,301	0,302
E2	0,168	0,168
E3	0,529	0,530

According to the ratings the decision makers have given, the pairwise comparison matrices are formed in order to weight the problem's criteria and to obtain the relative priorities of the subjective criteria.

At this level of the application, the consistency ratio is measured according to the instructions given in Chapter 8.6.3. First the fuzzy values are made crisp (see Table 9.21), and the matrix is normalized (see Table 9.22). Then the eigenvalue vectors are calculated (see Table 9.23. With λ_{max} value, consistency index (CI) and consistency ratio (CR) are found.

$$\lambda_{max} = 3,09$$

$$CI = 0,046$$

$$RI(n) = 0,58 \text{ (see Table 8.4)}$$

$$CR = \frac{CI}{RI(n)} = 0,078 < 0,1$$

Table 9.24: Normalized weights for criteria

Criteria	**C1**	**C2**	**C3**
Weights	0,338	0,126	0,536

Table 9.25: Normalized weights for alternatives

	With respect to		
Alternatives	**C1**	**C2**	**C3**
Cheap	0,0000	0,0000	0,2352
Energy saving	0,1251	0,1354	0,0938
Less transportation	0,0000	0,1171	0,1737
Easy to reuse	0,0000	0,1233	0,1584
Easy to recycle	0,0000	0,1236	0,1379
Durable	0,0800	0,0595	0,0677
Ergonomic hold	0,1290	0,0000	0,0000
Easy to clean	0,1185	0,0000	0,0000
Less material use	0,0000	0,1077	0,0486
Easy to use	0,1146	0,0000	0,0000
Easy to disassemble	0,0000	0,0565	0,0511
Easy to repair	0,0327	0,0000	0,0337
Quiet	0,0861	0,0000	0,0000
Safe to use	0,0806	0,0000	0,0000
Easy to maintain	0,0802	0,0000	0,0000
Lightweight	0,0767	0,0000	0,0000
Reliable	0,0544	0,0000	0,0000
Free of hazardous substances	0,0000	0,1422	0,0000
Environmentally safe	0,0000	0,1347	0,0000
Visually attractive-Aesth.	0,0222	0,0000	0,0000

From these comparison matrices, using FAHP method, the normalized criteria and alternatives' weights are calculated respectively (see Table 9.24 and 9.25). Finally the following global weights results presented in Table 9.26 are obtained. Considering cost, quality, and environmental concerns, "Cheap"ness is the most important feature.

9.4.2 House of Quality

The House of Quality at Phase I is prepared with SR weights and the relationships between SR and EM given by the decision makers. At crossing-points between VoSR

Table 9.26: Global weights for alternatives

Alternatives	Weights
Cheap	0,1261
Energy saving	0,1096
Less transportation	0,1078
Easy to reuse	0,1004
Easy to recycle	0,0894
Durable	0,0708
Ergonomic hold	0,0436
Easy to clean	0,0401
Less material use	0,0396
Easy to use	0,0388
Easy to disassemble	0,0345
Easy to repair	0,0291
Quiet	0,0291
Safe to use	0,0273
Easy to maintain	0,0272
Lightweight	0,0260
Reliable	0,0184
Free of hazardous substances	0,0178
Environmentally safe	0,0169
Visually attractive-Aesth.	0,0075

items and EM items are shown numbers indicating the magnitude of both factors called "relational strength" determined by the experts in consensus over a 1-3-9 scale. The total of the sum multiplied by "customer weights" and "relational strength" is the "raw score (weight-importance)" for each EM item. Furthermore, "Relative weight (Rw)" for each item is obtained by the raw score/sum of the raw score.

A relative importance ranking is obtained, according to the relationships and the weighting factors of stakeholder requirements. From the results, it can be concluded that the most important environmental EM for the hand blender is "Materials used" to fulfill the multi aspect stakeholder requirements, with an importance degree of 10,5%. The "Usability" and the "Waste" follow as second and third most important environmental parameters, with 8,6% and 8,4% respectively. Overall ranking results for engineering metrics are shown on Figure 9.7.

	SR	w	Weight	Volume	Supply parts env. Performance	Lifetime	Functionality	Materials used	Production technology	Production waste	Packaging	Transportation	Usability	Energy Consumption	Waste EoL	noise and vibrations	Emissions in use	Maintenance	Reparability	Fasteners and joints	Time for dissassembly	Rate of reusability	Rate of recyclability
unit			kg	m³		h					kg	km		kWh		dB					h	%	%
direction of improvement			↓	↓	↑	↑	↑	↓		↓	↓	↓	↑	↓	↓	↓	↓	↓	↑		↓	↑	↑
	SR	**w**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Cheap	**1**	*12,61*	3	1				3	9		1	3		1								1	1
Easy to use	**2**	*3,88*	9	9			9	1					9				1						
Energy saving	**3**	*10,96*					3		3					9		1							
Durable	**4**	*7,08*	1		3	9							9			3		3	3				
Lightweight	**5**	*2,60*	9					9			3		9										
Easy to maintain	**6**	*2,72*				3												9		1			
Easy to repair	**7**	*2,91*			3	3													9	3	3	1	
Quiet	**8**	*2,91*														9							
Ergonomic hold	**9**	*4,36*	3	9				1					9										
Reliable	**10**	*1,84*				3												9	9				
Visually attractive-Aesth.	**11**	*0,75*		3				9			1												
Easy to clean	**12**	*4,01*						3										3		1			
Safe to use	**13**	*2,73*					1						9				9						
Easy to reuse	**14**	*10,04*			3	3									9						3	9	
Easy to recycle	**15**	*8,94*						9							3						3		9
Easy to dissassemble	**16**	*3,45*			3										9					9	9	9	
Free of hazardous substances	**17**	*1,78*	1	1	3			9	1	3	9	1			9								9
Less material use	**18**	*3,96*	1					9			3				1								1
Environmentally safe	**19**	*1,69*			3				9				1		9		9						
Less transportation	**20**	*10,78*						1	1			9											
		Rw	*0,056*	*0,041*	*0,037*	*0,053*	*0,032*	*0,105*	*0,079*	*0,002*	*0,022*	*0,062*	*0,086*	*0,051*	*0,084*	*0,027*	*0,020*	*0,034*	*0,029*	*0,021*	*0,044*	*0,062*	*0,052*
		Raw score	122,04	90,84	80,86	116,26	70,52	231,17	174,16	5,35	49,08	136,65	187,55	111,25	183,41	58,42	43,64	74,27	64,00	46,47	96,69	136,88	113,10

Figure 9.7: House of Quality (HoQ)

The relative weights obtained from Phase I are used in the Phase II (see Figure 9.8). For the second phase of QFDE, five main parts of the hand blender are determined: motor, axle, housing, cable and blade. With the new relational strengths between EM and the five hand blender parts, the relative importance degrees of these parts are calculated. The results show that the motor is relatively the most important part and it is the first candidate to examine possible effects of the design changes. Housing follows the motor as the second most important part.

Before completing the final phase of QFDE, the possible improvement strategies are defined for the hand blender as following: *selecting non hazardous materials, reducing weight, optimizing product use, using recyclable materials, using reusable parts and components, reducing energy consumption in use phase, improving disassembly*. The strategies are obtained from the relevant literature (Wimmer et al., 2004; Luttropp and Lagerstedt, 2006).

The relative weights obtained from Phase II are used in the Phase III (see Figure 9.9). With the new relational strengths between the five hand blender parts and possible improvement strategies, relative importance degrees are calculated. The results show that "Recyclable material" has relatively the highest value. "Selecting non hazardous materials" and "Reusable parts and components" follow it as the improvement strategies with the second and third highest value respectively.

9.4.3 Results and related Ecodesign strategies

There are several potential improvement strategies mentioned in the literature to implement ecodesign (Brezet et al., 1997; Wimmer et al., 2004; Luttropp and Lagerstedt, 2006). However none of them proposes a structured model to show the decision makers which strategy to implement by considering different factors required for a successful product development. They tend to neglect the cost for the implementation and the possible effects which may lower the product quality. Therefore it is crucial to select the most suitable ecodesign improvement strategies for the studied product.

