Ida Midžić
Mario Štorga
Dorian Marjanović

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ECO-EVALUATION IN CONCEPTUAL DESIGN PHASE – A CASE STUDY

Summary

The use of qualitative eco-evaluation methods for product concept eco-evaluation is explored in a case study where mechanical engineers performed an eco-evaluation of product concepts in a two-stage evaluation process. In the first stage of the case study, the evaluators were asked to evaluate the environmental friendliness of the product concepts and to rank the concepts accordingly. The obtained rankings were based upon subjective preferences of the evaluators and their subjective interpretation of the eco-value of the considered concepts. In the second stage of the case study, the evaluators eco-evaluated the same concepts, but this time they used ecodesign guidelines as eco-criteria. The evaluators have obtained different rankings of the concepts, so the results of the two sets of rankings are compared. Findings are analysed in the context of confounding variables of the case study design.

Key words: *concept evaluation, environmental friendliness, conceptual design phase, ecodesign methods and tools, ecodesign guidelines*

1. Introduction

Environmental friendliness of products is revealed in the detailing design phase of product development. In that phase, the level of information about the product and its life cycle allows for an environmental impact assessment to be performed. Environmental impact is a measure of influence of products on the environment and is thus used as a measure of environmental friendliness of products [1, 2]. Environmental impact assessment is an analysis of product life cycle and material and energy flows concerning material acquisition, production, transport, use and end-of-life. It is primarily a quantitative method and used from the embodiment and detailing design phase onward. The use of quantitative eco-evaluation methods, such as environmental impact assessment, requires that quantitative and detailed information about products and their environmental performance is available or at least approximated in a scientifically valid and methodologically rigorous way. In the conceptual design phase, however, knowledge about the future product is lacking, product key features and embodiments are not finalized, and product environmental performance and life cycle are unknown or vague. Evaluation in the conceptual design phase is performed under uncertainty. The study presented in this paper addresses the problem of performing an eco-evaluation of product concepts in the early decisive conceptual design phase of the product development process when there is a lack of information about the future product and the information about available concepts is qualitative.

Usability of ecodesign methods and tools for qualitative eco-evaluation of product concepts is the focus of the paper. Quantitative ecodesign methods and tools efficiently manage the approximation of future product life cycle and environmental performance, but their suitability for the conceptual design phase depends upon the availability of that same quantitative information about the considered concepts. There are no such limitations in using qualitative ecodesign methods and tools in the conceptual design phase, but evaluation is more prone to influences of personal preferences of evaluators and their ability to interpret attributes of concepts as good or bad and grade them accordingly. Three groups of qualitative methods and tools are established: purely qualitative, semi-quantitative and methods and tools that require a combination of qualitative and quantitative information about product concepts considered for eco-evaluation. To demonstrate the suitability of the qualitative methods for the eco-evaluation in the conceptual design phase, a case study is performed and the results are presented in this paper.

2. Background

2.1 Motivation

It is widely believed that the product environmental profile and most of the factors that determine product final environmental performance, quality and cost are defined in the conceptual design phase of the product development process [3, 4]. Bhamra et al. specify that the final setting of product specifications is a critical point of product development, since from there on the most important technical properties of the product are decided upon [3]. They further conclude that environmental improvement options are limited after the product specifications are fixed. Concept selection is based upon concept evaluation according to criteria such as quality, cost, technical feasibility and other, so environmental friendliness criteria may be neglected in the concept evaluation process [5, 6]. Significant environmental improvements, for example changes in the concept, functions, physical effects, working principles or principle solutions may cause additional costs and delays to the development process if they are performed in the later design phases.

2.2 Eco-evaluation in the conceptual design phase

Products pollute the environment during their life cycle, and they do this due to unintended side-effects (emissions and waste) that are released into the environment. Environmental impact is recognized as a measure of influence of products on the environment and is thus used as a criterion for eco-evaluation of products. There is, however, a difference in evaluation methods used for product evaluation and concept evaluation, and not all product evaluation methods can be used for concept evaluation purposes.

Assessment of the environmental impact of products requires that a detailed analysis of the product life cycle is performed. This includes that information on material and energy flows in all life cycle phases is predictable with sufficient certainty, which implies a certain level of knowledge about the future product life cycle. Product life cycle is not fully known prior to the embodiment and detailing design phase, when a more detailed product analysis could be performed [7]. There are also difficulties when quantitative eco-evaluation methods are used concerning data collection, modelling of energy and material flows and interpreting the results of assessments [8].

