Eco-ideation and eco-selection of R&D projects portfolio in complex systems industries

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Abstract: Eco-innovation methodologies and tools are being applied in companies to an increasing extent. None of them, however, are particularly adapted to complex systems industries, where the eco-design requirements are highly specific. These systems are characterized by large size and mass, and relatively long and uncertain life cycles. The associated organization is also complex as there are multiple highly specialized experts, who rarely collaborate, and much less so on environmental aspects. In this paper, an adapted eco-innovation process based on the eco-design strategy wheel is proposed for use with a working group of internal technical experts. A first phase involves generating a high number of potential eco-innovative R&D projects that are then analyzed and assessed using an appropriate multi-criteria grid. Three structured filters enable an informed selection of the most promising projects that will then make up a balanced R&D project portfolio. The whole process has been successfully applied at Alstom Grid on large electrical stations used in the primary aluminium industry.

Keywords: Eco-design, eco-innovation, complex industrials system, R&D project portfolio, creativity.

1. Introduction

With heightening awareness of the impact of human activities on the environment, environmental concerns have become increasingly important. In companies, this has resulted in a need to respond to new environmental requirements and regulations (Bey et al., 2013). From this perspective, eco-design allows us to consider, manage and improve the environmental performance of products, processes and services (ISO 14006:2011).

However, if this approach is now recognized and well deployed in competitive mass-consumer goods producers (Business to Consumer, B to C), the situation is not so advanced in B to B (Business to Business) industries, in particular for complex industrial systems. They are characterized by a long and uncertain life cycle, involving a high number of subsystems and components or strong interactions with their environment (Cluzel et al., 2012). The technological and regulatory constraints associated with these systems may slow down the ability to innovate, as reliable technologies proven over the long-term are often favored. Nevertheless, the need for eco-innovation is clearly present, as these systems are linked to substantial environmental impacts.

However, eco-innovation on complex industrial systems is a challenging task. R&D projects in complex systems industries are often driven by technological, not environmental, considerations. These projects need to be identified fairly early in the design process, with little information available. On the other hand, it is generally agreed that environmental-oriented R&D (Research & Development) projects are necessary, but the complexity of the products and organization makes it tricky to introduce an eco-innovation approach. This type of organization is characterized by multiple highly-specialized experts, who rarely communicate together. Furthermore, only a few are trained in eco-design or Life Cycle Assessment (LCA). This is why a simple and effective eco-innovation method is necessary, requiring little preliminary environmental knowledge. This would make the collaboration between multidisciplinary experts possible.

This paper proposes one such intuitive eco-innovation methodology to answer to the following research question: how to generate and select an adapted portfolio of eco-innovative R&D projects for a complex industrial system? From a classical ideation phase, based on the eco-design strategy wheel (Brezet and Van Hemel, 1997), and a simple scoring model taking five dimensions into consideration - including potential environmental benefits - a powerful portfolio of eco-innovative R&D projects is identified via three successive filters using limited resources. The whole eco-innovation process is then deployed at Alstom Grid on complex electrical substations.

Section 2 presents a literature review of eco-innovation and R&D project evaluation and selection for complex industrial systems. In section 3, an adapted methodology is introduced. Section 4 deals with the application of this process at Alstom Grid. Section 5 tests the robustness of the model and discusses the validity of the results. Concluding remarks and perspectives are presented in section 6.

2. Literature review

2.1 Complex industrial systems

This paper focuses on complex industrial systems whose specificities have yet to be taken into account in eco-design and eco-innovation: these are industrial systems where complexity induces major issues in terms of modelling, prediction or configuration. From the systems engineering domain (Blanchard and Fabrycky, 2011), we define a complex industrial system in the eco-design vein as (Cluzel et al., 2012):

- A large-scale system in terms of sub-systems and components, mass and resource usage;
- A system whose life cycle is unpredictable at the design level in the long-term, in particular with regard to its lifetime, upgrades, maintenance and end-of-life;
- A system whose sub-systems may have different life cycles and different obsolescence times;
- A system which is in close interaction with its environment (e.g. super system, geographic site);
- A system which is supervised by human decisions and management.