			Motor	Axle	Housing	Cable	Blade
	SR	**w**	**1**	**2**	**3**	**4**	**5**
Weight	**1**	*0,0557*	9	1	9	1	1
Volume	**2**	*0,0414*	3	3	3		3
Supply parts env. Performance	**3**	*0,0369*				9	
Lifetime	**4**	*0,0530*	9			1	3
Functionality	**5**	*0,0322*	9	3			3
Materials used	**6**	*0,1054*	9	1	9	3	3
Production technology	**7**	*0,0794*	9	3	9		3
Production waste	**8**	*0,0024*	3	1	3		1
Packaging	**9**	*0,0224*	3		3	1	
Transportation	**10**	*0,0623*	3		3	1	
Usability	**11**	*0,0855*			9	3	
Energy Consumption	**12**	*0,0507*	9				
Waste EoL	**13**	*0,0836*	3	1	3	1	1
Noise and vibrations	**14**	*0,0266*	9				
Emissions in use	**15**	*0,0199*	1				
Maintenance	**16**	*0,0339*			3		1
Reparability	**17**	*0,0292*	3			3	3
Fasteners and joints	**18**	*0,0212*	1		3		
Time for disassembly	**19**	*0,0441*	9		3		
Rate of reusability	**20**	*0,0624*	3			1	
Rate of recyclability	**21**	*0,0516*	1	3	9	3	3
		Rw	*0,385*	*0,066*	*0,332*	*0,114*	*0,104*
		Raw score	*502,89*	*86,10*	*433,29*	*148,66*	*135,24*

Figure 9.8: Parts deployment - Phase II

	SR	w	Selecting non hazardous materials	Reducing weight	Optimizing product use	Using recyclable materials	Using reusable parts and components	Reducing energy consumption in use phase	Improving disassembly
			1	**2**	**3**	**4**	**5**	**6**	**7**
Motor	**1**	*0,385*	9	9		3	9	9	3
Axle	**2**	*0,066*				1	1		3
Housing	**3**	*0,332*	3	1	9	9	1		1
Cable	**4**	*0,114*	1		1	3	3	1	1
Blade	**5**	*0,104*				3	1		1
		Rw	*0,175*	*0,145*	*0,119*	*0,186*	*0,165*	*0,137*	*0,073*
		Raw score	*4,574*	*3,797*	*3,099*	*4,859*	*4,308*	*3,579*	*1,902*

Figure 9.9: Production Improvement Planning - Phase III&IV

In this study, a multi-aspect QFDE technique led us to identify the most relevant ecodesign improvement strategies for the hand blender. Via the relationship levels given by decision makers, it is found that the product's most important aspect to improve is its materials. Selecting the right materials has the biggest potential to reach a better environmental performance. The possible actions to be considered by the producers can be stated as follows:

- *Using recyclable materials*: use of easily separable recyclable materials; improving the recyclability and waste treatment techniques.
- *Selecting non hazardous materials*: selecting the right materials; use of renewable, less/non hazardous, easily separable materials; avoidance of flammable, corrosive, reactive, ozone depleting, global warming contributing materials, toxic to humans or other organisms.
- *Using reusable parts and components*: use of reusable, easily separable parts and components; easy maintenance; easy upgradability; improving the disassembly;

avoidance the use of adhesives.

In Chapter 9.3 it is showed that the hand blender is a raw material phase intensive product, which means that the raw material phase has the most significant environmental impacts among others (manufacturing phase, distribution phase, use phase, and end of life phase). Although EEE are generally consuming big amounts of electricity (or batteries, any kind of power source, etc.) and are expected to be “Use Phase Intensive” products (Wimmer et al., 2004), according to the results of the energy consumption analysis of the previous study, hand blender is included in the “Raw Materials Phase Intensive” products family.

The obtained results in this paper are consistent with the previous study. The improvement strategies with the highest importance in QFDE are all related to materials used in the raw material phase. This indicates the possibility of merging the studies to obtain a holistic framework, by adding many other aspects needed for a successful sustainable production.

With the suggested actions, the impact occurring in this phase can be reduced. Hence the environmental performance of the hand blender will be improved.

9.5 Improvement Strategies

9.5.1 Improvement 1: Replace PCB with copper cables

PCB is actually used only for two functions.

1. Part of the switch function: A metal tongue closes the electric loop through pressing it on the PCB.

2. Part of the electric loop: The PCB-part reaches closest to the electrical engine. So the length of the conductors is very short.

A strategy for improvement is to replace the PCB with additional copper cables and a copper plate for the switch. In this assumption it would be possible to eliminate all PCB parts (10 g) by additionally using 25 g Copper. This improvement makes the total weight 0,865 kg by increasing it from 0,85 kg.

For closing the loop it is possible to use a second, fixed copper tongue (copper plate in the drawing). The additional conductors will connect the engine to the switch and the power supply.

9.5.2 Improvement 2: Change the mounting of the axle

The axle is mounted in a slide bearing, close to the blade. Above the bearing it is fixed by a ring, which stops the downward movement of the axle.

Steps for improvement:

- Change of mounting above the bearing
- Addition of a snap fit where the axle is connected to the motor
- Lowering of the connection between upper and lower part of the housing

These steps make it possible to completely disassemble the hand blender, except for the motor, which can be reused (see Chapter 9.5.3). This improves its End of Life characteristics; significantly the recyclability. The reparability, ease of maintenance and disassembly are increased as well. However, these are indirect consequences of this improvement and it is hard to measure the energy consumption and GWP effects on the product. Therefore the changes caused by this improvement will be ignored.

9.5.3 Improvement 3: Reuse the motor

Reusability of the motor is a possible ecodesign improvement for the hand blender, since the motor is not used densely during the whole life time. This was also observed in

Chapter 9.3 by the result telling that hand blender is a raw material intensive product rather than use phase intensive one.

To be able to reuse the motor, there has to be a new reverse logistics organization to bring the product back to the production site. For example a contract with the retailer service, or municipalities, etc. could be implemented or a small token could be given by the retailer, when the customer buys a new blender.

Investment for such a new organization is ignored in this thesis, since it requires lots of data about the logistics network, which is not available in our case. Only the changes in environmental performance will be considered for this improvement.

9.5.4 Changes in the Energy Consumption due to improvements

Improvement I has significant influence on energy consumption of the product, since it drops the use of PCB. It also contributes the overall environmental performance by phasing out the harmful flame retardants which are found in PCB.

The energy consumption calculations for each life cycle phase after improvement I can be seen on Tables 9.27 to 9.31 and on the Figure 9.10.

Table 9.27: Energy consumption for the raw material phase after improvement I

Material	**Weight**	**Energy consumption**	**Total**
	[g]	**[MJ/kg]**	**[MJ]**
Copper	215,00	102,00	21,93
Stainless steel	220,00	80,00	17,60
PP	150,00	78,00	11,70
PS	70,00	96,00	6,72
PVC	30,00	101,00	3,03
PCB	0,00	3500,00	0,00
		Total	60,98

As it is observed on Figure 9.10 the whole life-cycle energy consumption is decreased in total by about 28%.

Table 9.28: Energy consumption for the manufacturing phase after improvement I

Process	Material	Weight	Energy consumption	Total
		[g]	[MJ/kg]	[MJ]
Machining, bending, stamping	Copper	215,00	27,00	5,81
	Stainless steel	220,00		5,94
Injection molding	PP	150,00	29,00	4,35
	PS	70,00		2,03
Extrusion plastic pipes	PVC	30,00	23,00	0,69
Extrusion plastic film	LDPE	10,00	14,00	0,14
			Total	18,96

Table 9.29: Energy consumption for the distribution phase after improvement I

Product Weight	0,865	[kg]	
Packaging	**Weight**	**Energy Consumption**	**Total**
	[g]	[MJ/kg]	[MJ]
LDPE	10,00	98,00	0,98
Cardboard	170,00	28,00	4,76
Transport	**Distance [km]**	**Energy consumption [MJ/ton km]**	**[MJ]**
Transoceanic freight ship	25000,00	0,17	3,68
Truck	1400,00	2,70	3,27
Van	20,00	5,60	0,10
		Total	12,88

Table 9.30: Energy consumption for the use phase after improvement I

	Power	Time/use	Uses in Lifecycle	Electricity in Turkey	Total
	$[W]$	$[s]$	[1]	$[MJ/kWh]$	$[MJ]$
Energy cons.: Use	170,00	60,00	400,00	11	12,47
Energy cons.: Stand by	0,00				0,00
	$[l]$	$[MJ/m^3]$			
Water	0,50	6,70	400,00		1,34
				Total	13,81

Table 9.31: Energy consumption for the end of life phase after improvement I

Material	Weight	Type of EoL	Energy consumption	Total
	[g]		[MJ/kg]	[MJ]
Copper	215,00	recycling	-10,00	-2,15
Stainless steel	220,00	recycling	-8,80	-1,94
PP	150,00	incineration	-39,00	-5,85
PS	70,00	incineration	-48,00	-3,36
PVC	30,00	incineration	-50,50	-1,52
PCB	0,00	landfill	0,00	0,00
PE-LD	10,00	incineration	-49,00	-0,49
Cardboard	170,00	recycling	-32,00	-5,44
			Total	-20,74