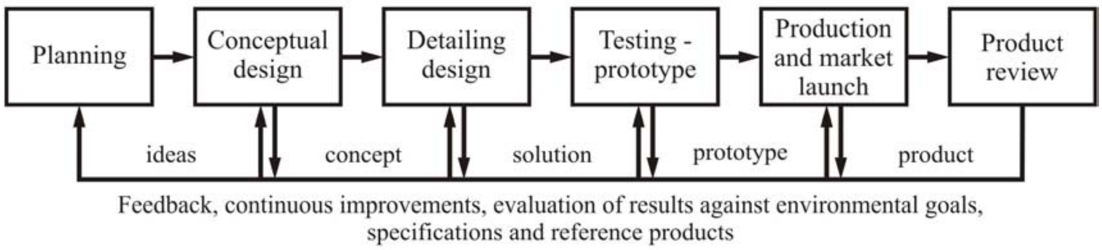

Fig. 1 Product development process with iterative evaluations at each design phase (adopted from ISO 14062 standards, illustration adopted from [9])

In the conceptual design phase, a description of the future product is abstract and information regarding final attributes of the product that determine its future environmental performance and life cycle characteristics is not available [4, 8]. Information about the concepts considered for selection in the conceptual design phase can be described as incomplete, inconsistent and qualitative. Knowledge about environmental profile and the life cycle of the future product is low at that point of the product development [4], as concept decisions have not been made yet and specifications have not been finalized [3]. Product description is at an abstract level in the conceptual design phase [10]. Decision about which concept to develop influences the direction of the remaining design activities, as well as quality and cost of the final product [7].

Usually, more than one concept is generated prior to concept evaluation and a suitable one is selected for further development. Following a recommended practice, a number of suitable concepts are generated and evaluated in order to select the most promising solution for further development. Decisions about concept variants have to be based on the information gained from the concept evaluation where alternative concepts can be compared according to a set of evaluation criteria and requirements that have to be fulfilled. Concepts are evaluated according to a number of relevant aspects, such as quality, safety, cost or how the concept relates to customer requirements defined earlier in the development process. Once the product concept is decided upon, physical embodiment of the product can be established. From this point forward, information about the product future life cycle is easier to attain and environmental improvement options regarding embodiment and life cycle can be proposed. Predicted capability, behaviour and performance of the future product are tested by simulation or experimentally before the product is manufactured (Fig. 1). This also enables designers to suggest product improvements to reduce the environmental impact.

2.3 Ecodesign methods and tools for eco-evaluation

Ecodesign methods and tools can be generally classified according to their purpose as product improvement methods and tools and environmental assessment methods and tools. Product improvement methods and tools provide guidance and generic recommendations on aspects that need to be considered during product development. They are not developed for eco-evaluation of products or concepts specifically, but to point out suitable environmental assessment or eco-evaluation methods. Environmental assessment methods and tools provide quantitative evaluation of the product environmental performance and assist in the identification of specific functions and properties that need to be optimized for a more environmentally sound product to be developed.

According to data required as inputs, ecodesign methods and tools can be classified into four major groups: fully qualitative, semi-quantitative, qualitative/quantitative and fully quantitative methods and tools. The classification criteria are type and amount of data required by the method or tool [9, 11]. Qualitative methods require only qualitative input data or information. Semi-quantitative methods and tools use qualitative input data, but provide quantitative outcome as a result of applying the weighting to each qualitative criterion. Qualitative/quantitative methods and tools require qualitative or quantitative data types as inputs, depending on the criterion, so the results consist of aggregated qualitative and quantitative scores for each criterion. Purely quantitative methods and tools require quantitative data as inputs to the method or tool.

The level of complexity of the method or tool indicates the level of difficulty of implementing a particular method or tool, which is closely related to either: 1) type and amount of data required by the method or tool, 2) time, cost and knowledge required, and 3) information access and availability (easy or limited input data access). Level of knowledge required by the users might be low, medium or high depending on the minimum level of expertise required (engineering designers or environmental experts) and depending on the situation whether a method or tool is used by individuals or by multidisciplinary teams where consensus has to be obtained [11, 12].

The classification of ecodesign methods and tools according to their purpose and data requirements is illustrated in Table 1. Examples of ecodesign methods and tools are noted for each category.

Table 1 Ecodesign methods and tools classified according to data requirements (type of input data)

Qualitative	Semi-quantitative	Qualitative/ quantitative	Quantitative
Ten Golden Rules [13] *(prescriptive guidelines)*	Eco-products tool [18] *(prescriptive comparative index)*	Ecodesign checklist *(prescriptive checklist)*	Volvo's black, grey and white lists *(prescriptive list)*
Eco-design Strategy list [14] *(prescriptive checklist)*	LiDS Wheel/ Ecodesign Strategy Wheel [14] *(graph & schematic tool)*	MSPD - Method for sustainable product development *(analytical prescriptive)*	Cumulative energy demand (CED) *(environmental impact indicator method)*
Philips Fast Five Awareness [15] *(comparative checklist)*	ERPA matrix [19] *(analytical matrix method)*	Econcept Spider web *(graph & schematic tool)*	EcoIndicator 95/99 *(environmental impact indicator method)*
Eco-Design Value guidelines [16] *(prescriptive guidelines)*	Eco-Functional Matrix [5] *(analytical matrix method)*	MET matrix [14] *(matrix method)*	Environmental impact approximation methods [20] *(environmental impact assessment method)*
Design for Environment guidelines [17] *(prescriptive guidelines)*	-	QFDE [21] *(matrix method)*	Life Cycle Assessment *(environmental impact assessment method)*

