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Linking Use Stage Life Cycle Inventories with Product Design Models of Usage

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Abstract

Usage can have a significant environmental impact on the product life cycle. A precise evaluation and understanding of this impact during design is crucial to support early and adapted feedbacks to design experts to encourage the eco-design practice. Information on usage is spread across different field of expertise, and involves explicit and tacit knowledge. This research aims at improving the link between the available usage information, and the environmental expert's explicit knowledge on usage. A five steps method is proposed and exemplified in this paper to formalize this link. The paper finally raises the question of how to deal with conflicting usage information during design in industry.

Keywords: Product Design; Life Cycle Assessment; Model Driven Engineering; Usage integration

1. Introduction: usage in eco-design

Each expert intervening during product design has his own view on how the product will be used. The design brief gives instructions to designers about the product's functionalities. The mechanical and material engineers design the product's mechanisms for a given lifespan and under certain conditions of use. The ergonomic expert anticipates the product design to be error-free. Retailers interact with clients and advise them. After sale agents receive feedbacks from users and repair products. Waste treatment plan agents observe all kind of used products. Each view may be close or less from the real use due to the non-negligible influence of individuals. Yet, for products having major environmental impact during use phase, ecodesign seeks to minimize the environmental impacts of the use stage, and other potential environmental impacts generated during its life cycle, while optimizing the product's functional values [1]. The divergent of design views on usage should not slow down the ecodesign effort for this life cycle stage.

Industries and researchers insisted on the necessity to integrate the global lifecycle environmental expertise as early as possible during design with adapted tools to provide specific feedbacks to each expert. A combination of methods to evaluate the environmental aspects, tools to integrating the environmental aspects into the design process, and methods for integrating environmental and other traditional requirements are indeed required [2]. However, a precise correlation between the design parameters and a usage view, and how they influence the environmental impacts generated during the product's usage may be unknown by the expert in charge of defining the life cycle model for the environmental assessment.

This research therefore aims at supporting the ecodesign practice by linking available usage information, embedded in expert view, and the information needed by the environmental expert on usage. The hypothesis is that a formalized link would support adapted feedbacks to product designers as early as possible during design and encourage the ecodesign practice (section 2). A five steps method is introduced in section 3 to (a) improve information transfer of available information on usage from various expert outputs to the life cycle inventory - LCI (environmental expert inputs), and (b) support the provision of explicit environmental impact information from LCA results in the form of

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adapted feedbacks to design experts. This method is exemplified in Table 1. The last section discusses the research limitations and addresses further work.

2. Research focus: sharing explicit knowledge on usage to fuel ecodesign efforts during design

2.1. Linking expert parameters to the environmental lifecycle analysis

A number of solutions exist for the environmental expert to get access to information about the product being designed, for instance:

- The product's Bill Of Material (BOM) is generally accessible through the Product Life Cycle Management (PLM) software that gathers information about the product: material chosen, parts and components, assembly, manufacturing processes, etc.
- The associated material and components' providers, or suppliers referenced in the Enterprise Resources Planning (ERP) software of the company.

Automatic data transfer between product designers' software and LCA tools (mainly) can be supported by the information system of the company (for instance [3]). Commercial solutions exist (*e.g.* linking software from Dassault Systems©, PTC©, Granta Design©, to PE International© or CODDE©). However product models are usually centralized in a common model based on a standard model of data used to describe each component of the system. Information about the use stage are generally not included in the BOM (*e.g.* energy consumption), in particular if such information is not given by any supplier or other contract of any kind (*e.g.* leasing). Usage seems indeed hardly described by such a common product standard.

Complementary research have been published recently defining specific ontology, such as the Ontology Based Identification of Sustainable Options (OBISO) [4], or using existing ones, such as Model Driven Engineering based on Eclipse Modeling framework in FESTivE (Federate EcodeSign Tools mEthod) [5] to express and organize the information on the product spread across the experts' tools during product design. FESTivE is based on the federation approach of interoperability (*cf.* [6], and [7]addressing the different type of interoperability). Dynamic links are defined between different software based on different syntax. The information contained in those links deals with semantic interoperability between data that could have different meaning for different expertise. To generate data transfer the explicit links between the environmental impacts generated by design parameters and usage views must therefore be defined first. FESTivE, for example, supports the definition of such links through *knowledge transformation* mechanisms.