Concerning eco-innovation, the main problem of such systems is that the customers' specifications or the regulations and standards severely limit the ability to radically innovate, as only long-term proven technologies are used. Thus, the challenge associated with an eco-innovation approach is how to identify a set of reliable incremental eco-innovative projects, and/or to be able to make radical eco-innovations possible which are acceptable to customers.

2.2 Eco-innovation

Eco-innovation is an emerging field, for which there are numerous definitions and tools in the literature.

2.2.1 Definition

Eco-innovation has been associated with numerous definitions in recent years. Carrillo-Hermosilla et al. (2010) list, for example, 16 different definitions, before proposing the following: an eco-innovation is *"an innovation that improves environmental performance, in line with the idea that the reduction in environmental impacts (whether intentional or not) is the main distinguishing feature of eco-innovation"*. This specifically includes innovations where the reduction in environmental impacts is a side-effect, and not the main or initial goal. More importantly, it also includes radical and incremental innovations.

For other authors, an eco-innovation is necessarily radical. This is highlighted by Tyl (2011), and also clearly expressed by Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010). But Pujari (2006) also shows that few eco-innovations are really radical with regards to mass-consumer goods. In some other definitions, an eco-innovative product is significantly less environmentally harmful than the existing ones, but O'Hare (2010) highlights the fact that *"different companies may have different opinions as to what constitutes a 'significant' improvement in environmental performance"*.

Given the hierarchical nature of complex industrial systems, as well as the fact that radical changes are rarely acceptable for customers in complex system industries, the eco-innovation framework defined by Carrillo-Hermosilla et al. is well adapted to complex industrial systems: *"Eco-innovations, particularly when they are radical and require techno-institutional system-level changes, are difficult to achieve because the prevailing system may act as a barrier to the creation and diffusion of a new system"* (Carrillo-Hermosilla et al., 2010).

2.2.2 Eco-ideation tools

An eco-innovation approach indicates two major activities: eco-ideation, defined as the generation of ideas that reduce environmental impacts throughout the product life cycle of products (Bocken et al. 2011), and the evaluation and selection of the most promising ideas (Jones et al., 2001). This paragraph studies eco-ideation and the associated methods and tools. Section 2.3 deals with the evaluation and selection of R&D projects, a field as will be seen below that it extends beyond eco-innovation. Indeed Byggeth and Hochschorner (2006) state for example that eco-design and eco-innovation tools usually lack strategic planning considerations.

Regarding the eco-ideation process itself, expert groups are widely used through creativity sessions (Bocken et al., 2011). Pujari (2006) shows that multidisciplinarity in the working group is a key factor for success in eco-innovation. Finally, eco-ideation processes in companies are often performed as classical creativity sessions supported by an eco-innovation tool. Different eco-ideation tools are well known or regularly referred to in the literature, such as the eco-design strategy wheel (Brezet and Van Hemel, 1997; van Hemel and Cramer, 2002), also known as the LiDS (Life cycle Design Strategy) wheel, Eco-compass (Fussler and James, 1997), Product Ideas Tree (Jones et al., 2001), BEC (Business-Environment-Customer) synergy diagram (O'Hare et al., 2007), or TRIZ-based tools (TRIZ is the Russian acronym for Theory of Inventive Problem Solving). Baumann et al. (2002) and Bovea and Pérez-Belis (2012) classify eco-design and eco-innovation tools.

The eco-design strategy wheel is a simple tool that proposes eco-design guidelines divided into eight axes on a graphic wheel. Seven axes cover the life cycle of the product, whereas the last one aims at identifying new concepts. According to Tyl (2011), it is extremely simple to implement and to use, as it does not require specific knowledge, and the graphic representation is very clear. It is ideal for a multidisciplinary working group in a company. But as a simple tool, the eco-design strategy wheel may become simplistic, and the pre-defined guidelines restrict usage to product-level considerations. The wheel is shown in Figure 1 with the axis labels.

