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Life Cycle Assessment Tool in Product Development: Environmental Requirements in Decision Making Process

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Abstract

In recent years, sustainable development has acquired a relevant position in our society. In this context, the design of modern products must consider these issues when creating eco-friendly and socially acceptable solutions, seeing sustainability as a matter of optimization in the use of available resources along the entire product lifecycle. This research aims to propose a dedicated Environmental Assessment Framework, using LCA methodology allowing designers to make environmental sustainability as an achievable and measurable requirement for developing new products. The case study presented is adapting the Life Cycle Assessment framework in the household refrigerator sector, of comparison between conventional gas-compression refrigeration and magnetic cooling system. The critical point of magnetic refrigerator is the presence of rare earths, and for this reasons a Life Cycle Assessment toll is needed to investigate the whole lifecycle.

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Keywords: Toolbox, LCA, Life Cycle Assessment, Refrigerators, Magnetic Cooling, Sustainability

1. Introduction

In recent years, Sustainable Development, in the case the part related to environment, has acquired a relevant position on the scene and many initiatives are encouraging sustainability in our society. In this context, the design of modern products must take these issues into account when creating eco-friendly and socially acceptable solutions, seeing sustainability as a matter of optimization in the use of available resources along the entire product lifecycle. This could be achieved with the collaboration of all the involved actors (designers, engineers, managers, suppliers, customers), with the common goal of adopting sustainable practices. Being designers responsible for the system design from its early stages, they are relevant decision-makers in sustainability terms. For example, it is up to them finding solutions to create less polluting cars, engines that are more reliable, more efficient materials, innovative design and production methods, or more energy efficient products. Unfortunately, designers are often unaware of all of the impacts (both economic and environmental ones) that the product they are creating will cause during its life. This is due by the absence of adequate tools able to match different sustainability aspects (or performance indexes) and relate them to any specific choice designers are considering during their work. The eco-design directive has been extended in 2009 to all energy-related-products, like product which do not necessarily use energy, but have an impact on energy consumption (direct or indirect) and can therefore contribute to saving energy, such as windows, insulation material or bathroom devices (e.g. shower heads, taps) [1]. One of the most important topics of the Directive is the lifecycle evaluation, which wants to consider the energy consumption throughout the whole product lifecycle, from the raw materials selection to the waste production. Other standards developed for product classification including environmental aspects are the environmental labelling defined by ISO (ISO 14021, 14024 and 14025 [2] [3] [4]), which is can be applied to all product categories, and they consider the entire lifecycle with streamlined if needed.

Under this scenario, the research presented aims to develop a multi-criteria toolbox approach to be useful for designer who want to include the environmental aspects into the product development. Eco-design has been defined by Karlsson and

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Luttropp (2006) [7] in the literature as the integration of environmental considerations into product development, and that eco-design tools ought to be made available to designers during the product development process. One of the aspects taken into account is the necessity of designer to have an instrument, which can be dynamic with the prototype evolution. The toolbox will integrate the performance indexes with the environmental issues, based on the Life Cycle Assessment Criteria [5] [6].

After the methodology toolbox description, a case study application will be described. The toolbox has been implemented by considering the global domestic refrigeration sector, in particular the development of a prototype of magnetic cooling appliance. However, the again not well-defined production process together with the lack of information about the composition of many of its components (especially the magnetic ones) makes magnetic cooling technology a sort of "black box" for designers willing to implement it inside their products. Hence, a dedicated Decision support Toolbox is needed, allowing designers to make this promising refrigeration technology a more comprehensible system, and better assessing its real sustainability potentials.

2. State of the art of multi-criteria decision making tools

In the literature, many papers and researches, around 30 from 2010 to 2014, about qualitative and quantitative analysis including environmental aspects have been investigated, starting from Bovea and Belis (2011) [8]. In particular, the classification adopted by them has been followed to clarify the type of tools that designer may already use, and to propose a new tool overcomes limits and gaps of the others. Bovea and Belis (2011) have been classified the tools considering the follow criteria [8]:

- methods applied for the environmental assessment;
- product requirements that need to be integrated in addition to the environmental one (multi-criteria approach);
- whether the tool has a life cycle perspective (i.e. it considers all the stages of the life cycle of a product);
- the nature of the results (qualitative or quantitative);
- the stages of the conceptual design process where the tool can be applied;
- the methodology taken as a basis for such integration.