2.3.1 Qualitative and semi-quantitative ecodesign methods and tools

Qualitative methods and tools are used in early design stages when there is less data about the future product and an overall screening is needed. The goal is to provide information necessary to improve product parameters regarding eco performance early in the design process avoiding design changes in the later stages of the product development. Methodologies, frameworks, guidelines and manuals are prescriptive ecodesign methods and tools. Ten Golden Rules [13] is a set of prescriptive guidelines, i.e. ten recommendations for ecodesign. The Rules form a set of eco-criteria on their own, but are too general to be used for eco-evaluation purposes. However, if the procedure for weighting and assigning values to each eco-criterion (guideline) is applied and eco-criteria are customized for the conceptual design phase, the Ten Golden Rules and similar prescriptive statements about eco-products might be used as eco-evaluation criteria. Consequently, such a newly developed method would be seen as semi-quantitative.

Checklists are usually formed as a set of questions that concern issues of environmental performance and functional aspects through the life cycle phases of the future product. Similarly to guidelines, checklists are intended to be applied as early in the product development process as possible. Some of the questions require more detailed information that can be obtained only when product design and production features are defined. For example, Philips Fast Five Awareness [15] is used in order to evaluate and compare different product concepts with a reference product. The comparison is based on questions divided in five groups concerning different environmental aspects of the product. The questions can be checked with ‘yes’ or ‘no’ answers. A strategy for product improvements is based on the number of positive answers obtained.

2.3.2 Qualitative/quantitative and quantitative ecodesign methods and tools

Quantitative data about the product, its life cycle and environmental performance is needed for the calculation of product environmental impact and this information is available from previous similar product cases. Additional methods and techniques are used so that product environmental impact can be approximated already in the conceptual design phase. Fitch and Cooper identified a lack of quantitative environmental impact approximation methods [20] to be used for eco-evaluation for all different types of design: original, adaptive and variant design. Design uncertainty, lack of knowledge and unavailability of information regarding a future product are the greatest for original design concepts with a degree of novelty higher than in the case of adaptive or variant design. There is a significant difference in functions or physical principles between original design concepts and reference products. That is why environmental performance and environmental profile of the future product are less predictable when original design concepts are compared to their reference concepts or product than when adaptive design concepts are considered.

Life cycle and environmental impact data needed for assessments is retroactively collected from the previous product generation already on the market and used only if those products are suitable as reference products. If the similarity between the future product and the reference product is manageable, the environmental impact and life cycle data from previous cases can be stored and reused for future concept generation and evaluation purposes (in a life cycle inventory, design repository, etc.).

Requirements and specifications in an environmentally enhanced version of the QFD method (for example Quality Function Deployment – QFDE [21]) include embodiment and detailing design issues such as recyclability, disassembility and upgradeability. Puglieri et al. [22] state that these issues can hardly be assessed in the conceptual design phase and that many issues concerning the use phase of the life cycle of a product are often neglected when environmental QFD methods are used. In order to use the environmental QFD-based methods or similar methods that implement qualitative and quantitative criteria, a suitable aggregation method is to be selected and a criteria weighting scheme specified. Byggeth and Hochschorner [23] recommend that whenever a quantitative dimension is required from the user, a more comprehensive method or tool should be used, so that a fair grade could be assigned to a certain criterion or its weighting.

2.4 Research approach and aim of the case study

Quantitative ecodesign methods and tools are used in the late design stages of product development, since they require a significant amount of data about the future product [20]. Due to a relatively smaller number of ecodesign methods and tools that are less applicable in the conceptual design development phase than in later design stages, Dewulf [24] proposed that some of ecodesign methods and tools, conventionally purposed for the improvement of product design, should be customized or slightly modified to make them applicable to a certain conceptual design related problem. Voß et al. [25] explain the problems related to implementing methods for the selection of ecodesign strategies when engineers are provided with a list of ecodesign strategies, as for example the Eco-design Strategy list [14]. The authors conclude that deciding on the ecodesign strategies must be based on the environmental assessment of a reference product performed aforehand.

Ecodesign guidelines are among the most basic tools used to help designers achieve a more environmentally friendly design. They are used for prioritisation of ecodesign objectives by providing a set of general rules of developing an environmentally friendly design. Eco-Design Value guidelines [16] are preferably used for managing ecodesign objectives and in an on-going product development process. Most guidelines are general and some of them vague or ambiguous. A question arises weather designers can judge environmental friendliness of concepts using general guideline criteria.