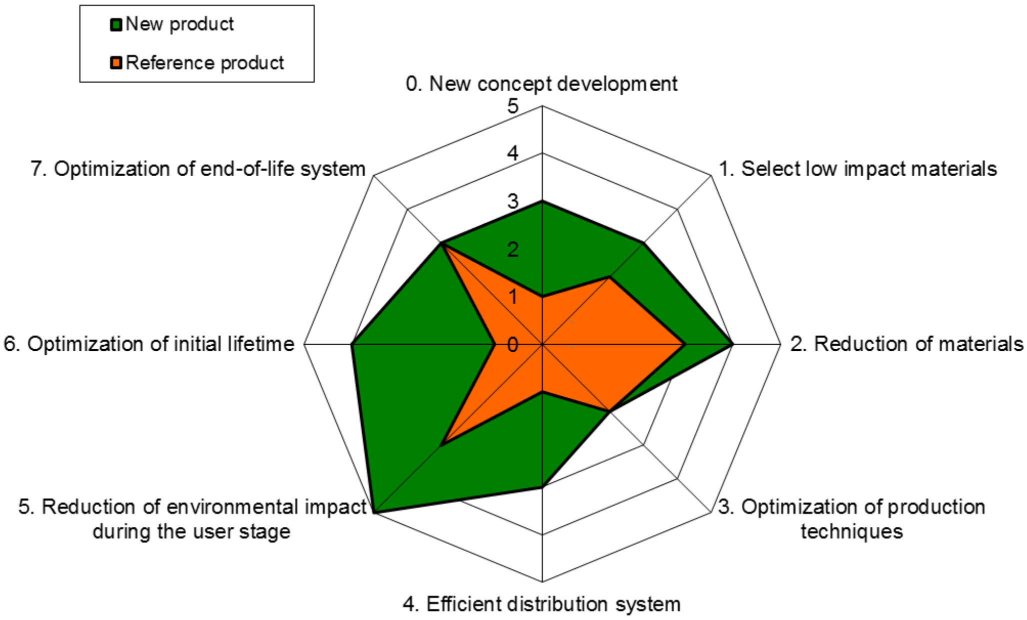

Figure 1. Illustration of the eco-design strategy wheel proposed in Brezet and Van Hemel (1997)

Eco-compass is another simple graphical tool. It is composed of five axes that are less linear than the axes of the eco-design strategy wheel, because they incorporate life-cycle-oriented and impact-oriented considerations. But like the eco-design strategy wheel, it is often considered as an eco-design or strategic-oriented tool, limited to a product-level approach (Tyl, 2011).

The BEC synergy diagram is a tool that proposes a positioning of ideas according to considerations of business, environment or customer aspects (O'Hare et al., 2007). This tool is also really simple to use; however it is considered too simple according to the value chain of complex industrial systems, as it is more complex than a simple "supplier-client" relationship (these are for instance several stakeholders that may be called "clients").

Product Ideas Tree (PIT) aims to structure eco-innovation creativity sessions using mind-mapping techniques. It is thus more oriented towards idea structure than ideation. The use of such a structuring tool allows a reduction of destructive interactions in the group. However, it also shows that it can restrict the creativity potential (Jones et al., 2001).

Finally, several examples of TRIZ-based tools for eco-innovation exist in the literature (Kobayashi, 2006; Mann and Jones, 2002; Yang and Chen, 2011). TRIZ is known as a highly effective ideation tool, but it is also perceived as a complex approach. Tyl (2011) also states that the TRIZ innovative principles do not adequately fit the eco-innovation principles and need to be reworked. He proposes a TRIZ-based tool, EcoASIT, which offers good performance in the eco-ideation phase. In this paper, we focus more on the project selection phase, and that is why a very simple and appropriable tool is adopted later.

These tools are able to support an eco-ideation process. However, they do not ensure an effective and multi-criteria evaluation and selection step of the most promising ideas. Currently *“there are more opportunities and concepts than can be supported with the funding available within the company”* (O’Hare, 2010). The next section considers general methods in the field.