2.2. How use stage information are usually chosen today to model the product life cycle?

The information used to model use phase for life cycle purposes can be quite heterogeneous. Most of the time the model aims at representing average conditions of use and if possible it is based on a standard [8]. Analyzing the latest edition of the LCE conference, the following examples provide a good overview of current practices in research and in industry. Van Lieshout et al. used information from national surveys (US) to estimate water consumption for washing hands and dishes [9], while Bhakar et al. used recommendations from EPA mixed with manufacturers information [10]. For legislatives purposes, LCA in the preparatory studies for the European ecodesign directive implementation used various sources of information (such as phone surveys for refrigerators and washing machine), but none of them are tied to other design activities. Additionally, outsourcing data collection on usage can be resource intensive, leading to using "old data" to model current usages.

With an average scenario disconnected from current design activities, it has been difficult to propose eco-design improvements on the use stage. To overcome this, researchers have disconnected the improvement efforts from the assessment in approaches such as design for sustainable behavior [11]. They have been used in various design processes with relative success on improving use phase performance. In order to be aligned with life cycle thinking and ecodesign, Design for Sustainable Behavior (DfSB) requires to be reconnected to the other phases of product life cycle. Impact transfers can therefore be avoided.

2.3. Problem statement

Federation of design tools has been applied successfully to connect life cycle model for environmental assessment to design parameters from PLM or others design. Building on this approach, the research question is: **is there information on usage available during product design that can be transformed into explicit knowledge for the environmental expert:**

a. To construct the Life Cycle Inventory (LCI) of the product? And,

b.To fuel the eco-design effort across design experts?

3. Proposal

Considering this research problem a method is required to (a) improve information transfer between available sources on usage from various expert outputs to LCI (environmental expert inputs) – using *Knowledge transformation* [5], and (b) support the emergence of explicit environmental impact knowledge from LCA results adapted into feedbacks to design experts. A five steps process has been proposed:

Step 1 – *Describing* the coexisting usage information models from different fields into explicit knowledge.

Step 2 – *Linking* the explicit knowledge on the use stage of the product required to complete a LCI.
Step 3 – *Transforming* knowledge from diverse expertise into environmental lifecycle inputs (*e.g.* Life Cycle Inventory–LCI)**.**
Step 4 – ***Generating*** different LCI instances based on combined data set(s) from Step 3**.**
Step 5 – ***Fueling eco-design efforts*** by encouraging adapted environmental feedbacks to reduce conflicts about usage during design**.**

Table 1 is used in this five steps method to map out the different design expertise providing a specific vision of usage, and to complete the product lifecycle model. This table is a snapshot of potential coexisting usage models during the product's life cycle. Any new column can be added referring to a new type of usage model used by experts and/or shared with others to increment this table.

3.1. Step 1 – Describing coexisting usage information models from the different fields into explicit knowledge

Step 1 has been started by researchers and the results are to be enriched and adapted to the specificity of companies' product development processes by the LCA practitioner or by the project manager.

The following questions were used in the columns of Table 1 to describe usage (table 1 details three out of eleven models characterized by researchers. The full table is available for download here).

1			**Marketing**	**Design**	**Mechanics**
2		What is the *common name* for this usage source model?	Brief	Expertise [12]	FMEA
3	Does this source model require *knowledge transformations* to describe usage?	Does the model contain *tacit or explicit knowledge* about usage?	Explicit	Tacit	Tacit
4		How does it *structure understanding* about this usage model?	By describing the target audience	By questioning the rationale behind design decision	By recording and detailing the user actions associated to failure
5	Instance characterizations	Data type and format	Report with text, image, comprising a layout	NA	Sheet
6		Data sampling procedure	Market research: Market survey and competitors analysis	NA	Experience on similar products or mechanical calculation
7		Data sampling instrumentation	Web or Phone survey; Bibliography	Designer known-how and habits	Statistics
8		Usage Block	Shop window	Initial, Habitudinal	Decommissioning
9		How to link usage model to the environmental parameter?	Distribution network > Logistics scenario	Justification of design decision > Intensity of use flow	Time to failure > Product lifetime

Table 1: Mapping of the inventory of models referring to usage in the design process.