Maud *et al*. (2011) [9] investigated the related point to integrate the LCA into the design process. In particular, they analysed many instruments which use LCA during the design, i.e. DfX, materials selection. They reported an overview of these tools already implemented and used. Many authors described the Life Cycle Sustainability Assessment [10] [11], as a tool that considers the three pillar of sustainability in addition to performance requirements during the prototype development. Barberio *et al*., (2014) [12] presented a framework for combining life cycle assessment (LCA) and Risk Assessment (RA) to support the sustainability assessment of emerging technologies. They described the two different framework, with a tentative to correlate them in a single one. All the Tools discovered in the literature as the same theoretical approach combining the quantitative instruments like LCA. Only few papers have tested their framework on real application trying to use it as part of designer implementation toolbox.

3. Toolbox methodology approach

The literature review discovered the huge numbers of decision making frameworks developed during the last decade. The general limitation spotted is the qualitative or semi-quantitative approach, which are not directly applicable on real business. The Decision support Toolbox, is a set of computer-based tools supporting the assessment of economic and environmental information that are summarized into a calculation sheet. Physically, this research wants to develop a Toolbox able to consider all the different phases along the product lifecycle, by considering both manufacturing, use and disposal data. Such a Toolbox is needed by engineers and designers of modern companies, up to change their focus from a mere technical performance comparison to a more advanced sustainability performances comparison. This paper aims to present the methodology behind the Toolbox and the requirements, supported by the Toolbox during the early design or prototype development decision process, including the sustainable criteria. The Toolbox is divided in two different evaluators.

1) An Economic Assessment Tool: in which the typical engineering performances evaluator is supported by economic indexes. An overall economic assessment tool has been developed in order to give the possibility to designers and engineers to define how much their product configurations will cost during their whole life, before the real implementation. Within such a tool, the economic performance of the product along its life has been modelled, for example, from the point of view of materials and labor costs, commodities expenditures, etc.
2) An Environmental Assessment Tool: in which different resources consumption scenarios could be tested and compared in a virtual way. The different scenarios involving and interacting with the product along its life will be modelled and evaluated in terms of relevant performances (e.g. Endpoint indicators or Midpoint indicators).

The Decision support Toolbox may be used at different levels of the design process (for both single components and whole products) and as cross-reference tool for the comparison of different domain solutions (for both single components and whole products). Hence, it can be used to:

- Assess the economic and environmental aspects of a current component (or sub-component) before its manufacturing;
- Assess the economic and environmental aspects of a current whole product, given a pre-defined set of embedded components;

- Assess the economic and environmental aspects of competitive prototype (at component level and final product level), given a comparable current one;

The sustainability criteria may be include into the decision making process if they are in line with the process too. In that direction the idea is to set all the steps necessary to conceptualize the toolbox in agreement with the performance requirements defined as the physical feasibility of a prototype.

The Toolbox may evaluates the two aspects giving the results on the two dimensions, leaving the practitioner to decide the mosts important aspect from their side.

3.1. Toolbox conceptualization process

The IDEF scheme reported in Fig. 1 describes all the steps included into the Decision Support Toolbox for developing a multi-criteria framework. The Toolbox has been conceptualized considering a first part where the product is described, and a second part where the real analysis is conducted. The first method pertaining to the Toolbox is the functional groups analysis. This procedure allows engineers to better understand the real composition of a final product (or its single components) and how the different elements relate each other. The types of relations can be summarized in: spatial proximity, material flow, information flow or energy transfer [13] [14] [15] [16]. After functional groups diagram development and identification, an accurate data acquisition shall be done, for both products and components. During this phase, the official bill of materials can offer a good starting point, but a direct interview of designers can avoid any sort of misunderstanding. Once collected all the available information about materials and processes production the actual analysis may start, with two different path for environmental and economic evaluation. Environmental data are needed to support the LCA process. Instead, economic data are inserted for the subsequent LCC analysis. Finally, the data elaboration phase translates both environmental and economic results into a series of performance indexes that could be useful for a direct comparison of the assessed product (or component) with similar ones in terms of the two dimensions.

