ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 00 (2016) 000–000

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

14th Global Conference on Sustainable Manufacturing, GCSM 3-5 October 2016, Stellenbosch, South Africa

Life Cycle Assessment Tool Implemented in Household Refrigeration Industry: A Magnetic Cooling Prototype Development

Rossella Luglietti[a]*, Paolo Rosa[a], Sergio Terzi[a]

[a]*Politecnico di Milano, Piazza Leonardo da Vinci, 32, 20132, Milano, Italy*

Abstract

The continuous development of innovative technologies should improve the resources efficiency and pollution reduction awareness. Sometimes, innovative technologies can improve the environmental aspects from one hand increasing other aspects for the other. For this reason, Life Cycle Assessment can guide the development of these innovative technologies in the right direction, taking into account all the environmental aspects during the whole lifecycle.

Designers and engineers should consider many indicators during the prototype phase of new products. For this reason, a Decision Support Toolbox has been implemented. In this paper, the results of the test phase, using a real industrial case.

Peer-review under responsibility of the organizing committee of the 14th Global Conference on Sustainable Manufacturing.

Keywords: Magnetic refrigeration; Life Cycle Assessment; DSS; Toolbox.

Nomenclature

DST	Decision Support Toolbox
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
REEs	Rare Earth Elements

* Corresponding author. Tel.: +390223994822.
E-mail address: rossella.luglietti@polimi.it

2351-9789 © 2016 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the organizing committee of the 14th Global Conference on Sustainable Manufacturing.

1. Introduction

The continuous development of innovative technologies should improve the resources efficiency and pollution reduction awareness. Sometimes, innovative technologies can improve the environmental aspects from one hand increasing other aspects for the other. For this reason, this paper wants to implement a methodological tool to include the environmental aspects into the decision making process at early phases of product development (design phase and prototype implementation).

For this reason, this paper wants to implement a methodological tool to include the environmental aspects into the decision making process at early phases of product development (design phase and prototype implementation).

The ELICiT project, funded by the European Commission, aims to apply the magnetic cooling technology to the domestic refrigeration market, in order to reduce the overall environmental impact in terms of energy and resources consumption. Under this goal, a multi objective analysis has been required studying the optimal magnetic machine and comparing it with the conventional gas-compressor refrigerator. The multi-objective analysis takes into account the standard indicators, like performance, technical requirements and economic costs, and the environmental indicators like, energy and resources consumption or CO2 emissions.

When a new technology is going to be developed, the engineers should include some questions regarding technological aspects, like: "is the magnetic refrigeration an innovative technology, which can replace the conventional refrigeration?" but they also includes questions regarding the effectiveness efficiency of the new product: could the new refrigerator reduce the overall impacts in terms of resources depletion, energy consumption and CO2 emission?

This paper wants to present a Decision Support Toolbox development under the ELICiT project. The main methodology and implementation has already been presented in [1], during the 13th Global Conference on Sustainable Manufacturing. At this stage of the research the final interface and results are presented.

The first section wants to summarized the four steps of the Toolbox implementation and its concept, describing the motivation and the goals of the DST. Many details of the methodology may be found in [1].

The second section describes the case study elaborated in order to adapt the methodology. in this paper the magnetic refrigerator is presented. In particular, a briefly introduction on scientific methodology and on the product is presented. After the four steps toolbox procedure is applied to the case under analysis.

Finally, the results of the environmental assessment are reported for both the first goal defining the optimal machine and the second goal comparing it with the conventional refrigerator.

2. Decision Support Toolbox definition

The Decision Support Toolbox (DST) aims to help designers and engineers to include the environmental indicators into the decision making at the prototype phase. Thanks to this Toolbox the lifecycle information of the product, like materials extraction and transportation, production process, assembly phase, usage phase and end of life. The environmental evaluation allow to compare different components or products not only considering performances, economic costs. The DST is able to compare different alternatives proposed by engineers at the prototype stage, finding the optimal solution. A second goal of the toolbox is to compare the innovative optimal product with a conventional machine, in order to understand if the environmental aspects have been improved with the prototype.

The DST conceptualization has been described and detailed in Luglietti et al., 2016, using the IDEF diagram as the following: (I) functional group analysis, (II) on-site data acquisition, (III) environmental and economic assessment, (IV) data elaboration.