First line: what is the *related field* of expertise concerned by the model of use? This line specifies the expert mainly in charge of 'writing', 'documenting' or 'specifying' the model, such as: Marketing; Design (in the sense of engineering design); Mechanic...

Second line: what is the *common name* for this model? For instance: the Design Brief expressed in the Marketing language. The common name can also refer to specific methods such as the Failure Mode Effects Analysis (FMEA). In the case of design, in order to define the heterogeneous and informal usage model of designers, Design expertise terminology has been used to describe the mental models detailed in [12].

Third and fourth lines are defining how the model is linked to product usage: does this source model require *knowledge transformations* to describe usage? Does it contain *tacit or explicit knowledge* on usage? How do it *structure understanding* on this usage model? Usage information can be clearly available. For instance the design brief provides explicit information on the distribution network for products. Models based on tacit knowledge about usage require additional work to formalize information on usage. For *e.g.* FMEA is not explicitly referring to usage but the definition of failure mode encompasses assumption on the user behavior with the product (repetition of a task, misuse and errors). Similarly design expertise is a tacit model of usage but not because it does not refer to usage directly but because it is a mental model rather than an IT embedded one. Referring to the experts intervening during the product life cycle helps to understand the reason behind the choices made during design, *i.e.* a compromise in a multi-constrained context that included some usage requirements to satisfy.

Fifth, sixth and seventh lines are defining the instances characteristics (data sets) that can be used in order to 'run' the model. For example, FMEA model is often documented in a worksheet, and, according to the standard, uses information from experience and testing on similar products. To combine the collected data, a combination of statistical methods is used.

3.2. Step 2 – Linking the explicit usage knowledge to the product use stages to complete a LCI.

Step 2 helps the LCA practitioner in finding available data on usage that can be used in his own usage scenarios. The usage models inventoried in Step 1 need to be dissected on their ability to instantiate a usage scenario involved in the environmental assessment of the product, especially for life cycle inventory -LCI purposes.

That leads to questioning what usage means in the environmental expert language. The question is very much opened in the ecodesign community [8], [11]. Since no compromise have been reached, in this research, Hasdogan proposal [13] was selected to define what usage encompasses. The author's definition is chronological, which makes it compatible with the LCA approach of product life cycle. These concepts come from the field of design rather than the field of environmental assessment, which ties it to the inventory of models in Table 1. The author decomposed usage in three, depending on user expectation toward the product: the *shop window,* the *initial usage,* the *habitudinal usage.* They represent blocks of time where the user activities are relatively different from one another. For example, for *shop window*, the user activities are restricted to the buying act and for *initial usage* he is an apprentice of product functional capabilities. They are referred in this paper as *usage blocks.*

An additional block has been added in this research proposal to make it compatible with performing LCA. It represents the moment in time when the product stops to be used, in the *habitudinal usage* block, but is not referred to the end-of-life network yet. It is named *decommissioning*.

Line eight specifies which usage blocks the usage information is linked to. Usage models' instance for a specific product is used to instantiate one or more usage blocks LCI.

3.3. Step 3– Transforming knowledge from diverse expertise into environmental lifecycle inputs

Line nine indicates which knowledge transformations are required to link the source usage model to the environmental parameter, *i.e.* from the expert (line 1) to the environmental expertise. The marketing brief report may provide quantitative information on where the company pictures the product will be bought (*e.g.* retailer, on line shop). This refers to the *shop window* localization, which supports the elaboration by the environmental expert of the distribution scenario from the manufacturing plant up to the user home. The consumption of auxiliary flows during the product's first use may be evaluated by referring to video recording of user testing, which represents the *initial usage* block of the use phase model. Lines 1-8 guide the environmental expert for decoding, translating and transforming available data from another language into LCA instances. His explicit knowledge about usage will therefore be based on available information provided by the experts intervening during the product lifecycle.