Table 2 Number of guidelines implemented in qualitative and semi-quantitative ecodesign methods

Method or tool considered for qualitative and semi-quantitative eco-evaluation of product concepts	Number of main ecodesign principles or key eco-values implemented by the method	Total number of sub-values, ecodesign principles, guidelines or statements implemented by the method (total number of eco-criteria)
Ten Golden Rules [13]	10	10
Philips Fast Five Awareness [15]	12	12
Eco-Design Value guidelines [16]	4	50
Design for Environment guidelines [17]	6	67
Eco-products tool [18]	8	8
ERPA matrix [19]	5	25

Guidelines from the six methods listed in Table 2 were considered for eco-evaluation of the product concepts. Eco-Design Value guidelines [16] are selected for the case study in which evaluators used guidelines as eco-criteria for concept evaluation purposes [26]. The ERPA matrix [19] was not chosen for this case study, because each eco-criterion considers phases of the product life cycle, and it was not able to provide information about the product concepts that would consider environmental performance in different life cycle phases. The eco-criteria used by the Ten Golden Rules [13], Philips Fast Five Awareness [15] and Eco-products tool [18] were considered as candidates, but were not selected for this case study. In these three methods, there are between 8 and 12 eco-criteria, so it was predicted that the results of the evaluation in which a smaller number and more general eco-criteria are used would not allow for a comprehensive overview of how the evaluators ranked the product concepts in regard to different sub-values. The Design for Environment guidelines [17] were not used as eco-criteria in this case study, as majority of these guidelines aim at the embodiment design aspects.

The research questions of the study are:

1. Can Eco-Design Value guidelines [16] be used as eco-criteria in qualitative eco-evaluation of products concepts?
2. Which are possible factors that may influence the qualitative eco-evaluation of product concepts?

Eco-Design Value guidelines [16] consist of 50 design principles that are potentially guidelines for designers for establishing design strategies from the ecological point of view and can be used for evaluation purposes. The guidelines represent sub-values of environmentally friendly products or concepts and are divided into four core value categories.

Table 3 Eco-criteria in Eco-Design Value guidelines [16]

Key values	Sub-values	Number of sub-values	Key values	Sub-values	Number of sub-values
Low impact on nature	Clean and safe	4	Long lifespan of the product	Durable and reliable	3
	Natural recovery	3		Repairable and reusable	3
	Airy harmony	3		Affection	4
	Natural mimicry	3		Oldies but goodies	4
Less resources used	Minimize and unify	3	Last intensity of utilization	Disassemble and recycle	4
	Optimizing and efficiency	3		Multifunctional	3
	Awaken	2		Customizable	2
	Linking and sharing	3		Universal	3

3. Case study and results

3.1 Elaboration of the case study

The case study was performed to explore the influence of ecodesign guidelines when used as eco-criteria in the product concept eco-evaluation. The goal was to investigate the value of utilizing ecodesign guidelines as criteria of environmental friendliness of the concepts. The evaluators that participated in the case study were 11 mechanical engineers (with a minimum of 1 and maximum of 6 years of experience in the field). The task of the mechanical engineers was to evaluate and rank five concept variants of a product, first without applying any method or eco-criteria and then after they had been provided with ecodesign guidelines [26].

The case study was organized in two stages. In the first stage, the evaluators were not informed about ecodesign guidelines or any eco-evaluation criteria. They were instructed to eco-evaluate concepts based on their personal preferences of environmentally preferable and environmentally less preferable concepts. The evaluators were informed about the task and presented with the conceptual solutions. The concepts were explained with textual descriptions of functions and working principles accompanied by figures to illustrate functions, working principles and, where available, the embodiment design of solutions. The evaluators were asked to rank the five concepts according to environmental friendliness and to do this based upon their own understanding of environmentally better and worse concepts. The evaluators were instructed to note this ranking and to place concepts on a scale from 1 to 5; where 1 represents environmentally the best concept and 5 represents environmentally the worst concept.

In the second stage of the case study, the task of the evaluators was to produce the second ranking of the product concepts, and now the evaluators were instructed to use the ecodesign guidelines from the Eco-Design Value method [16] as eco-evaluation criteria. The ecodesign guidelines and the semi-quantitative method were presented to the evaluators at this point of the case study. The semi-quantitative method presented to the evaluators includes the ecodesign guidelines and the procedure for assigning scores to each guideline. The guidelines were presented in a list of statements about the concept under consideration. Each guideline represented one eco-value criterion. The evaluators were asked to estimate if each of the 50 ecodesign guidelines is realized by each of five conceptual solutions. There were three available answers: 'Yes' (meaning that the principle or sub-value is inherent to the product concept variant), 'No' (if, on the contrary, the principle or sub-value is not inherent to the product concept variant) and 'Estimation cannot be made' (if the evaluators could not make a sound evaluation about the principle or sub-value due to insufficient information about the concept variant, attributes, characteristics or properties). Scores were then assigned to the answers as follows: 1 for 'Yes', -1 for 'No' and 0 for 'Estimation cannot be made'. The evaluators had not used the Eco-Design Value guidelines before, and were instructed to rank the product concept variants according to the proposed scoring system. When the scores for the concepts are assigned, the best concept alternative is the one with the highest score obtained, and on the other hand, the worst concept alternative is the one with the lowest score obtained.