The IDEF scheme reported in Fig. 1 describes all the steps included into the DST for developing a multi-criteria framework. The Toolbox has been conceptualized in [1], considering a first part where the product is described (with the functional groups analysis and on-site data acquisition), and a second part where the real analysis is conducted (with the economic and environmental assessment and the data elaboration).

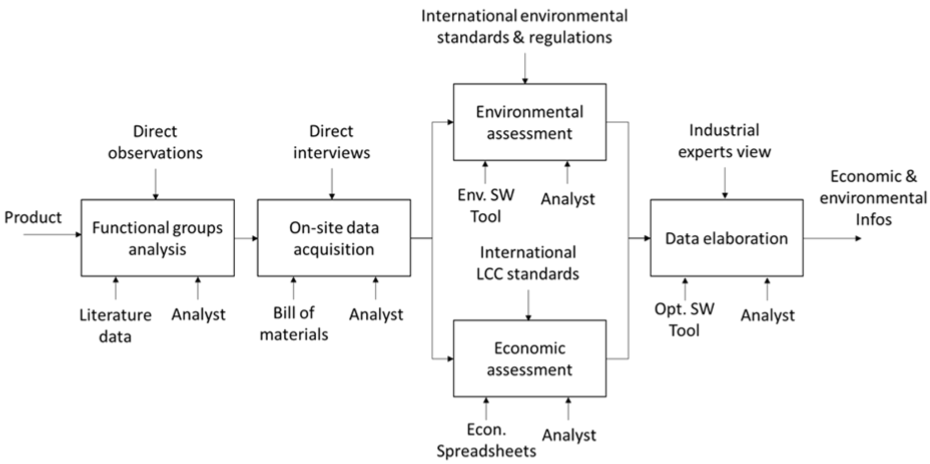

Fig. 1: Decision Support Toolbox process description with IDEF Diagram [1]

The DST interface has been developed taking into account the lifecycle phases. Fig 2 shows the interface idea, where, for each step of the lifecycle, the components and the relative alternatives are analyzed. In addition, specific boxes allow a selection of parameters, which can be responsible of results variation, for example the country of production and usage, where the electricity mix may change, or the country of recycling, where different legislation may cause changes in the recycling activities.

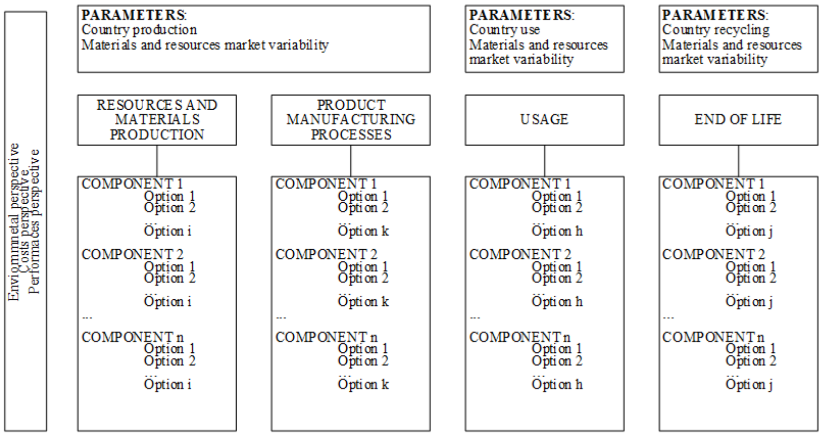

Fig. 2: Decision Support Toolbox interface definition.

The DST interface has been designed to be used for the first goal, comparing different alternatives of each components, and for the second goal, comparing the innovative machine with a conventional one.

3. Case study application

The Decision Support Toolbox has been applied at the refrigeration industry, and it wants to evaluate the innovative technology based on the magnetic cooling system that could replace the conventional domestic refrigeration. The Toolbox elaborates the information from the environmental and the economic point of view. For this report, the analysis has been presented only from the environmental perspective due to privacy policy of economic results.

In [1] the first two steps of the DST procedure have already been described. This paper wants to report the assessment results (focusing only on the environmental impacts) and the data elaboration.

The Toolbox environmental assessment has been supported by the Life Cycle Assessment methodology and the economic assessment by the Life Cycle Costing methodology. The focus of this paper is to understand how the LCA can be used by the designer in an innovative toolbox to support the decision making process, in the case of refrigeration households.