Transformation between models

Starting from the last column, the environmental expert identifies the parameters of the LCA model that can be instantiated by the available models. A matching table between the element of each model (column) and the environmental model targeted may be additionally developed step by step to capitalize on the development of those links. For example, the parameter from the FMEA model 'Failure rate' is linked to the product components lifespan. The lifespan is indeed used in LCA to define the following parameters: the coefficient of Reference Flow on Functional Unit (RF/FU), as well as the use stage duration. Both usage parameters may also be calculated from the economical lifespan, deduced from the parameter referring to the timespan the company chose to support the product through after-sale service, available in the After Sale Strategy model.

If the model tacitly refers to use phase parameters an additional transformation may be required to firstly formalize the usage parameters deductible from the tacit knowledge [14] involved in the expert activity (using the forth column). Mental models transcription to physical ones may be needed. Giving the example of designers' tacit knowledge, interviewing them systematically about their design choice may help identifying which parameter of use designers wished to influence through the design feature they have created. This link between usage parameters and product feature will be the basis to link usage to LCI.

Appropriate format for instantiation

Data sampling procedure and instrument are required to analyze statistically the available data, and to establish representativeness of the available data, which will be required to perform sensitivity analysis in the LCA. For example, in the case of design expertise, one may find that a specific feature has been added for people with vision impairment (for example a noise notification instead of a luminous one). Since the feature will be used by a small sub-set of the population of users, the environmental expert has to take this parameter into account when instantiating his model for environmental assessment.

3.4. Step 4 – Generating different LCI instances based on combined or single data set(s) from Step 3

This five steps method helps to document and trace datasets and associated transformation processes, as required by the LCA ISO Standard 14040-44 [1] report – *assumptions and hypothesis* on the LCI. Figure 1 illustrates instances defined during the LCI stage of LCA.

The four chosen usage blocks are documented by a combination of information coming from different expertise sources (I(1) and I(2) Figure 1). I(1) is based on one source: the previous design information established by the environmental expert. I(2) is based on the combination of three information sources: marketing brief information (for the shop window), design expertise (for the initial usage and for the habitudinal usage), and FMEA (for the decommissioning usage block). The LCI model is then completed with complementary data covering the upstream life cycle stages (distribution and manufacturing) and downstream ones (end-of-life operations). The use phase instances provide multiple life cycle impact assessment scenarios of the same product (results on right side of Fig. 1). A 'sensitivity' analysis comparing the environmental impact results based on the different instances used provides several benefits:

- Traceability: causal links between information sources and environmental consequences related to usage blocks.
- Clarity: identification of collateral impacts caused by the information sources chosen on the different usage blocks.

Traceability and clarity offers the possibility to appreciate the overestimation or the underestimation of environmental impact usage blocks regarding the information source chosen. On Figure 1 – right side illustrates firstly that the assessment results from previous hypothesis of LCA have overestimated the impact of the *shop window* block compared to the instances based on the brief information source. Secondly, on *initial usage*, both instances provide similar environmental results. Finally, environmental impacts have been underestimated for *habitudinal usage* and *decommissioning*. Based on the design expertise and the FMEA respectively, the results of impacts assessment show that I(1) gives a value about three time lower less than I(2).

Based on this comparison the information source may be improved (*e.g.* avoiding using certain sources for modeling this usage block for a type of product). This process can encourage refining information models that have been used to identify environmental hotspots (*e.g.* the user manual overestimates the user behaviors by having a tendency to promote intensive care during use). Recommendations to expert can be made.

3.5. Step 5 – Fueling ecodesign efforts

With data set varying vastly in sources and types, it is reasonable to assert that the results of the environment assessment will vary as well. This variation will be crucial to integrate for ecodesign if the use phase is among the significant environmental aspect [1].