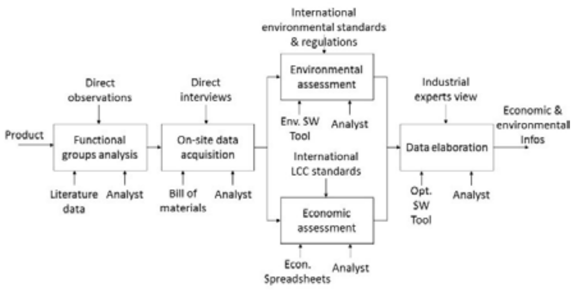

Fig. 1. Decision Support Toolbox general IDEF schematics.

The different analysis dimensions described have been carried out thorough the whole lifecycle. In particular, for each lifecycle step the list of options has been identified.

Considering a generic product (the whole system and its components), after the functional groups description the components list options, including materials and manufacturing, shall be defined. Fig. 2 reports the Toolbox conceptualization.

At this level, only the Environmental assessment will be described.

3.2. Life Cycle Assessment as a methodology of decision support toolbox

As already described, the Toolbox considers the entire product lifecycle preventing the negative situation of shifting boundaries where it reduces the impacts in some lifecycle stages to postpone in other downstream stages. The methodology selected for the environmental analysis is Life Cycle Assessment, which is part of a package of tools settled for a Sustainable development. Life Cycle Assessment is a structured, comprehensive and internationally standardized method. It quantifies all the relevant emissions and resources consumed, both directly and indirectly, and the related environmental and health impacts and resource depletion issues that are associated with the entire life cycle of any goods or services (in general terms, of a product). Life Cycle Assessment is a vital and powerful decision support tool, complementing other methods, which are necessary to help effectively and efficiently make consumption and production more sustainable from the environmental side [17]. The LCA approach is called “from cradle to grave” because it takes into account the impacts from raw materials extraction to the disposal of waste.

The decision Support Toolbox has been implemented following the LCA framework. In particular, each step of Toolbox has been defined to be adapted for the LCA:

- Scope and Goal definition: the preliminary phase where in the LCA the functional unit and the system boundaries has defined. In the Toolbox is the product functional group description.
- Life Cycle Inventory: it lists all the input and output that may cause an impact during the lifecycle of a product. Also in the Toolbox is the data collection, in according with the experts.
- Life Cycle Impact Assessment: is the effectiveness LCA. The purpose is to provide additional information to help the assessment of LCI results so to better understand their environmental significance. For the Toolbox is carried out using SIMAPRO, or any other LCA software.
- Life Cycle Interpretation: is the final phase of the LCA procedure, in which the results of a LCI or a LCIA, or both, are summarized and discussed as a basis for conclusions.
- The analysis shall be implemented at system level or at components level, depending on the goal of the study.

The environmental evaluation includes all the possible options minimizing the specific indicator selected as priority. In particular, the Decision Support Toolbox implemented taken into consideration the following environmental indicators, giving the priority, as automatic selection, to Endpoint single score indicator [18].

- ReCiPe
- Abiotic depletion
- Global warming (100a)
- Ozone layer depletion (ODP)
- Human Toxicity
- Eco-toxicity (Fresh water, Marine aquatic, Terrestrial)
- Photochemical oxidation
- Acidification
- Eutrophication

3.3. Decision Support Toolbox interface definition

The evaluation includes all the options available during the beginning of life (resources and materials production and product manufacturing processes), the options about the middle of life, and the end of life scenarios. All the results may change considering different parameters. As reported in Fig. 2 the parameters included in this Toolbox take into account the energy and materials possible variations, in particular:

- Country production and use: which considers the energy mix used and the energy costs
- Materials and resources market variability
- Country recycling: which considers different waste management law.

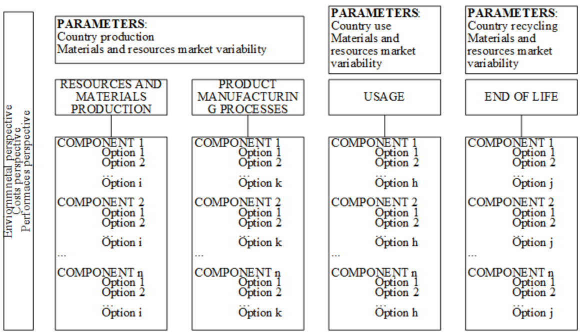

Fig. 2. Decision Support Toolbox definition.

The Toolbox definition reported in Fig 2 has been development for both environmental and economic dimension, but this paper will focus only on environmental evaluation as a first step of the implementation, taking into account the performance requirements. The costs indicators as a multi-criteria decision making will be integrate in a second time.