LCA is an international methodology standardized by ISO 14040 [2] and 14044 [3], which evaluates the environmental impacts of a product (good or service) during the whole lifecycle. The reason why this methodology has been chosen is the comprehensive evaluation of a product. Many times, the innovative prototype can reduce the impact in a stage of the lifecycle to increase it in some other stages. In this case, the toolbox shall be able to understand if the prototype can improve the overall environmental impact of the refrigeration sector, considering not only the usage phase in terms of energy consumption, but also the production system and the materials selection.

The ISO 14040 and 14044 define respectively the principles and guidelines to implement a full Life Cycle Assessment, describing a specific framework with four iterative phases.

1. Goal and Scope definition: identifies the objectives of the LCA, where it is possible to specify: purposes of the study, system definition (including the boundaries) and functional unit.
2. Life Cycle Inventory (LCI): includes data collection and calculation procedures description. In this phase, the incoming and outbound flows of the system described in the previous phase are quantified.
3. Life Cycle Impact Assessment: the environmental impact evaluation, where impact categories are defined. For each impact category, an indicator shall be chosen.
4. Life Cycle Interpretation: the last part of the LCA, where the results are analyzed with a critical review and a sensitivity analysis may be done.

In Luglietti et al., 2016, the two main goals of the DST were well discussed. The first level of the analysis aims to evaluate the ideal machine comparing different alternatives in term of materials and production process for the components from the environmental perspective. Instead, the second level aims to compare the ideal machine came out from the first one with the conventional refrigerator. In the next session, the two different products will be described and detailed. Thanks to the Toolbox, the practitioners are able to understand in which steps of the lifecycle the new prototype shall be improved, comparing to the conventional one.

A preliminary application of the toolbox were already described in [1]. The differences of this paper are the evolution of some hypothesis of the first two phases (the functional group analysis and the on-site data acquisition), and has been added the presentation of the third phase, which is the environmental assessment for both goals and the data elaboration with the results interpretation.

3.1. Phase 1: Case Study Description and Functional group analysis

A product’s functional group analysis has been used to describe the different components of the domestic refrigerator and how magnetic cooling can be different (e.g. see [4], [5], [6], [7]). Thanks to these schemes, it was possible to set up the main structure of the system under analysis, and provide environmental details of each component and option and not only of the whole system.

A domestic refrigerator can be described as composed by two main components [8]:

- the complete refrigeration system defined as “conversion device”, which is composed by the cooling engine and the heat exchangers;
- the insulated cold-box defined as the “passive system”.

This subdivision is a difference from the previous article, were only the following groups identification were done. The importance to define a conversion device and a passive system is to understand the changes of the magnetic system with the conventional one.

The functional group analysis of conventional domestic refrigerator identified four mains groups: i) cabinet, ii) door, iii) cooling system, iv) thermostat. The cabinet and the doors are the central structure of the fridge, aiming to hold food and giving to the product a bearing structure and they are the main component of the “passive system”. The temperature controller, of which the thermostat is main component, is the only element responsible for the correct management of the internal refrigerator temperature and drives the cooling system. The temperature controller and the cooling system define the “conversion device”, which is the set of elements that are physically responsible for reaching the correct level of cold inside the cabinet. In the case under examination, the conversion device, based on magnetic refrigeration principles, is composed by the electric motor, the permanent magnet assembly, the pump, the heat exchangers, the regenerators and the fluid management system [1].

About the magnetic refrigerator, the changes are limited to the cooling system. In fact, one of the main target of the ELICiT project is to minimize the changes to production technologies up to limit costs.

Once defined the refrigerators functional groups and components, the functional unit, as first requirements of an LCA or a LCC, is defined as the household refrigerator with a working time of 24 hours d-1, and an average lifetime of 10 years; all the sub-components have been analyzed with the same lifespan and no-maintenance was considered. Because the conversion device is still a prototype phase, it is assumed that it has the same lifespan of the conventional refrigerator.

3.2. Phase 2: On site data acquisition

In the second step of Decision Support Simulation Toolbox, a comprehensive on-site data acquisition has been done. During this phase, all the information related to materials, production process and alternatives, specially referred to the conversion device, have been collected and elaborated (Table 1). The passive system of the magnetic refrigerator has been supposed to be equal to the conventional one, and for this reason, any different alternative has been analyzed. The same approach has been used by [9], to evaluate the Life Cycle Assessment for the comparison of a magnetic and a conventional refrigerator. About the conventional refrigerator there are not alternatives, because the product is already on the market and well-known.

Table 1: Conversion device alternatives of magnetic refrigerator.