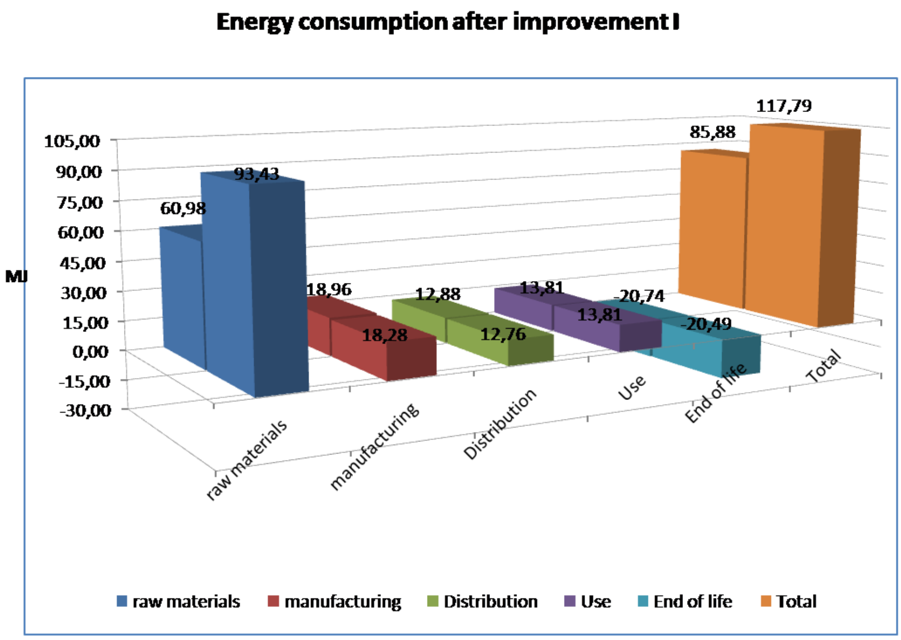

Figure 9.10: Energy consumption changes after improvement I

The energy consumption calculations for each life cycle phase after improvement III can be seen on Tables 9.32 to 9.36 and on Figure 9.11.

Table 9.32: Energy consumption for the raw material phase after improvement III

Material	Weight	Energy consumption	Total
	[g]	[MJ/kg]	[MJ]
Copper	190,00	102,00	19,38
Stainless steel	220,00	80,00	17,60
PP	150,00	78,00	11,70
PS	70,00	96,00	6,72
PVC	30,00	101,00	3,03
PCB	10,00	3500,00	35,00
		Total	93,43

Table 9.33: Energy consumption for the manufacturing phase after improvement III

Process	Material	Weight	Energy consumption	Total
		[g]	[MJ/kg]	[MJ]
Machining, bending, stamping	**Copper**	190,00	27,00	5,13
	Stainless steel	220,00		5,94
Injection molding	**PP**	150,00	29,00	4,35
	PS	70,00		2,03
Extrusion plastic pipes	**PVC**	30,00	23,00	0,69
Extrusion plastic film	**LDPE**	10,00	14,00	0,14
			Total	18,28

As it is observed on Figure 9.11 the whole life-cycle energy consumption is decreased in total by about 34%.

The energy consumption calculations for each life cycle phase after all improvements all together can be seen on Tables 9.37 to 9.41, and on Figure 9.12.

As it is observed on Figure 9.12 the whole life-cycle energy consumption is decreased in total by about 58%.

Finally, the overall changes in total energy consumption values for different scenarios can be seen on Figure 9.13.

Table 9.34: Energy consumption for the distribution phase after improvement III

Product Weight	0,85	[kg]	
Packaging	**Weight**	**Energy Consumption**	**Total**
	[g]	**[MJ/kg]**	**[MJ]**
LDPE	10,00	98,00	0,98
Cardboard	170,00	28,00	4,76
Transport	**Distance [km]**	**Energy consumption [MJ/ton km]**	**[MJ]**
Transoceanic freight ship	25000,00	0,17	3,61
Truck	1400,00	2,70	3,21
Van	20,00	5,60	0,10
		Total	12,76

Table 9.35: Energy consumption for the use phase after improvement III

	Power	**Time/use**	**Uses in Lifecycle**	**Electricity in Turkey**	**Total**
	[W]	[s]	[1]	[MJ/kWh]	[MJ]
Energy cons.: Use	170,00	60,00	400,00	11	12,47
Energy cons.: Stand by	0,00				0,00
	[l]	[MJ/m^3]			
Water	0,50	6,70	400,00		1,34
				Total	13,81

Table 9.36: Energy consumption for the end of life phase after improvement III

Material	**Weight**	**Type of EoL**	**Energy consumption**	**Total**
	[g]		**[MJ/kg]**	**[MJ]**
Copper	15,00	recycling	-10,00	-0,15
	175,00	reuse	-102,00	-17,85
Stainless steel	20,00	recycling	-8,80	-0,18
	200,00	reuse	-80,00	-16,00
PP	150,00	recycling	-70,00	-10,50
PS	70,00	recycling	-70,00	-4,90
PVC	30,00	incineration	-50,50	-1,52
PCB	0,00	landfill	0,00	0,00
PE-LD	10,00	incineration	-49,00	-0,49
Cardboard	170,00	recycling	-32,00	-5,44
			Total	-57,02

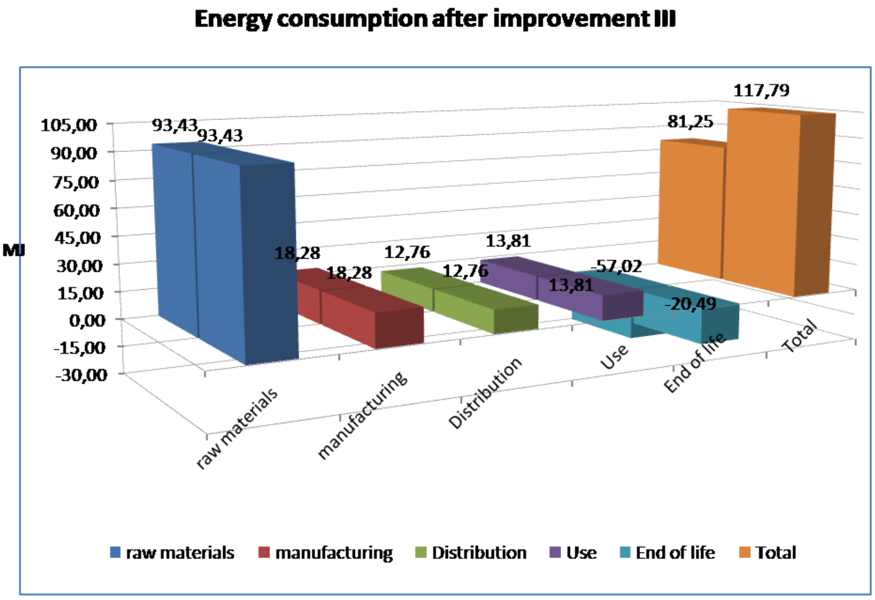

Figure 9.11: Energy consumption changes after improvement III

Table 9.37: Energy consumption for the raw material phase after all improvements

Material	**Weight**	**Energy consumption**	**Total**
	[g]	**[MJ/kg]**	**[MJ]**
Copper	2150,00	102,00	21,93
Stainless steel	220,00	80,00	17,60
PP	150,00	78,00	11,70
PS	70,00	96,00	6,72
PVC	30,00	101,00	3,03
PCB	0,00	3500,00	0,00
		Total	60,98

Table 9.38: Energy consumption for the manufacturing phase after all improvements

Process	**Material**	**Weight**	**Energy consumption**	**Total**
		[g]	**[MJ/kg]**	**[MJ]**
Machining, bending, stamping	**Copper**	215,00	27,00	5,81
	Stainless steel	220,00		5,94
Injection molding	**PP**	150,00	29,00	4,35
	PS	70,00		2,03
Extrusion plastic pipes	**PVC**	30,00	23,00	0,69
Extrusion plastic film	**LDPE**	10,00	14,00	0,14
			Total	18,96

Table 9.39: Energy consumption for the distribution phase after all improvements

Product Weight	0,865	[kg]	
Packaging	**Weight**	**Energy Consumption**	**Total**
	[g]	**[MJ/kg]**	**[MJ]**
LDPE	10,00	98,00	0,98
Cardboard	170,00	28,00	4,76
Transport	**Distance [km]**	**Energy consumption [MJ/ton km]**	**[MJ]**
Transoceanic freight ship	25000,00	0,17	3,68
Truck	1400,00	2,70	3,27
Van	20,00	5,60	0,10
		Total	12,88

Table 9.40: Energy consumption for the use phase after all improvements

	Power	**Time/use**	**Uses in Lifecycle**	**Electricity in Turkey**	**Total**
	$[W]$	$[s]$	[1]	$[MJ/kWh]$	$[MJ]$
Energy cons.: Use	170,00	60,00	400,00	11	12,47
Energy cons.: Stand by	0,00				0,00
	$[l]$	$[MJ/m^3]$			
Water	0,50	6,70	400,00		1,34
				Total	13,81

9.5.5 Changes in the Global Warming Potential due to the improvements

The global warming potential (GWP) is reduced by the proposed improvements. However the accurate calculation for GWP cannot be done, without any detailed information about the product. Consequently some estimates will be used in this study, such as the total amount of sold products, in order to compare GWP before and after product improvements. Because of the lack of data about some processes in manufacturing, such as cutting, gluing, coiling engine, GWP calculations are done by neglecting them.