The environmental dimension has been introduced into the decision criteria using the Eq 1. and Eq. 2. The second equation represents the total value of each environmental implication for any possible options and components. For example, considering the $Env_{material}$ the Eq. 2 considers the components with the optimal option.

$$Env_{tot} = Env_{materials_{tot}} + Env_{manufacturing_{tot}} + Env_{usage_{tot}} + Env_{EndofLife_{tot}} \quad (1)$$

$$Env_{material_{tot}} = Env_{component1_{option\ i}} + Env_{component\ n_{option\ i}} \quad (2)$$

The environmental impacts are calculated considering input and the related indicators, as shown in Eq. 3.

$$Env_{results} = kg_{input} \cdot Env_{indicator} \quad (3)$$

The environmental indicators are expressed in [indicators unit/input unit], for example, considering as a input the energy consumption, as a environmental indicator the ReCiPe (expressed in mPt) the unit of $Env_{indicator}$ is [mPt/kWh].

The final part of the Toolbox is a user interface to show the environmental results with the economic perspective, in according to performances required. The Designer may use the Toolbox dynamism to evaluate the prototype evolution in real time.

4. Toolbox case study

The Decision Support Toolbox has been customized for the household refrigeration industry, in particular for the new promising refrigeration technology of magnetic cooling system, which has been compared with the conventional one. This implies that the toolbox has to cope with components and attributes of the two different types of technologies: the current one (vapour compression) and the new one (magnetic cooling).

This specific Toolbox will be a dynamic device for the magnetic cooling technology evaluation, which will be compared with the conventional vapour compression one, already well-defined and commercialized, both specifications and standardized performances terms. As reported in Fig. 3, the Toolbox works considering both level, components and system. Indeed, during the prototype development. As already said the Toolbox is part of decision-making process, which engineers can use during the design phase. In fact, the prototype development is implemented during the design phase.

Fig. 3. Logic description of Decision Support Toolbox algorithm applied to refrigeration system.

4.1. Functional group analysis

Following the LCA framework, the functional unit has been defined as one refrigerator during its life (10 years). The idea of the functional unit is to be representative with the system, and that can weight up different product typologies. The system boundaries considered for the evaluation is the entire lifecycle, from cradle to grave. Fig. 4 reports the product lifecycle flow of the environmental evaluation including all the required information.

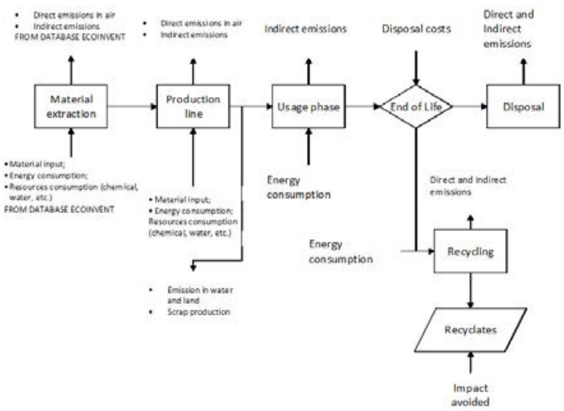

Fig. 4. Product lifecycle, and relatives input and output included into the environmental analysis.

The environmental indicators will be expressed in addition to the performance indicators, which are expressed by the temperature and energy efficiency.

An example of Functional Group of magnetic system is reported in Fig. 5. It is possible to clearly understand what the main elements are constituting the final product. The cabinet is the central structure of the fridge, aiming to physically contain food and giving to the product a bearing structure. This element could be made of several materials (e.g. metals) and sub-divided into five main components, a cabinet frame, a cabinet liner, a side wall, a cross-bar and a water tray (for the recovery of condense). Other elements that, even if independent, are strictly linked to the cabinet are foam (insulation material) and the set of shelves and drawers for the collection of food. The hinge is the element that connect the cabinet to the doors (one in this case). Doors are composed: by a doorframe, a door liner and a gasket (and also foam, shelves and drawers). The thermostat is the only element responsible for the correct management of the internal temperature of the fridge. The final group to describe is the cooling system. Thermostat 1 receives information about the internal temperature of the cabinet. This data is transferred to thermostat 2. Thermostat 2 controls an electric motor that transfers a kinetic energy to a regenerator. This component (made of a series of magnetic elements) rotates around its axis and is immersed into a magnetic field generated by a permanent magnet. The rotation allows the cooling of the fluid (e.g. glycol) that goes through it. The fluid is, then, re-pushed through a pump (also controlled by thermostat 2) into two heat exchangers (cold and warm sides) absorbing heat from the compartment. The fluid is re-transferred to the regenerator by a fluid driving system (a sequence of electro-valves able to allow - or not - the flowing of the fluid) and then into a heat exchanger rejecting the heat to the ambient.