The product concept variants chosen to undergo the evaluation are divergent in terms of their commercial and technical feasibility and innovativeness. Different concepts of the laundry washing function were selected for this case study [26]. Concept A represents a conventional, commercially available and technically feasible solution implemented in most automatic washing machines for use in households. Laundry washing is performed with the use of warm water, detergent and electrical energy to acquire centrifugal force for washing, cleaning and agitating laundry fibres [27]. Laundry is rinsed with water and centrifugal force of the drum is used for soaking laundry fibres and rinsing.

Concept B represents a solution of washing laundry with foam and water at a lower temperature than in conventional washing machines. EcoBubble™ [28] washing machine uses air and water to dissolve detergent and create cleansing foam. EcoBubble™ is commercially available on the market. The manufacturer (Samsung) claims that laundry washing is performed with less mechanical action, maintains efficacy of laundry washing when washing at lower temperatures and energy savings are up to 55 %.

In Concept C, ultrasonic cleaning performs laundry agitation. Due to the cavitation effect produced by the ultrasound wave in a liquid medium, dirt is removed from fibres without damaging them. Technical feasibility of the concept is demonstrated [29] and the laundry washing system that works on this principle is patented [30].

Concept D represents a solution for laundry cleaning where cleaning is not performed by using water but by using dry ice. The concept, named Orbit, was envisioned by its designer Elie Ahovi, and submitted to the Electrolux Design Lab competition. Electrolux Design Lab competition is an annual event organized by the company Electrolux where innovative product concepts can be presented that eventually one day can be turned into commercial and technically feasible products. The 'Orbit' concept is not technically feasible, since a large amount of energy is required to power such a machine [31].

In Concept E, polymer beads are used instead of water to clean laundry, so cleaning can be achieved at lower temperatures and with less detergent than required for conventional laundry washing. Water acts as a lubricant rather than as the main washing medium, so much less water is required. The amount of rinse water is also reduced due to less detergent to be rinsed away. With the help of centrifugal forces, polymer beads mechanically remove soil and dirt from the laundry. For effective cleaning, around 20 kg of polymer beads and one cup of water is required. 20 kg of beads is sufficient for around 100 cleaning cycles. The concept is implemented in a technically feasible product marketed by a spin-off company called Xeros Ltd [32].

Table 4 Information about concepts presented to evaluators

Information about concepts	**A**	**B**	**C**	**D**	**E**
Description of functions, text	Yes	Yes	Yes	Yes	Yes
Functions, figure/sketch	No	No	No	No	No
Description of working principle, text	Yes	Yes	Yes	Yes	Yes
Working principle, figure/sketch	No	Yes	Yes	No	Yes
Suggested embodiment design, text	Yes	No	No	No	No
Suggested embodiment design, figure/sketch	No	Yes	Yes	Yes	Yes
Advantages of the suggested concept, text	No	Yes	No	No	No
Disadvantages of the suggested concept, text	No	No	No	Yes	No
Advantages suggested in a way to relate the concept to conventional washing machine concept, text	No	Yes	No	Yes	Yes
Disadvantages suggested in a way to relate the concept to conventional washing machine concept, text	No	No	No	Yes	No
Qualitative or quantitative information about expected energy, water or detergent consumption, text	No	Yes	No	Yes	Yes
Qualitative or quantitative information about expected product life cycle and environmental performance (life span, CO_2 consumption, emissions, …)	No	No	No	No	No
Qualitative or quantitative information about materials used for embodiment, manufacturing process, recyclability or reusability of parts	No	No	No	No	No

Information availability: Yes (dark) No (light)

3.2 Results

Individual evaluators' rankings of the product concept variants in the first subjective stage of the case study show that the majority of the evaluators ranked Concept C ('Ultrasound concept') and Concept B (EcoBubble™) as environmentally most preferable concepts. In the course of the case study, the evaluators had no knowledge about other evaluators' preferences, so their judgements were subjective and not influenced by other evaluators. According to their subjective and individual preferences Concept D ('Orbit') and Concept E ('Polymer Beads') were ranked at the bottom of the scale, so they were evaluated as the least environmentally favourable concepts. However, the distribution of average preferences of the evaluators for the second and the third rank levels indicate that Concept D ('Orbit') equally aspire to be ranked as the second best environmentally friendly concept.