- Scenario for improvement I:

  Total amount of products sold in one year: 150.000 pieces (assumption for Euro-

Table 9.41: Energy consumption for the end of life phase after all improvements

Material	Weight	Type of EoL	Energy consumption	Total
	[g]		[MJ/kg]	[MJ]
Copper	40,00	recycling	-10,00	-0,40
	175,00	reuse	-102,00	-17,85
Stainless steel	20,00	recycling	-8,80	-0,18
	200,00	reuse	-80,00	-16,00
PP	150,00	recycling	-70,00	-10,50
PS	70,00	recycling	-70,00	-4,90
PVC	30,00	incineration	-50,50	-1,52
PCB	0,00	landfill	0,00	0,00
PE-LD	10,00	incineration	-49,00	-0,49
Cardboard	170,00	recycling	-32,00	-5,44
			Total	-57,27

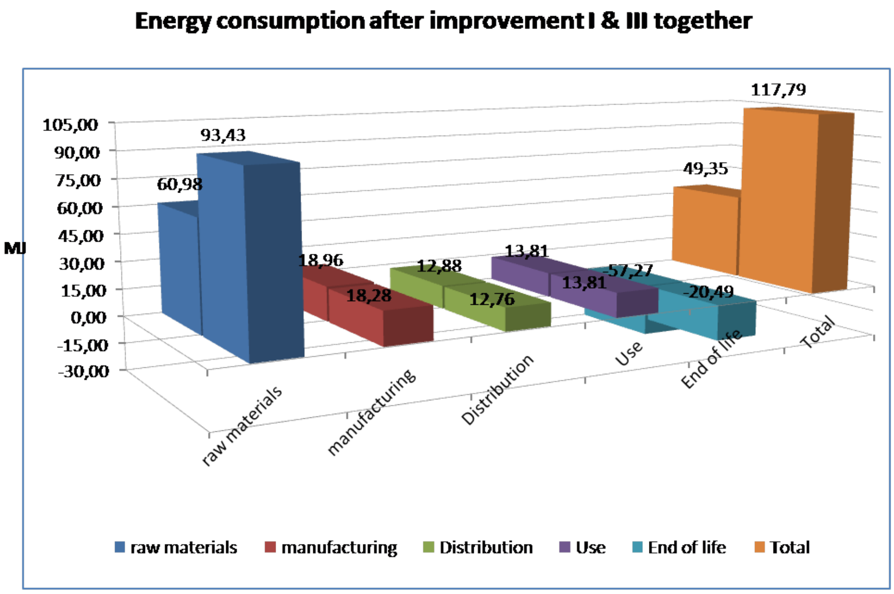

Figure 9.12: Energy consumption changes after all improvements

pean market)

GWP – (CO_2-eq): approx. 4,1 kg/product (see Table 9.17)

Total GWP/year: 4,1*150.000/1000 = 615 tone CO_2

Reduction: 37% by the proposed measure in previous section (see Table 9.42)

Total saving: 235,69 ton CO_2 for this hand blender over the whole expected lifetime.

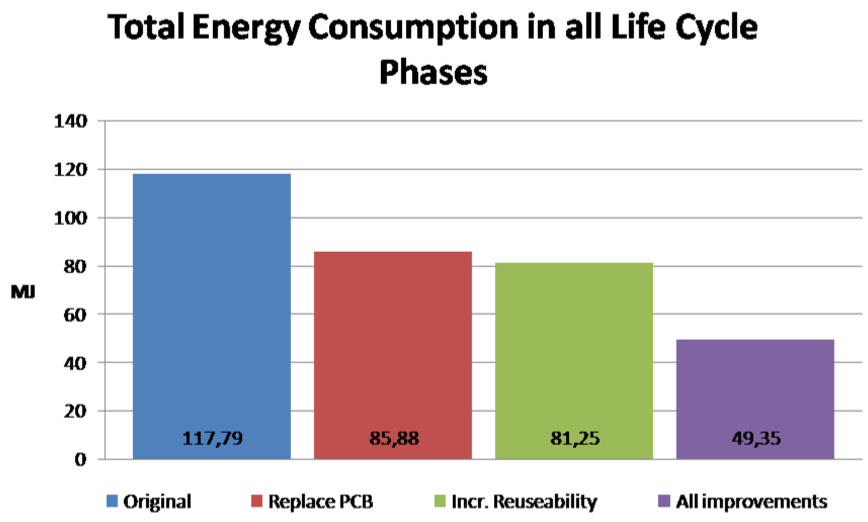

Figure 9.13: Total energy consumption values comparison

- Scenario for improvement III:

  Total amount of products sold in one year: 150.000 pieces

  GWP – (CO_2-eq): approx. 4,1 kg/product (see Table 9.17)

  Total GWP/year: 4,1*150.000/1000 = 615 ton CO_2

  Reduction: 27% by the proposed measure in previous section (see Table 9.43)

  Total saving: 166,05 ton CO_2 for this hand blender over the whole expected lifetime.

- Scenario for all improvements:

  Total amount of products sold in one year: 150.000 pieces

  GWP – (CO_2-eq): approx. 4,1 kg/product (see Table 9.17)

  Total GWP/year: 4,1*150.000/1000 = 615 ton CO_2

  Reduction: 64% by the two proposed measures in previous sections (see Table 9.44)

  Total saving: 393,6 ton CO_2 for this hand blender over the whole expected lifetime.

  The Table for the calculation can be found on .

  The overall calculations for each life cycle phase can be seen on Table 9.44.

Finally the overall changes in total GWP values for different scenarios can be seen on Figure 9.14.