Functional Group	Alternatives
PUMP	Option 1: Gear Pump Option 2: CR Pump
HEAT EXCHANGER	Option 1: Natural convection Option 2: Forced Convection
REGENERATORS	Option 1: Lanthanum with Silicate and Cobalt alloy Option 2: Lanthanum with Manganese alloy and a final hydrogenation. Option 3: Lanthanum with Cerium and Manganese alloy, Cobalt and a final hydrogenation. Option 4: Manganese alloy and Phosphor without REEs
PERMANENT MAGNET	Option 1: Neodymium alloy. Option 2: Neodymium and Cerium alloy.
VALVING SYSTEM	Only 1 option
ELECTRIC ENGINE	Not included

3.3. Phase 3: Environmental Assessment

Luglietti et al., 2016 ended the analysis at the second phase of the procedure. In this paper, the environmental assessment is described and presented. As already said the methodology used to support the assessment is the LCA, where the environmental impacts are calculated throughout the whole lifecycle. the evaluation has been done used the SimaPro software, which is one of the most important software used to implement a LCA. Thanks to the information gathered and elaborated used Ecoinvent 3.1 and other scientific sources (i.e. [10] to study the REEs extraction).

The DST includes different indicators (endpoint or middle point) that users can choose. In particular, the analysis has been done considering the endpoint indicator Recipe, developed by Pré Consulting, or a list of middle point indicator, using the CML methodology (abiotic depletion, global warming, ozone layer depletion, human toxicity, eco-toxicity, photochemical oxidation, acidification, and eutrophication).

3.4. Decision Support Toolbox Interface

In Luglietti 2016, the interface has been described using Fig. 2. The DST interface includes separate boxes for the life cycle steps: the materials and resources production, the production processes, and the usage phase. At this level of the analysis, the end of life as not been included into the evaluation, due to the unknown information about the recyclability of the magnetic cooling system components. In addition, the interface has specific boxes to select the parameters, like country production and usage, and to select the indicator. In the last part of the toolbox there is a box which includes the results for the ideal configuration. All the results are also reported and presented in graphs.

In the Fig 3, 4, 5 examples of DST interface are presented. Fig. 1 is the interface of the Magnetic cooling system, where the red boxes represent the choices that the user can do (parameters, indicators and configuration), and the big boxes represent the lifecycle phases with the components alternatives. Fig. 4 is the interface of heat exchanger, where the screenshot allows to see also the graph with the results. In the next section, the results of the components will be presented and discussed. Finally Fig. 5 is the interface of the pump evaluation. Both, the heat exchanger and pump interface includes the lifecycle phase from material extraction and production to usage phase, due to electricity consumption used by these components. This is the difference within the magnetic cooling system interface, where the usage phase is not included.

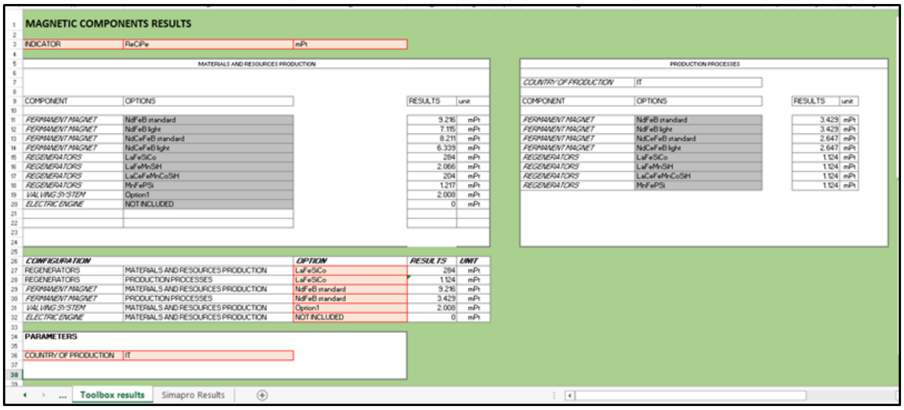

Fig. 3: Magnetic cooling system interface.