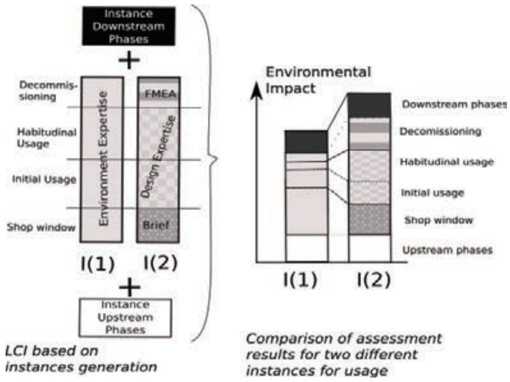

Figure 1: Instance generation and environmental assessment

Rather than being a deterrent to ecodesign the usage meaning for each expert and its consequences on the LCA results can be discussed in project meeting. It has been documented for example that product lifespan has a least three different definitions [11]: technical life, economical life and psychological life. This five steps method provides resources to define the 3 values from the current product design models. FMEA can provide one for the technical life, after-sale strategy one for the economical life, and marketing or design for the emotional one. By associating a value, a model and an expert that generated it to the environmental assessment, involvement of design experts in the ecodesign effort might increase. It can also be used as a support to converge toward a common definition of specific LCI parameter, such as product lifespan or intensity of energy flows in use.

The traceability of information will also improve the reliability of LCI. Instead of 'making up assumptions' or seeking external data sources for use scenarios, the environmental expert can source his data locally and use them as a way to challenge the perception of usage in design activities. Little by little the design team may converge on a common vision of usage.

This also helps rationalize the data collection process for use phase LCI scenarios. It can free up resources to focus data collection on specific moments of the use phase where the design teams have little to no information on.

Data collection rationalization and traceability is really critical for the environmental assessment of complex systems. Mapping design parameters directly to the assessment model is likely to support both. The focus on usage model is of particular interest for products that have the use phase among their significant environmental aspects.

4. Proposal limitation and industrial validation

4.1. Limitation on the method

Establishing knowledge transformations is an iterative and a collaborative process. As pointed out in the case of design expertise a lot of information used to define product use is based on mental models, *i.e.* tacit knowledge. The task of transforming mental models into shareable representation requires cognitive specialists. By being so multifaceted the representation of usage for each individual involved in the design process might never be totally shared with other individuals. Only extractions of individual vision may be sufficient to properly and commonly build instantiations. The study of designers by Goodman-Deane et *al.* [12] showed that a lot of expertise on usage by designers is based on introspection, brainstorming and informal discussion. In term of model transformation, it means major efforts are required in order to access designers' vision of usage activities.

Another limitation might be the difficulty to make different expertise converge toward a common vision of usage compatible with lifecycle thinking. There is no proof that this may not exacerbate opposition between design actors, and spoil ecodesign practice benefits.

4.2. On the integration of this method in industry

To capitalize the traceability of such use stage information the FESTivE method [5] can be used to support the Steps 1-3 of the five steps method proposed in this paper:

a. to model properly the targets and sources datasets;

b. to formalize knowledge transformation models at the interface of different experts and the environmental expert.

Appropriate IT solutions based on Model Driven Engineering developed by IT developers in collaboration with the environmental experts and related design experts is a key to integrate the proposed method in the company. In practice, two main actions have to be taken by the environmental expert. The first one is to systematically review the design models that refer to usage in any form. Table 1, in its extended version available here, has listed potential (and obvious) sources of information. However a completed list needs to be developed based on literature review and industrial audits to be adapted to several industrial contexts. The second one is to develop the conversion table between models in order to generate the instances for lifecycle inventory creation. The resulting dynamic linkage supports accurate usage information access to the environmental expert. The risk of using outdated data for the assessment due to a lack of reactivity during design may be therefore limited. The creation of conversion tables included in the knowledge transformations is under development at G-SCOP on the following models: FMEA and Maintenance guidelines (currently based on the *Talend* plugin of the *Eclipse Modeling Framework* (EMF), coded in dedicated transformation language (e.g. ATL)).

5. Conclusion

The aim of this research is to improve information transfer between available information about usage from various expert outputs and the environmental impact assessment inputs. This will also support the emergence of explicit correlation between environmental impact results and usage knowledge. This paper presents and illustrates a five steps method to gain clarity and traceability in assessing the life cycle impact of the product using the coexisting usage instantiations during design.

This method offers interesting perspective to explicit tacit knowledge about usage from product design experts and others experts such as ethnographic field studies or functional analysis. Ongoing developments concern the application of the method in an industrial case study with proper IT developments (dynamic linkage and Case Base Reasoning mechanism to support environmental expert feedbacks during design).

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