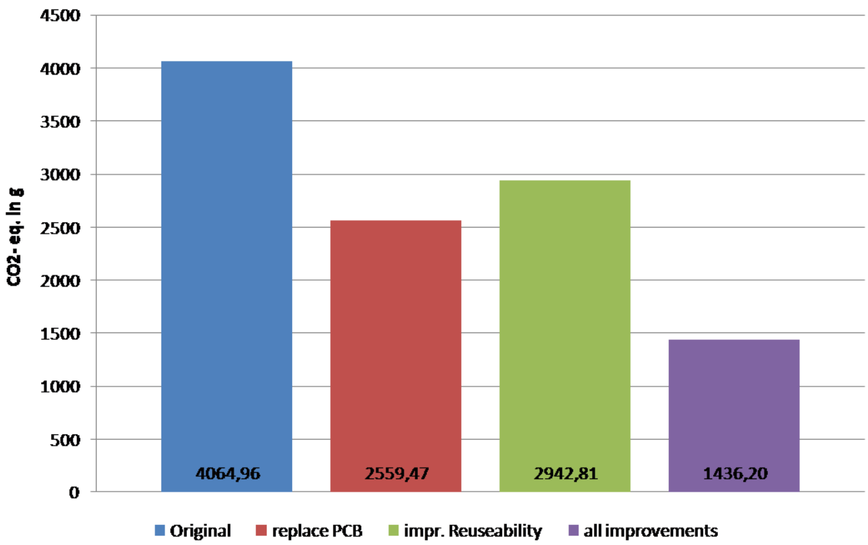

Figure 9.14: Total GWP values comparison

Table 9.42: Global Warming Potential changes after improvement I

RAW MATERIALS	**Parameter**	**Category**	**Unit of materials**	**GWP (CO2-eq g) / unit**	**Amount of materials**	**Total GWP (CO2-eq g)**
Copper	CO2	Air	kg	2038.5	0.22	438.28
Stainless Steel	CO2	Air	kg	3650	0.22	803
PCB	CO2	Air	kg	155840	0.00	0.00
PP	CO2	Air	kg	1800	0.15	270
PVC	CO2	Air	kg	1972.8	0.03	59.184
PS	CO2	Air	kg	3400	0.07	238
LDPE	CO2	Air	kg	2076	0.01	20.76
Cardboard	CO2	Air	kg	467	0.17	79.39
						1908.614
MANUFACTURING	**Parameter**	**Category**	**Unit of process**	**GWP (CO2-eq g) / unit**	**Amount of processed materials**	**Total GWP (CO2-eq g)**
Injection Molding	CO2	Air	kg	1335	0.22	293.7
Extrusion for plastic film (PVC)	CO2	Air	kg	526	0.03	15.78
Extrusion for plastic pipe (cable)	CO2	Air	kg	378	0.01	3.78
						313.26
TRANSPORTATION	**Parameter**	**Category**	**Unit of transp.**	**GWP (CO2-eq g) / unit**	**Distance (km)**	**Total GWP (CO2-eq g)**
40 t truck (1 t-km)	CO2	Air	ton-km	93	1400	112.62
USE	**Parameter**	**Category**	**Unit of energy use**	**GWP (CO2-eq g) / unit**	**Consumption**	**Total GWP (CO2-eq g)**
Electricty	CO2	Air	kWh	290	1.15	333.5
END of LIFE	**Parameter**	**Category**	**Unit of process**	**GWP (CO2-eq g) / unit**	**Amount of processed waste**	**Total GWP (CO2-eq g)**
Recycling (1 kg waste)	CO2	Air	kg	-200	0.55	-110.5
Landfill	CO2	Air	kg	19	0.06	1.13
Incineration	CO2	Air	kg	3.56	0.24	0.85
						-108.52
					TOTAL GWP (CO2-eq g)	**2559.47**

Table 9.43: Global Warming Potential changes afterl improvement III

RAW MATERIALS	**Parameter**	**Category**	**Unit of materials**	**GWP (CO2-eq g) / unit**	**Amount of materials**	**Total GWP (CO2-eq g)**
Copper	CO2	Air	kg	2038.5	0.19	387.32
Stainless Steel	CO2	Air	kg	3650	0.22	803
PCB	CO2	Air	kg	155840	0.01	1558.4
PP	CO2	Air	kg	1800	0.15	270
PVC	CO2	Air	kg	1972.8	0.03	59.18
PS	CO2	Air	kg	3400	0.07	238
LDPE	CO2	Air	kg	2076	0.01	20.76
Cardboard	CO2	Air	kg	467	0.17	79.39
						3416.05
MANUFACTURING	**Parameter**	**Category**	**Unit of process**	**GWP (CO2-eq g) / unit**	**Amount of processed materials**	**Total GWP (CO2-eq g)**
Injection Molding	CO2	Air	kg	1335	0.22	293.7
Extrusion for plastic film (PVC)	CO2	Air	kg	526	0.03	15.78
Extrusion for plastic pipe (cable)	CO2	Air	kg	378	0.01	3.78
						313.26
TRANSPORTATION	**Parameter**	**Category**	**Unit of transp.**	**GWP (CO2-eq g) / unit**	**Distance (km)**	**Total GWP (CO2-eq g)**
40 t truck (1 t-km)	CO2	Air	ton-km	93	1400	110.67
USE	**Parameter**	**Category**	**Unit of energy use**	**GWP (CO2-eq g) / unit**	**Consumption**	**Total GWP (CO2-eq g)**
Electricty	CO2	Air	kWh	290	1.15	333.5
END of LIFE	**Parameter**	**Category**	**Unit of process**	**GWP (CO2-eq g) / unit**	**Amount of processed waste**	**Total GWP (CO2-eq g)**
Reusability (Copper)	CO2	Air	kg	-2038.5	0.19	-387.32
Reusability (Stainless Steel)	CO2	Air	kg	-3650	0.22	-803
Recycling (1 kg waste)	CO2	Air	kg	-200	0.21	-42.33
Landfill	CO2	Air	kg	19	0.06	1.13
Incineration	CO2	Air	kg	3.56	0.24	0.85
						-1230.67
					TOTAL GWP (CO2-eq g)	**2942.81**

Table 9.44: Global Warming Potential changes after all improvements

RAW MATERIALS	**Parameter**	**Category**	**Unit of materials**	**GWP (CO2-eq g) / unit**	**Amount of materials**	**Total GWP (CO2-eq g)**
Copper	CO2	Air	kg	2038.5	0.22	438.28
Stainless Steel	CO2	Air	kg	3650	0.22	803
PCB	CO2	Air	kg	155840	0.00	0.00
PP	CO2	Air	kg	1800	0.15	270
PVC	CO2	Air	kg	1972.8	0.03	59.18
PS	CO2	Air	kg	3400	0.07	238
LDPE	CO2	Air	kg	2076	0.01	20.76
Cardboard	CO2	Air	kg	467	0.17	79.39
						1908.61
MANUFACTURING	**Parameter**	**Category**	**Unit of process**	**GWP (CO2-eq g) / unit**	**Amount of processed materials**	**Total GWP (CO2-eq g)**
Injection Molding	CO2	Air	kg	1335	0.22	293.7
Extrusion for plastic film (PVC)	CO2	Air	kg	526	0.03	15.78
Extrusion for plastic pipe (cable)	CO2	Air	kg	378	0.01	3.78
						313.26
TRANSPORTATION	**Parameter**	**Category**	**Unit of transp.**	**GWP (CO2-eq g) / unit**	**Distance (km)**	**Total GWP (CO2-eq g)**
40 t truck (1 t-km)	CO2	Air	ton-km	93	1400	112.62
USE	**Parameter**	**Category**	**Unit of energy use**	**GWP (CO2-eq g) / unit**	**Consumption**	**Total GWP (CO2-eq g)**
Electricty	CO2	Air	kWh	290	1.15	333.5
END of LIFE	**Parameter**	**Category**	**Unit of process**	**GWP (CO2-eq g) / unit**	**Amount of processed waste**	**Total GWP (CO2-eq g)**
Reusability (Copper)	CO2	Air	kg	-2038.5	0.19	-387.32
Reusability (Stainless Steel)	CO2	Air	kg	-3650	0.22	-803
Recycling (1 kg waste)	CO2	Air	kg	-200	0.21	-42.33
Landfill	CO2	Air	kg	19	0.00	0.00
Incineration	CO2	Air	kg	3.56	0.24	0.85
						-1231.8
					TOTAL GWP (CO2-eq g)	**1436.20**

9.6 Life Cycle Costing Analysis

In this part of the study, referring to the eco-cost estimation types mentioned in Chapter 4, the combination of the two, percentage of the capital cost of each element and cost per unit are used.

Moreover, as Rebitzer et al. (2003) indicated, since there are high uncertainties in respect to expected costs of the hand blender regarding the potential improvement strategies; it is focused in this study on the costs and assumptions that differ in the alternatives, on the changes in cost on a comparative basis. A total cost calculation is not provided due to this handicap.

The possible improvement strategies have been determined as follows, in the previous chapter:

- *Using recyclable materials*
- *Selecting non hazardous materials*
- *Using reusable parts and components*

According to these possible improvement strategies, the environmental actions taken and the improvement made in environmental performance are mentioned in Chapter 9.5.

Regarding these tables, the changes in the cost of the product can be calculated (see Table 9.45.

For the Improvement Strategy I, PCB is replaced by 25 g of Copper. As of June 2013, the price of one tone of Copper is given by London Metal Exchange (LME)[15] as 6.777 $/tone. Given this information, 25 g of copper costs:

25 g = 0,000025 tone

[15] http://www.lme.com/home.asp

0,000025*6.777 = 0,169 $

The price of a standard 50*50 mm of a PCB with its microprocessors, suitable for the use in a standard hand blender is about 3 $[16].

Given this information, the change in total cost/product is:

0,169 – 3 = -2,831 $

The result in minus shows a clear reduction in total cost of the product.

As indicated for Improvement Strategy II, changing the mounting of the axle does not provoke a significant change in the cost. Therefore, the calculation for LCC is ignored for this improvement action.

For Improvement Strategy III, the change in environmental performance of the hand blender was presented in the previous section. Figure 9.11 shows that there is a decrease of 34% in energy consumption in total, when the reusability is considered in end of life phase of the product. This brings automatically a decrease of 32,5% in the cost allocated to energy consumption too. The number of the products which will be taken back to the facility is unknown and the estimation depends on several parameters, which are hard to define for the moment. Nevertheless it is clear that any number of returned products will bring a decrease in raw material and manufacturing costs. If the producers decide not to build their own reverse logistics network and make agreement with outside partners, such as municipalities, for the collection of returned products, then the total change in cost will expectedly be a reduction, since such contracts cost usually less than the investment cost for the waste collection network. Otherwise depending on the complexity of the network, the implementation cost may affect the total change in cost in an increasing way.