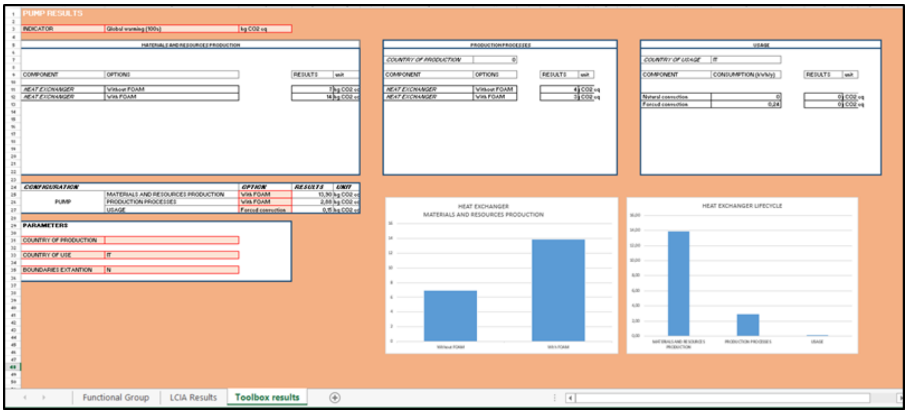

Fig. 4: Heat exchanger interface.

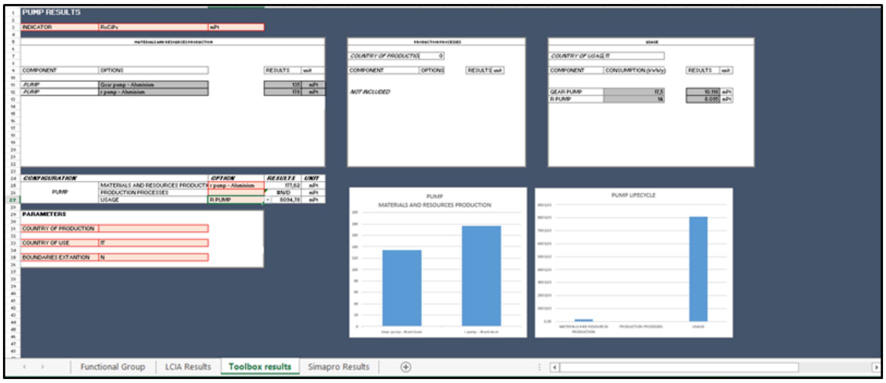

Fig. 5: Pump interface.

4. Results and Discussion

This section wants to present the results of the two goals of the toolbox, in order to highlight the importance of using such as toolbox to support the product development process. Thanks to the toolbox the engineer could analyzed the options in terms of production process and materials from the environmental point of view.

The first goal of the analysis aims to compare the alternatives of the magnetic cooling system components. In particular, as explained before, the three components analyzed are: the pump, the heat exchanger, and the magnetic system that includes the permanent magnets the regenerators, the valving system and the electric engine (not included in the evaluation, due to lack of data).

The results are reported using the ReCiPe indicator, which provide a full overview of the three main categories (Resources Depletion, Human Health and Ecosystem Depletion). ReCiPe uses eighteen midpoint indicators, but also calculates three much more uncertain endpoint indicators. The motivation to select the endpoint indicators is that the large number of midpoint indicators are very difficult to interpret. The final indicator at the endpoint level is intended to facilitate easier interpretation, and it has a more understandable meaning.

Fig. 6 is an example of toolbox results in the case of magnetic cooling system, and it reports the results for the alternatives of the permanent magnet and the regenerators throughout the lifecycle under analysis.

Fig. 6: Example of Toolbox results in the case of magnetic cooling system.

Fig 7 shows the total impacts throughout the life cycle (material extraction and production process) of the magnetic cooling system components, considering the optimal solution defined with Fig 6. In the specific case, the option three, with lanthanum, cerium and manganese alloy, cobalt and a final hydrogenation has been chosen as best option of regenerators, instead, the permanent magnet with cerium is the one preferred for the permanent magnet. Fig. 7 wants to present the importance of production process in the final configuration. In fact, considering the regenerators, because the mold is complex, the impacts of the production process are higher that the impacts caused by the material extraction and transformation. In the case of permanent magnet is the opposite.