The results of average scores supplied by individual evaluators when using the semi-qualitative eco-evaluation method indicate that in the average group results, the ranking of the concept variants can be obtained without conflicts as described for Concept D, when the evaluators used no methods for eco-evaluation. It can be concluded that when the ecodesign guidelines are used for the eco-evaluation of product concepts, the results were less dependent on personal preferences of the evaluator, so using guidelines was a better alternative than not using any method or tool at all. The results of the second rankings indicate a better distribution of concepts on each rank level, and the concepts were ranked either to the top or bottom part of the rank as opposed to the case when subjective eco-evaluation was performed. However, when the evaluators were not provided with the Eco-Design Value guidelines [16], their estimations of less environmentally friendly concept variants were very different from evaluator to evaluator. On the other hand, the results of the subjective preferences in the first stage of the case study were coherent among individual evaluators when choosing the most environmentally favourable concept variant.

Table 5 Comparison of first and second rankings of product concept variants performed by evaluators

Ranking level (1 ÷ 5)	No eco-evaluation method used (subjective eco-evaluation)	Semi-quantitative eco-evaluation method used (Eco-Design Value guidelines)
1 (best concept)	C (7), B (4)	C (6), B (4), A (1)
2	D (5), C (3), A (1), B (1), E (1)	B (5), A (3), C (2), D (1)
3	E (4), B (3), D (2), A (1), C (1)	E (4), A (3), C (2), B (1), D (1)
4	A (6), B (3), E (2)	E (5), D (3), A (2), C (1)
5 (worst concept)	D (4), E (4), A (3)	D (6), A (2), E (2), B (1)

Concept A - 'Conventional'; Concept B - 'EcoBubble™'; Concept C - 'Ultrasonic'; Concept D - 'Orbit'; Concept E - 'Polymer Beads'; no. in brackets () – number of evaluators that ranked the concept at that level, out of 11 evaluators in total).

Table 6 Overview of results of eco-evaluation of concepts with semi-quantitative method

Ranking level	Score of '1' per concept	Score of '-1' per concept	Total score ('1' + '-1')	Score of '0' per concept
1 = C (best concept)	Average: 21 Mean: 20 Range: 8 ÷ 34	Average: 7 Mean: 6 Range: 2 ÷ 17	Average (21-7): 14 Mean (20-6): 14	Average: 23 Mean: 25 Range: 10 ÷ 33
2 = B	Average: 25 Mean: 25 Range: 15 ÷ 37	Average: 11 Mean: 10 Range: 0 ÷ 28	Average: 14 Mean: 15	Average: 15 Mean: 15 Range: 3 ÷ 23
3 = A	Average: 24 Mean: 22 Range: 13 ÷ 45	Average: 14 Mean: 14 Range: 0 ÷ 26	Average: 10 Mean: 8	Average: 12 Mean: 13 Range: 2 ÷ 28
4 = E	Average: 12 Mean: 12 Range: 0 ÷ 24	Average: 11 Mean: 9 Range: 4 ÷ 29	Average: 1 Mean: 3	Average: 26 Mean: 30 Range: 7 ÷ 40
5 = D (worst concept)	Average: 13 Mean: 12 Range: 0 ÷ 31	Average: 14 Mean: 16 Range: 13 ÷ 28	Average: -1 Mean: -4	Average: 23 Mean: 24 Range: 13 ÷ 28

Concept A - 'Conventional'; Concept B - 'EcoBubble™'; Concept C - 'Ultrasonic'; Concept D - 'Orbit'; Concept E - 'Polymer Beads'; value of scores represent number of guidelines corresponding to scores '1', '-1' and '0' per concept. Average, mean and range values show scores for the group of 11 evaluators in total.

3.3 Discussion

The results of the concept ranking when the semi-quantitative method is used (i.e. guidelines as reference eco-criteria description) indicate that when a general value system is used for eco-evaluation purposes, consensus could be reached concerning environmentally more and less preferable concept variants. The factors that may have influenced the results of the eco-evaluation of the product concepts performed by the evaluators in the experimental setting are:

1. Amount and type of information about the product concepts presented to evaluators (Table 4).
2. Number of product concepts to be evaluated and the sequence of presenting the product concepts to evaluators (five product concepts were introduced to the evaluators in A-B-C-D-E sequence).
3. Ranking of product concepts required as output and choice of aggregation method.

The evaluators were instructed to rank the product concepts in levels from 1 to 5, whereby only one concept may be ranked at each level. The suggested aggregation method for the second ranking, when the semi-quantitative eco-evaluation method was used, implied the '1', '0' and '-1' scoring system.