2.3 Evaluation and selection of R&D projects

Once eco-innovation projects have been generated, it is then necessary to identify the optimal mix of R&D projects to undertake. Indeed the number of projects selected by a working group may be too high compared to the available resources in the company. It is crucial to feed the management decisions with accurate data and adapted tools to select an optimal R&D project portfolio. Related methods are considered in the next paragraph.

2.3.1 Overview of the methods

Some interesting methods to select eco-innovative alternatives exist in the eco-design field. Bocken et al. (2012) propose the pain/gain tool to evaluate options. However, evaluating the environmental benefits of options requires being able to define those options. In this paper, eco-innovative propositions concern wider R&D fields it would be interesting to investigate rather than detailed options. That is why the field of R&D project evaluation and selection and R&D portfolio management are considered.

A significant panel of methods and tools have been produced during recent decades. Mikkola (2001) notes that *“portfolio techniques are powerful tools in that they allow products and R&D projects to be analysed in a systematic manner, providing an opportunity for the optimization of a company’s long term growth and sustainability”*. Methods such as Weighted Objectives Method, Analytical Hierarchy Process (AHP) or QFD matrix are not considered in this paper as they are not particularly well-adapted to assessing the (eco-)innovation potential of ideas (Justel et al., 2007).

Cooper et al. (1999) propose a classification of portfolio management techniques. The authors distinguish between financial models, strategic approaches, scoring models and checklists, analytical hierarchy approaches, behavioural approaches and mapping approaches (or bubble diagrams). Cooper et al. (1999) also state that mathematical models are not really deployed in companies, because they need a large amount of precise data and they are difficult to manage and to use for managers. Another point highlighted by Bitman and Sharif (2008) or Lawson et al. (2006) is that the methods based only on financial aspects do not yield the best results.

Finally, Cooper et al. (1999) show that a sound method should allow for:

- Identifying the right number of projects;
- Avoiding gridlocks in the portfolio;
- Highlighting high value projects;
- Ensuring a balanced portfolio (for instance long term versus short term);
- Being aligned with company strategy.

Among all the methods, scoring models are well-known and popular, mainly because they are easy to use and give acceptable results. They are also in line with previous success criteria. The next paragraph focuses on these models.

2.3.2 Scoring models

Scoring "*is the process of assigning ordinal scale values to R&D projects for the purpose of ranking the projects with respect to some criteria*" (Henriksen and Palocsay, 2008). Scoring models are simple, direct, effective and flexible (Bitman and Sharif, 2008). They show a balanced ratio between rigor and the time spent on the study (Henriksen and Palocsay, 2008). Projects are rated and scored according to several qualitative or quantitative indicators. Henriksen et al. define scoring as *"the process of assigning ordinal scale value to R&D projects for the purpose of ranking the projects with respect to some criteria"* (Henriksen and Palocsay, 2008). The weighting of the criteria enables a customization of the model for special needs (Cooper et al., 1999).

One of the main advantages of a scoring model is its ability to be easily implemented in companies. In fact, and contrary to mathematical or financial models, the use of qualitative scales allows wide diffusion of the tools, for example through an Excel sheet or a questionnaire. Examples of such approaches are given in (Henriksen and Palocsay, 2008) and in (Apperson et al., 2005).

However, the success of a scoring approach is clearly linked to the selection of sound variables and indicators (Mikkola, 2001). References from the existing literature often propose some categories to consider. For Coldrick et al. (2005), information concerning markets, customer needs, competitors and regulatory and environmental concerns need to be taken into account. In addition to 'classical' financial factors, Apperson et al. (2005) consider four general areas: external forces (including environmental impacts), marketing, company dynamics, and technical capabilities. However, among these different categories, environmental aspects are sometimes mentioned, but never analysed in depth.

A research gap is thus emerging from both the literature and the industrial diagnosis. On one hand, companies dealing with complex industrial systems need eco-innovation methods and tools. But on the other hand, existing methods and tools, in the eco-innovation filed or in the evaluation and selection of R&D projects field, are not adapted to this particular context, or they cover only partially the R&D development process. That is why the authors ask the following research question: how to generate and select an adapted portfolio of eco-innovative R&D projects for a complex industrial system? Based on the literature review, an adapted eco-innovation methodology for complex industrial systems is proposed in the next section.