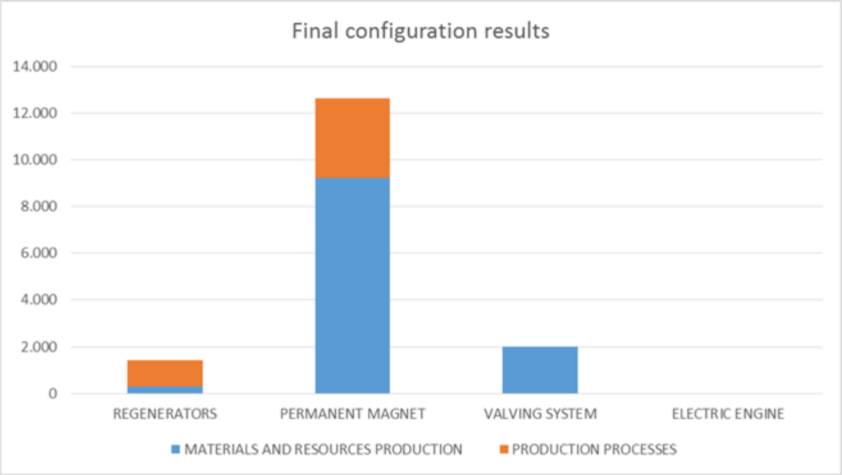

Fig. 7: Toolbox results of the optimal solution of magnetic cooling system.

The ideal machine is composed by the following: option 3 of regenerators, option 2 of permanent magnet, and option 1 for pump and heat exchanger. This machine has been compared with the conventional refrigerator, and the results are reported in Table 2.

Table 2: Results of second goal of the DST

Impact category	Unit	Cabinet	Door	Control unit	Cooling System	Electricity consumption
Conventional	*mPt*	6.059	2.369	920	11.551	46.003
Magnetic	*mPt*	6.059	2.369	1.840	16.059	44.445

5. Conclusions

The paper described the first application of an innovative Decision Support Toolbox, where the engineers and designers could includes the environmental aspects directly at the early prototype development phase. Thanks to this DST the continuous improvements on the materials shall follow the results (for example prefer the REEs instead of Manganese alloy). This could be a real benefit , which allow the developer to avoid wrong paths. As it can be seen from the work, different Toolboxes were developed for each of the main components constituting a magnetic refrigerator. However, the background logic is the same, following the LCA and LCC standards. This way, each actor can have a dedicated, and user-friendly, DST supporting designers during the development of innovative components with a real time comparison of economic and environmental indexes and diagrams. The final assessment of the second goal, discover a higher impacts of the magnetic system than the conventional one. The engineers should improve the cooling system if they wants to achieve a prototype with lower impacts.

Acknowledgements

This work was partly funded by the European Commission through the ELICiT Project (ENV-2013-603885, www.elicit-project.eu). In any case, the present work cannot be considered as an official position of the supporting organizations (EU Commission), but it reports just the point of view of the authors.

References

[1] R. Luglietti, P. Rosa, S. Terzi, M. Taisch, Life Cycle Assessment Tool in Product Development: Environmental Requirements in Decision Making Process, Procedia CIRP 40 (2016) 202 – 208.

[2] ISO 14040, Environmental Management. Life Cycle Assessment. Principles and Framework, 2006.

[3] ISO 14044, Environmental Management. Life Cycle Assessment. Requirements and Guidelines, 2006.

[4] T.U. Pimmler, & S.D. Eppinger, Integration Analysis of Product Decompositions, ASME Design Theory and Methodology Conference, Minneapolis, MN, 1994.

[5] B. Lilly, &C. Gill, Integrating design and engineering I: functional abstraction and product architecture. In DS 43: Proceedings of E&PDE 2007, the 9th International Conference on Engineering and Product Design Education, University of Northumbria, Newcastle, UK, 13.- 14.09. 2007.

[6] Chung WH, Okudan G, Wysk RA, Modular design to optimize product life cycle metrics in a closed-looped supply chain. In Proceedings of the 2011 industrial engineering research conference, Reno (pp. 21-25), 2011.

[7] S. Yu, Q. Yang, J. Tao, X. Tian, F. Yin, Product modular design incorporating life cycle issues-Group Genetic Algorithm (GGA) based method. Journal of Cleaner Production, 19(9), 1016-1032, 2011.

[8] J. M. Cullen, J.M. Allwood. The efficient use of energy: tracing the global flow of energy from fuel to service. Energy Policy 38, 75-81, 2010.

[9] B. Monfared, R. Furberg, and B. Palm, Magnetic vs. vapor-compression household refrigerators: A preliminary comparative life cycle assessment. International Journal of Refrigeration, 42, 69-76, 2014

[10] B. Sprecher, Y. Xiao, A. Walton, J. Speight, R. Harris, R. Kleijn, G. Visser and G.J. Kramer, Life Cycle Inventory of the Production of Rare Earths and the Subsequent Production of NdFeB Rare Earth Permanent Magnets, Environmental Science & Technology, 2014