4. Total number of the Eco-Design Value guidelines and suggested sequence of the guidelines presented to evaluators (Table 3).
5. Sequence in which the eco-evaluation methods (subjective and then the semi-quantitative eco-evaluation method) were introduced to evaluators.

The evaluators were instructed to perform a subjective eco-evaluation of the product concepts first and afterwards they used the Eco-Design Value guidelines [16] as the eco-evaluation criteria. Since the evaluators performed the subjective eco-evaluation first, their preferences of the best and the least environmentally favourable concepts may have influenced the way they evaluated the concepts in the second stage of the case study.

4. Conclusion

Concept evaluation is one of the most critical activities in the product development process. Features of the concepts are evaluated and compared, and an overall decision is made based upon the requirements. During the concept evaluation engineers also learn about the proposed concepts, as at that stage the product solution is at a high abstract level and valuable data on the future product performance is usually not available.

Inspired by the suggestion made by Dewulf [24] to use the ecodesign guidelines and principles in a way to point to environmentally conscious product designs and solutions, the Eco-Design Value guidelines developed by Koh et al. [16] are used as criteria of environmental friendliness of the product concept variants. A two stage case study was conducted with 11 mechanical engineers included. In the first stage their task was first to rank the concept variants according to environmental friendliness without using any eco-evaluation criteria, but their personal notions on environmentally better and worse concepts. In the second stage of the case study, the evaluators were instructed to eco-evaluate and rank the same concepts, but this time to perform this task by using the Eco-Design Value guidelines [16] as environmental friendliness criteria for the evaluation of the product concepts.

The two sets of rankings were more coherent in the case of the most environmentally favourable concept variant. The achieved results indicate that when the evaluators were not provided with the Eco-Design Value guidelines [16], the estimations of less environmentally friendly concepts were unreliable. It can be concluded that when the Eco-Design Value guidelines were used for the eco-evaluation of the product concepts, the results were less dependent on personal preferences of the evaluator. Using guidelines (as criteria of environmental friendliness) is therefore a better alternative that yielded more coherent results.

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REFERENCES

[1] Collado-Ruiz, D., Ostad-Ahmad-Ghorabi, H., "Influence of Environmental Information on Expert-perceived Creativity and Ideas", Design Creativity 2010, Taura, T., Nagai, Y. (Eds.), Springer-Verlag London Limited, 2011.

[2] Bevilacqua, M., Ciarapica, F. E., Giacchetta, G., "Design for Environment as a Tool for the Development of a Sustainable Supply Chain", Springer Verlag London Limited, 2012.

[3] Bhamra, T. A., Evans, S., McAloone, T. C., Simon, M., Poole, S., Sweatman, A., "Integrating Environmental Decisions into the Product Development Process: Part I - The Early Stages", Environmentally Conscious Design and Inverse Manufacturing, International Symposium on EcoDesign '99, 1999.

[4] Lindahl, M., "Engineering Designers' Requirements on Design for Environment Methods and Tools", Doctoral thesis, Royal Institute of Technology, Stockholm, Sweden, 2005.

[5] Lagerstedt, J., "Functional and Environmental Factors in Early Phases of Product Development - Eco Functional Matrix", Doctoral thesis, Royal Institute of Technology, Stockholm, Sweden, 2003.

[6] Sousa, I., Wallace, D., "Product classification to support approximate life-cycle assessment of design concepts", Technological Forecasting & Social Change 73, Elsevier, 2006, pp. 228-249.

[7] Ullman, D. G., "The Mechanical Design Process", 4th edition, The McGraw-Hill Companies, Inc., New York, 2010, ISBN 978–0–07–297574–1.

[8] Dewulf, W., Willems, B., Duflou, J. R., "Estimating the Environmental Profile of Early Design Concepts for an Electric Fruit Juicer Using the Eco-PaS Methodology", Proceedings of 12th CIRP International Seminar on Life Cycle Engineering, Grenoble, 2005.

[9] Poulikidou, S., "Literature review - Methods and tools for environmentally friendly product design and development", KTH, Royal Institute of Technology, Stockholm, Sweden, 2012.

[10] Andreasen, M. M., Hein, L., "Integrated product development, IFS Publications/Springer, Berlin, 1987.

[11] Pigosso, D.C.A., Rozenfeld, H., Seliger, G., "Ecodesign Maturity Model: criteria for methods and tools classification", Advances in Sustainable Manufacturing, Proceedings of the 8th Global Conference on Suistainable Manufacturing, Springer Verlag Berlin Heideberger, 2011, pp 241-245.

[12] Hernandez Pardo, R. J., Brissaud, D., Mathieux, F., Zwolinski, P., "Contribution to the characterisation of eco-design projects", International Journal of Sustainable Engineering, Vol. 4, No. 4, Taylor & Francis, 2011.