In this thesis, it is assumed that the producer of the hand blender does not implement a reverse logistics network and prefers to cooperate with municipalities, which costs less. Therefore only the change in product's unit cost is considered in LCC and not

[16]The price is given by the online retailer company Mouser Electronics. `http://eu.mouser.com/`

the investment for the network implementation.

The overall LCC analysis, including the improvement strategies and their effects on environmental performance and cost is given on Table 9.45. Although design phase is not included in the five basic life cycle phases, it is added to this table to show the economic benefit of the proposed simplified integrated methodology by eliminating the use of a commercial LCA software and the extra consultancy costs.

The stakeholders are also mentioned on the table to indicate which target group will directly be influenced by the environmental and cost changes.

Table 9.45: LCC Analysis

Life Cycle Phases	Potential Differing Costs	Stakeholders	QFDE Improvement Strategies	Implemented strategies / Actions taken	Improvement directions	Change in environmental performance after the improvement	Change in cost after the improvement
Design	- Development	- Producer	-	- Simplified integrated environmental assessment methodology	- Lower cost - Less time	-	- Decrease by £4560 for LCA software - Decrease in consultancy costs
Raw Material	- Purchasing - Transportation - Raw material generation	- Producer - Supplier	- Using recyclable materials - Selecting non hazardous materials	- Replace PCB by Copper - Reuse of motor	- Less energy consumption - Lower cost	- Decrease by 35% - Decrease in hazardous substances	- Decrease by 35% due to en.cons. - Decrease by 2 & 831 $/product
Manufacturing	- Energy	- Producer	- Using reusable parts and components - Selecting non hazardous materials	- Reuse of motor - Replace PCB by Copper	- Less energy consumption - Lower cost	-Increase by 0,08% - Decrease level in energy consumption due to reuse cannot be estimated, depends on the amount of returned products	- Decrease level in cost due to energy consumption cannot be estimated
Distribution	- Energy	- B2B companies	-	- Replace PCB by Copper	- Higher weight	- Increase by 0,009%	- Negligible
Use	- Energy	- User	-	- Change the mounting of the axle	- Improving the reparability and maintenance	- Increase in lifetime - the period cannot be estimated	-
End of Life	- Landfill - Incineration - Recycling - Reuse - Disassembly	- B2B Companies -Recyclers -Society	- Using recyclable materials - Selecting non hazardous materials - Using reusable parts and components	- Replace PCB -Change the mounting of the axle -Reuse of motor	- Less hazardousness - Improving disassembly - Improving rate of recyclability and reusability	-Increase in EoL phase energy recovery by 280%	-Gain by 280% due to energy recovery

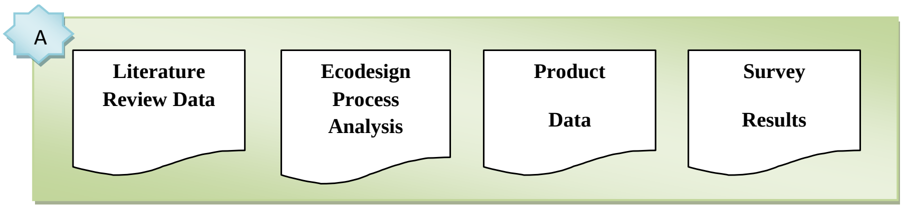

Figure 9.15: Integrated Methodology - part A

As a summary, it is clearly seen that, except the possibility to invest for a reverse logistics network, all possible improvement strategies aim to decrease the cost of the product. Therefore, all three of them can be applied by the producer to both increase the environmental performance and decrease the cost.

9.7 Discussion

The aim of this thesis was to provide a suitable holistic methodology, which fulfills the needs of the stakeholders for product development by combining economic, quality and environmental aspects together and to derive ecodesign improvement strategies to achieve sustainable production. The aim is achieved as in the following steps:

- Stage A

  At this stage, the theoretical base of the thesis is formed. Both the investigation about the situation in academia and industry showed that there was a need for a holistic ecodesign approach, covering all aspects of a traditional design and the environmental concerns. The need for a holistic approach was supported by the need of a simpler ecodesign methodology, since the existing tools are complicated enough for the decision makers and require complete information about the product and the design process. With the comparison between design and ecodesign processes, it was observed that the need for a simplified integrated methodology is mostly expected in early design phases.

  The analysis of the field should be completed by the producers, by gathering the data about the product, to start to ecodesign process. This data should include the

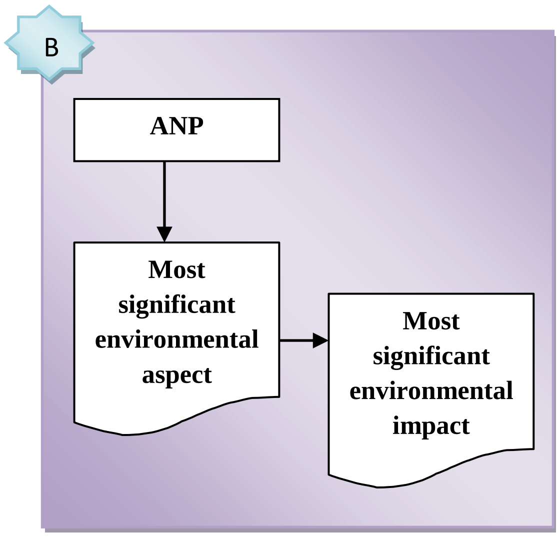

Figure 9.16: Integrated Methodology - part B

very basic information about the product which is going to be designed. There is no need for a detailed information since the proposed methodology is built on the idea of being serves at the early design phase, with less information need.

- Stage B

  At this stage, the environmental aspect selection problem is set and a suitable decision making technique, ANP, is used. The benefit of this stage for the producers is to obtain a base to conduct the environmental assessment of their product in an easy way, without using a complicated commercial tool, which needs a special expertise in the field. Instead, the opinions of decision makers who are experienced in ecodesign are asked. For this stage, the producers actually need a tool for the decision making, which is SuperDecisions in our case. However this tool does not cause a difficulty as much as other environmental assessment tools. First of all it is a free, web based tool, and secondly the producers do not need any data about the product but the experts' opinion.

  After obtaining the results from the decision making process, the most relevant environmental impact is chosen by the producers according to the environmental aspect given.

- Stage C

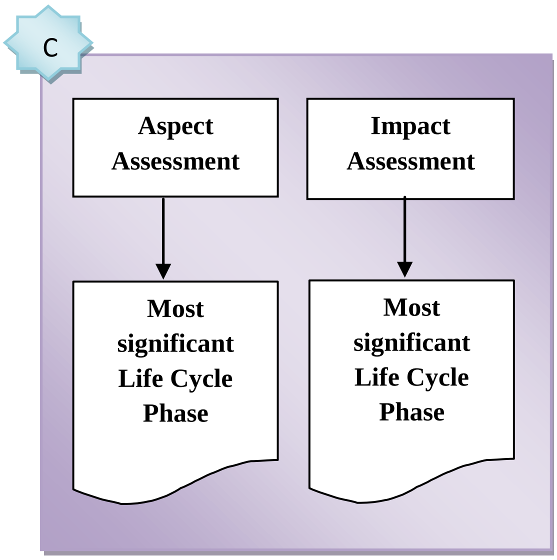

Figure 9.17: Integrated Methodology - part C

At this stage, based on the environmental aspect provided by the previous one, a simplified environmental assessment is conducted. Without requiring a complicated assessment tool, the most significant life cycle phase in environmental performance terms can be obtained with simple calculations. The only problematic aspect of this stage seems to reach the correct database, which includes all kind of data (about the materials, components, manufacturing processes', transportation, packaging, etc.) of the product. In 2006, European Commission released a free of charge database called ELCD (European reference Life Cycle Database), comprising Life Cycle Inventory (LCI) data from front-running EU-level business associations and other sources for key materials, energy carriers, transport, and waste management. The respective data sets are officially provided and approved by the named industry association and the data are accessible from the following link: http://elcd.jrc.ec.europa.eu

Such initiatives provide producers basic datasets to conduct their own environmental assessment. Thus they make the proposed integrated methodology even easier to apply. Nevertheless it should be kept in mind that the provided datasets can also be the limitation of the assessment. The standardization of the data among countries all over the world is still an issue waiting to be solved. A dataset for a country may