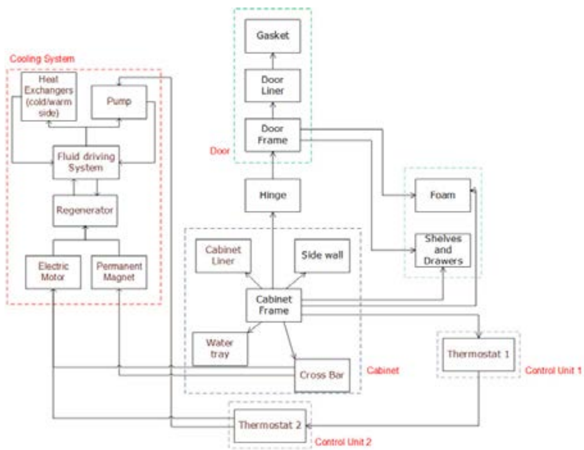

Fig. 5. Magnetic refrigerator's functional groups.

4.2. On-site data acquisition

The forward step after functional group identification is the data collection. In particular, for each functional group reported in Fig. 5, a list of data about materials, processing and performances requirements has been done. Table 1 shows an example of data collection considering the Cooling system and its components.

Table 1. Information required by the designers for product development. Starting point to identify the algorithm requirements.

Component	Type of info	Input required	Indicators
PUMP	Materials	Weight Extraction process	Procurement costs Env. Impacts
	Production process	Energy consumption Labor effort	Estimated process costs Env. Impacts

Component	Type of info	Input required	Indicators
		Scraps Pollutants	
	Technical performances	Overall efficiency Volume Lifetime Power range	Energy balance, spatial dimensions, reliability trend
HEAT EXCHANGER	Materials	Weight Extraction process	Procurement costs Env. Impacts
	Production process	Energy consumption Labor effort Scraps Pollutants	Estimated process costs Env. Impacts
	Technical performances	Heat exchange rate Temperature drop	Warm vs cold side temp. Watts, COP index
COOLING SYSTEM	Materials	Weight Extraction process	Procurement costs Env. Impacts
	Production process	Energy consumption Labor effort Scraps Pollutants	Estimated process costs Env. Impacts
	Technical performances	Overall efficiency Power range	Energy balance

The evaluation will be implemented for each option defined during the firsts steps of this analysis, for example, different materials or weight, different production processes, considering a product using energy (RuP) the specific class energy in according to the eco-design directive [1].

5. Environmental assessment and conclusion

The Toolbox provides a complete environmental evaluation using Simapro 8.0 and Ecoinvent 3.0, or any other database for Life Cycle Assessment. Thanks to the Toolbox the prototype developed in comparison to a conventional product, and in the case study the conventional refrigeration may include the environmental dimension into the decision criteria. In this case the innovative components and materials used (permanent magnets and magneto caloric materials) may be designed and developed including the environmental aspects. The designer and engineers thanks to the user-friendly application may conduct a simple evaluation.

After the full evaluation, the designer will define the optimal product giving a priority between performances, costs and environmental protection. Finally, the selected cooling system product will be compared with the conventional one already into the market.

The Toolbox described is one of the tools implemented in the last years to foster the sustainable development in new product. In this case, the user interface allow the designer to use directly the Tool during the prototype evolution. In fact, one of the problems of environmental evaluation is the ineptitude to be dynamic with the prototype modification. Instead, during the design phase, and in particular during the prototype development, the methodology may be applied many times during the development. They need an instrument which can make different times the LCA evaluation, in according with the prototype evolution in terms of components options and geography or market parameters, without have directly competence on LCA. The Toolbox can be directly implemented with any kind of products, considering the IDEF diagram and the steps sequence reported on.

The known methodology LCA and LCC are implemented into a web based application user friendly or a simple excel spreadsheet, who can easy used by designer and engineers to elaborate a LCA themselves, or at least to understand the LCA results.

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