[13] Luttropp, C., Lagerstedt, J., "EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development", Journal of Cleaner Production 14, Elsevier, 2006, pp. 1396-1408.

[14] Brezet, H., van Hemel, C., "Ecodesign: A promising approach to sustainable production and consumption", UNEP, Paris, 1997.

[15] Meinders, H., "Point of no return - Philips EcoDesign guidelines", Philips Electronics, Eindhoven, Netherlands, 1997.

[16] Koh, S.-Y., Lee, S.-J., Chang, M.-K., Liang, H.-Y., Lee, S.-H., Boo, S.-C., "Study on the guideline for analyzing ecodesign value system and establishing product design strategy", Proceedings of 2007 IASDR Conference, International Association of Societies of Design Research, Hong Kong, 2007.

[17] Telenko, C., Seepersad, C. C., Weber, M. E., "A Compilation of Design for Environment Principles and Guidelines", Proceedings of ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, New York, USA, 2008, pp. 289-301.

[18] Namikawa, O., "Development of the evaluation tool that integrate "Design for Environment" and "Eco-efficiency" at Hitachi"", Environmentally Conscious Design and Inverse Manufacturing, International Symposium on EcoDesign 2005, 2005, pp. 240-241.

[19] Hochschorner, E., Finnveden, G., "Evaluation of Two Simplified Life Cycle Assessment Methods", International Journal of Life Cycle Assessment, Vol. 8, No. 3, 2003, pp. 119-182.

[20] Fitch, P., Cooper, J. S., "Life-cycle modeling for adaptive and variant design. Part 1: Methodology", Research in Engineering Design, Vol. 15, Springer-Verlag London Limited, 2005, pp. 216–228.

[21] Fargnoli, M., Sakao, T., Notarnicola, S., "A procedure to identify effective redesign options in ecodesign", International Conference on Engineering Design ICED 2005, Melbourne, Australia, 2005.

[22] Puglieri, F. N., Ometto, A., Miguel, P. A. C., "Eco-design methods for developing new products based on QFD: a literature analysis", Product: Management & Development, Vol. 9, No. 1, 2011, pp. 23-29.

[23] Byggeth, S., Hochschorner, E., "Handling trade-offs in Ecodesign tools for sustainable product development and procurement", Journal of Cleaner Production, Vol. 14, Elsevier, 2006, pp. 1420-1430.

[24] Dewulf, W., "A Pro-Active Approach to Ecodesign: Framework and Tools", Doctoral thesis, Katholieke Universitet Leuven, Belgium, 2003.

[25] Voß, M., Dewulf, W., Willems, B., Duflou, J., Birkhofer, H., "A Proposal to Adapt Design for Environment Methods to the level of Abstraction Needed in Early Phases of Product Development", 16. Symposium "Design for X", Neukirchen, Germany, October, 2005.

[26] Midžić, I., Štorga, M., Marjanović, D., "Using ecodesign guidelines for concept evaluation: Findings from an experiment", Proceedings of the 13th International Design Conference DESIGN 2014, Marjanović, D., Štorga, M., Pavković, N., Bojčetić, N. (eds.), Dubrovnik/Cavtat, Croatia, 19-22 May, 2014, pp. 313-322.

[27] Germani, M., Mengoni, M., Raffaeli, R., “Multi level Representation for Supporting the Conceptual Design Phase of Modular Products”, The future of product development, Krause F.-L. (Ed.), Springer Berlin Heidelberg New York, 2007, pp. 209-224.

[28] Samsung, “Samsung Home Appliances – Laundry – EcoBubble – Wash Cool, Save Energy”, Online web-page, available at <http://www.samsung.com/uk/ecobubble/>, Accessed 1 November 2014.

[29] Sethi, S., “Ultrasonic cleaning of highly soiled apparel”, Doctoral thesis, University of Delhi, Delhi, 2012.

[30] Gallego-Juarez, J. A., Riera, E., Acosta, V., Rodríguez, G., Blanco, A., “Ultrasonic system for continuous washing of textiles in liquid layers”, Ultrasonics Sonochemistry 17, Elsevier, 2010, pp. 234–238.

[31] Wired magazine, “'Orbit' washing machine concept levitates your clothes”, Online web-page, available at <http://www.wired.co.uk/news/archive/2012-02/17/dry-ice-washing-machine>, Accessed 1 November 2014.

[32] Xeros, “Xeros Bead Technology”, Online web-page, available at <http://www.xeroscleaning.com/xeros-bead-technology>, Accessed 1 November 2014.

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Ida Midžić, mag.ing.mech.
ida.midzic@fsb.hr
Prof. dr.sc. Mario Štorga
Prof. dr.sc. Dorian Marjanović
University of Zagreb
Faculty of Mechanical Engineering and
Naval Architecture
Ivana Lučića 5, 10000 Zagreb, Croatia