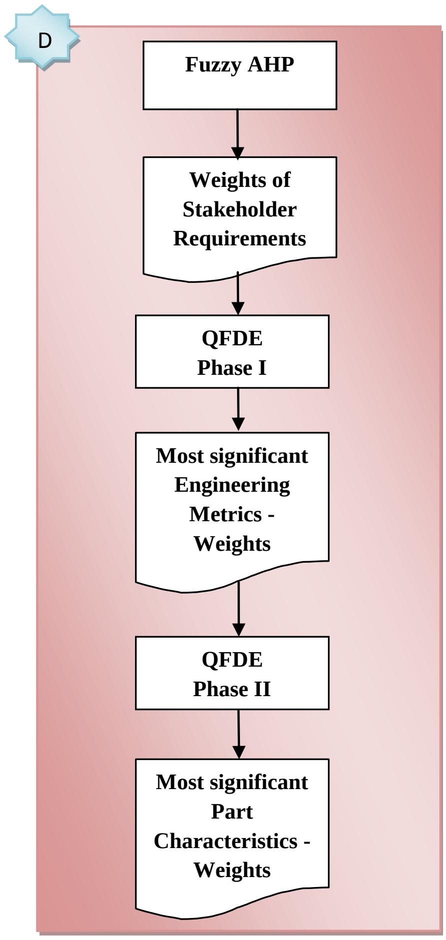

Figure 9.18: Integrated Methodology - part D

not fit to the other one. Nevertheless, it still gives a good rough estimation about the performance of the product and is very helpful to obtain the most problematic life cycle phase.

- Stage D

  At this stage, environmental and quality specifications of the product are set and a two phased QFDE is applied to reach the most significant part characteristics.

  The benefit of this stage is first to listen to all stakeholders' voices, to get their opinions about an ecodesigned product. With this approach not only the environmental but also the quality, functionality, aesthetics, etc. aspects are included in the proposed integrated methodology. Another contribution of this stage is being suitable to be used in early design phases since it does not require any technical,

Figure 9.19: Integrated Methodology - part E

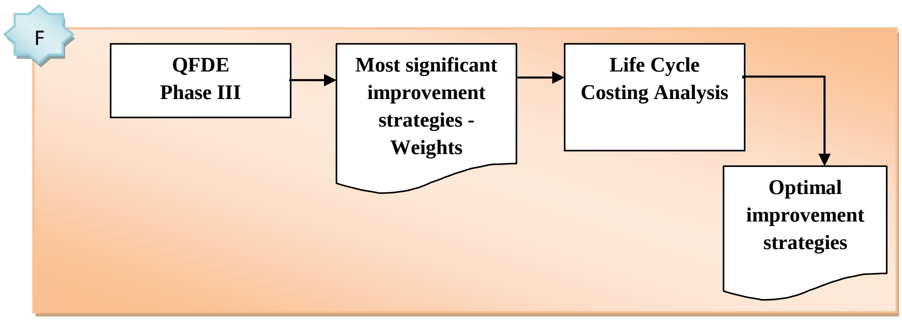

Figure 9.20: Integrated Methodology - part F

specific data about the product itself.

- Stage E

  At this stage, all the results obtained from the previous stages are gathered and the most relevant possible improvement strategies are proposed. The strategies are multi-aspects and reflect a wide perspective thanks to the improvement ideas collected from three previous stages, considering different approaches to ecodesign. The contribution of this stage is to provide a holistic point of view.

- Stage F

  At this stage, the final decision about the product's ecodesign procedure is given. The third phase of QFDE is conducted to obtain the weight of the most suitable improvement strategies. With the results of QFDE, the changes in both environmental performance of the product and cost are evaluated for every life cycle phase. This stage is supported by the complementary economic approach of environmental assessment, Life Cycle Costing analysis.

  The contribution of this final stage is to include clearly the cost aspect into the ecodesign process.

10 Conclusions

Environmental problems present the need for a transformation of traditional production into a sustainable one since almost two decades, and the increasing awareness of this procedure brings ecodesign popularity. However, the popularity of the term does not bring high levels of adoption by producers.

There are important methodologies, such as Life Cycle Assessment, provided in ecodesign and sustainable production to conduct environmental assesment. Nevertheless, except for large corporate companies, the manufacturers tend not to carry out an LCA since it is time and cost intensive, generates additional workload, requires a full data set about the product and knowledge in environmental assessment.

The producers, especially SMEs and the ones who lack experience in fulfilling the environmental regulations, require a simplified LCA approach rather than a full methodology which analyses the whole of life cycle by considering every type of environmental impacts. They first need to have a general overview of the environmental performance of their product and focus on the right environmental aspect causing most of the impacts. Electrical and Electronic Equipment is one of the product families having the highest impacts on the environment and human health. Therefore it's crucial to assess deeply their performance and to determine the most significant environmental aspect.

Regarding the problems faced in the field, this thesis proposed as its main contribution to the literature, a simplified ecodesign methodology which does not ignore the cost and quality parameters, listens to the voice of stakeholders with different perspectives, helps to obtain more realistic results by integrating fuzzy approach into product development and thus provides a holistic approach.

The thesis started by investigating the current situation in academia and in industry. With the findings of the investigation, first, a decision-making technique, Analytic Network

Process was used to determine the most significant environmental aspect to focus on. The selected problem for EEE was modeled by setting all the network relationships with their dependence and feedback. Using the Super Decisions software the results were computed and the best alternative, i.e. the most significant environmental aspect was found to be "energy consumption". This result fits perfectly with the full LCA methodology studies.

With the findings of the previous step, a simplified life cycle based environmental assessment for a hand blender was conducted based on energy consumption aspect. In order to define the improvement strategies of the product, the life cycle thinking approach and the QFD for Environment method were used in parallel. First, energy consumption and Global Warming Potential values were calculated for each phase. Secondly, an integrated QFDE methodology to identify the improvement strategies, considering cost, quality and environmental parameters for sustainable product development was proposed. It is crucial to weight the stakeholders' requirements, since they have different perspectives on a product. Therefore the FAHP Extent Analysis technique is used by determining stakeholder requirements as alternatives and by setting cost, quality, and environment as the criteria of the decision problem. With the fuzzy weights obtained by FAHP, a three-phased QFDE is applied in order to select the most relevant improvement strategies for the hand blender.

It is observed that the results of the QFDE are consistent with the results of the environmental aspect and impact assessment study, both showing the raw material phase as the most problematic one among others.

At the last step of the study, a Life Cycle Costing approach was used to evaluate the changes in the cost of the product related to its environmental performances before and after the implementation of the defined ecodesign strategies.

The proposed methodology contributes to the current literature in the following ways: First, since it does not require detailed information about the product, it is suitable for use in the early design stage. Secondly, it adds cost and quality parameters to the usual improvement strategy selection problem and provides a holistic approach. Finally it helps to obtain more realistic results by integrating fuzzy decision making into QFDE.

As another contribution, the proposed methodology showed us no matter how difficult it is, every producer should do the environmental assessment of his/her own product. Common acceptances for the product family help to give a general point of view but may fail in the specific product analysis. It should be kept in mind that each product has its own properties and behavior during different phases of its lifetime.

Finally, potential outcomes of the thesis can be summarized for different target groups as follows:

For the producers

- A holistic approach concerning environmental, quality and cost issues at the same time
- A methodology consuming less time and cost, suitable especially for SMEs
- Increase at the implementation of ecodesign thanks to the simplification
- A more flexible approach with more environmental data at the early design phase

For the scholars

- New directions to study the most significant life cycle phase for the products
- Guidance for the industry and studies in developing new EPDs, especially in the area of EEE
- Possibility of cooperation with the industry to build free and easy-to-use databases

For the society

- High quality cheaper green products with better environmental performance, less harmful to the environment and the people

- A sustainable future

Concerning future work, QFDE can be extended by adding benchmarking for the hand blender to identify areas for further improvement, make new strategic decisions, and set targets on desired environmental performance.

The current study is restricted to a framework “for the identification of the ecodesign improvement strategies”. To have a wider holistic framework for a successful ecodesign implementation, the proposed integrated methodology can be extended by considering many other sustainability factors, including social ones, which are mainly missing in this study, and by introducing an optimization model, which can be used to select the optimal environmental improvement strategy, to complete the ecodesign process. In this terms, the two key requirements investigated in the survey, motivation and creative environment, of which the results are ignored under the scope of this thesis, can be also considered in a future work to provide producers a solution to foster the use of ecodesign among engineers.

This study had some limitations which need to be overcomed, such as the non standard structure of the ecodesign databases. Standardization studies for each country’s data, especially for Turkey, can be another future working direction.

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Appendix A   Survey

PERSONAL INFORMATION

Affiliation

Country

Sector

Position

Main product of your affiliation

Years of experience in design

Contact details (e-mail)

The purpose of this questionnaire is to survey the requirements of designers for successful implementation of ecodesign and sustainable product development in the Electrical and Electronic Equipment (EEE) industry. We greatly appreciate your time to complete the survey and your contribution to this study.

SURVEY QUESTIONS

1. Which of the following statements do you relate to Design (D) and which of them to Ecodesign (ED) approaches and methods? Please consider both processes for each choice. (multiple answers possible)

D	ED	
		Reducing energy consumption
		Reducing environmental impact
		Reducing wastes
		Reducing materials used
		Resource conservation
		Increasing product durability
		Reduction of packaging
		Optimizing transport processes
		Optimizing production processes
		Improving quality
		Improving performance of a product
		Reducing costs
		Avoiding hazardous substances
		Improving recyclability
		Improving reusability
		Creativity
		Innovation
		Environmental legislations
		Sustainable future
		Competitive advantage
		Social responsibility
		Other (please specify)

2. Which one of the following statements does apply to you?

☐	I have used ecodesign methods and tools.
☐	I have not used ecodesign methods and tools in my work however I have profound knowledge in this area.
☐	I have not used ecodesign methods and tools in my work however I have a general overview on ecodesign.
☐	I have not used ecodesign methods and tools and I do not have any background in this area.

If you have **used** ecodesign methods & tools before, **go to question 3** and **answer ALL the questions to the end**.

If you **have not used** ecodesign methods & tools before, **jump to question 7** and **answer ALL the remaining questions**.

If you have **used** ecodesign methods & tools before, please answer from here through ALL questions to the end.

3. Which of the ecodesign aspect(s) have you focused on in your work? (multiple answers possible)

- ☐ Reducing energy consumption
- ☐ Reducing environmental impact
- ☐ Reducing wastes
- ☐ Reducing materials used
- ☐ Resource conservation
- ☐ Increasing product durability
- ☐ Reduction of packaging
- ☐ Optimizing the transport
- ☐ Optimizing the production process
- ☐ Avoiding hazardous substances
- ☐ Improving recyclability
- ☐ Improving reusability
- ☐ None of them
- ☐ Other (please specify) ....

4. Which of these methods and tools have you used before to reach a sustainable product design? (multiple answers possible)

☐	Life Cycle Assessment (LCA)
☐	TRIZ
☐	Quality Function Deployment (QFD)
☐	Failure Mode Effect Analysis (FMEA)
☐	Material-Energy-Toxicity (MET) matrix
☐	Environmental Risk Assessment (ERA)
☐	Ecodesign Checklists
☐	10 Golden Rules
☐	Ecodesign PILOT
☐	Lifetime Design Strategies (LIDS) Wheel
☐	Tool for Environmental Sound Product Innovation (TESPI)
☐	Key Environmental performance Indicators (KEPI)
☐	None of them
☐	Other (please specify) ....

5. How was your experience with these methods and tools?

YES	NO	
		They were easy to include in the design process.
		Their implementation was time intensive.
		Their implementation was cost intensive.
		Their proper use added workload.
		They made processes optimal.
		The results were easy to comprehend.
		The results were easy to interpret.
		They changed my point of view in designing.

6. What is the most important driving force to implement ecodesign methods and tools in your company? (multiple answers possible)

- [ ] Material scarcity
- [ ] Toxic substances
- [ ] Reducing production cost
- [ ] Reducing raw material cost
- [ ] Reducing energy consumption
- [ ] Reducing electrical and electronic wastes
- [ ] Improving recyclability
- [ ] Improving quality
- [ ] Improving the environmental performance of the product
- [ ] Raising creativity
- [ ] Social responsibility
- [ ] Competitive advantage
- [ ] Future benefits of the company
- [ ] Fulfilling legislations
- [ ] Fulfilling voluntary requirements (eco-labels, etc.)
- [ ] Fulfilling customers' demand
- [ ] Other (please specify) ....

If you **have not used** ecodesign methods & tools before, please continue from here to the end.

7. What is the reason that you have not used ecodesign in your affiliation before? (multiple answers possible)

- [ ] It does not lead my company to innovation.
- [ ] It requires more financial capital.
- [ ] It provokes more workload.
- [ ] The tools were not easy to use.
- [ ] There was no proper consultancy/education for the application of the tools.
- [ ] It was not the main priority of the company's policy.
- [ ] Other (please specify) ....

8. What are your requirements and drivers to apply ecodesign? (multiple answers possible)

- [ ] Information
- [ ] Guidance / Support
- [ ] Motivation
- [ ] Multi-disciplinary cooperation
- [ ] Creative environment
- [ ] Other (please specify) ....

9. Please rank the requirements in order of importance. (from 1 - the most important to 6 - the least important)

- [ ] Information
- [ ] Guidance/ Support
- [ ] Motivation
- [ ] Multi-disciplinary cooperation
- [ ] Creative environment
- [ ] Other (please specify) ....

10. What are your additional requirements to implement ecodesign process in your sector?

Please specify.

11. What kind of information do you need to implement an ecodesign process? (multiple answers possible)

- [ ] Current and in progress legislations
- [ ] Eco-label requirements
- [ ] Environmental Impact Categories
- [ ] Market information
- [ ] Benchmark information, product reference information
- [ ] No information needed
- [ ] Other (please specify) ....

12. What kind of guidance/support do you need to specify your priorities in ecodesign of EEE? (multiple answers possible)

- [ ] Consultancy
- [ ] Experts' opinion
- [ ] General Methods & tools
- [ ] Ecodesign strategies' list for EEE
- [ ] Company specific tool
- [ ] Electrical and Electronic product specific tool
- [ ] No guidance needed
- [ ] Other (please specify) ....

13. What would increase your motivation to apply ecodesign? (multiple answers possible)

- ☐ Getting financial bonus
- ☐ Having the opportunity to continue education on this topic
- ☐ Understanding my product development efforts beyond the boundaries of my company
- ☐ Understanding customers personally better
- ☐ Taking global environmental responsibility
- ☐ No motivation needed
- ☐ Other (please specify) ....

14. With which departments do you need to cooperate in order to implement ecodesign successfully? (multiple answers possible)

- ☐ Procurement department
- ☐ Legal department
- ☐ Marketing department
- ☐ Logistics department
- ☐ Environmental department
- ☐ Production department
- ☐ Finance department
- ☐ No cooperation needed
- ☐ Other (please specify) ....

15. According to your experiences, in which of the following design stages ecodesign methods and tools are mostly used? Please let us know your opinion even if you have no experience with ecodesign. (multiple answers possible)

- ☐ Identifying needs
- ☐ Planning
- ☐ Conceptual design
- ☐ Detailed design
- ☐ Testing / prototype
- ☐ Market launch
- ☐ Product review
- ☐ Other (please specify) ....

16. According to your experiences, please assign requirements to design stages. Please let us know your opinion even if you have no experience with ecodesign. (multiple answers possible)

Requirements	**Information**	**Guidance/ Support**	**Motivation**	**Multi-disciplinary cooperation**	**Creative environment**	**Other (please specify) ....**
Design stages						
Identifying needs						
Planning						
Conceptual design						
Detailed design						
Testing/ prototype						
Market launch						
Product review						
Other (please specify)						

Thank you for sharing your time and being a part of our study.

Biographical Sketch

İlke Bereketli was born on December 1, 1981, in İstanbul. She studied at Saint Joseph French High School where she was graduated in 2000. She started her undergraduate studies at Galatasaray University, in Industrial Engineering department in the same year. In 2005, she obtained the B.S. degree in Industrial Engineering. She started her graduate studies at Galatasaray University, in Industrial Engineering in 2005 and earned her M.S. degree in 2007. Following year, she joined the doctoral program in Industrial Engineering, at the same university. From September 2010 to September 2011, she conducted her research at Vienna University of Technology, in the Institute for Engineering Design and Logistics Engineering, with the scholarship she received from the Council of Higher Education. Since December 2005, she has been working as a research assistant in Industrial Engineering Department of Galatasaray University.

Her research interests include ecodesign, sustainable production systems, waste management and product development.

Her selected papers are as follows:

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Bereketli, İ., & Erol Genevois, M. (2013). An Integrated QFDE Approach for Identifying Improvement Strategies in Sustainable Product Development. *Journal of Cleaner Production*, 54(1), 188-198.