3. Methodology

An industrial audit was conducted over a period of several months at Alstom Grid (see Section 4). We propose that an adapted and effective eco-innovation methodology for complex industrial systems should:

- Consider the different system levels (components, subsystems, system, etc.), as incremental innovations that are constantly made at a component or subsystem level, while radical innovations are more likely to appear at a system level (new unexpected architecture),
- Be very simple, as multidisciplinary knowledge is required to consider all the aspects of such a large-scale system, i.e. the process mainly involves non-environmental experts,
- Be flexible, implantable within a short time-frame with limited resources, and easily accepted by the management and the experts involved,
- Be very efficient, reaching the best possible ratio between resources used and results,
- Build a strong basis for future eco-design work, both to maximize the learning potential of the process and to maximize the success rate of the identified R&D projects,
- Take into account multi-criteria aspects, by considering technical, economic and marketing dimensions, to be easily accepted,
- Provide strong proof in terms of feasibility and interest for the customers, so as to be successful on the markets.

Considering these requirements and due to the fact that a significant number of eco-design tools are built and not fully tested in real conditions (Baumann et al., 2002), our methodology is based on a pre-existing eco-ideation tool. However, it does not seem possible to give in-depth training to the working group, whether it

concerns eco-design or creativity tools. The ideal tool to assist creativity should give predefined stimuli based on checklists or guidelines. The eco-design strategy wheel is chosen according to its simplicity and the good adequation of the axes' contents with complex industrial systems. This choice is in line with the requirements summarized by O'Hare to increase the industrial adoption of design tools, one of which is for instance to *"decrease the level of effort required to apply the tool or the complexity of the tool"* (O'Hare, 2010).
However, the eco-design strategy wheel does not propose any post-processing treatment of the generated ideas, i.e. there is no process to evaluate and select the most promising ideas. R&D projects associated with complex industrial systems may be long-term studies, and they would probably be too numerous for available resources. It is thus essential to build an adapted portfolio of R&D projects through multi-criteria assessment of each project, even if it is based mainly on qualitative evaluations. The participation of a multidisciplinary working group appears to be the best way to obtain complete knowledge of the system.
The next paragraph proposes an adapted eco-innovation process for complex industrial systems, based on a multidisciplinary working group, supported by the eco-design strategy wheel and using an original scoring model for R&D project evaluation and selection.

3.1 Prerequisites and general approach

The eco-innovation process for complex industrial systems presented is this paper is part of a larger methodology described in (Cluzel et al., 2012) and built on the following hypotheses:

- Eco-innovation is deployed in a company providing complex industrial systems, but with no specific knowledge in eco-design/eco-innovation;
- The approach is supported by at least one eco-design expert;
- An environmental evaluation (Life Cycle Assessment or simplified LCA) has identified high impacting elements (materials, components, subsystems, life cycle phases) of the complete system life cycle.

Moreover, as expressed widely in research, one major success factor is the support of the management of the company (McAloone, 1998; O'Hare, 2010). This ensures in particular the ability to build a multidisciplinary working group, if department managers give their acceptance to include their experts in the working group.
The choice of a collaborative approach as opposed to an individual one is justified by the fact that the global vision of a complex industrial system is necessarily shared by several persons with different knowledge (product, life cycle, technical aspects, design process, customers etc.). That is why the main departments of the company need to be represented: R&D, engineering, commercial & marketing, sourcing…. 6 to 10 participants is

generally perceived as the optimal number for an efficient creativity process. The eco-design expert required to support the approach is the leader of the creativity sessions.

The objective of the eco-innovation process is to identify a set of pertinent environmental improvement projects (incremental or radical eco-innovations) ready to be assessed by the decision-makers. This portfolio needs to be composed of powerful individual projects, but also to have global coherence. This is also a way to prepare the company for the future and further extended eco-design work, as the members of the working group will be able to act as eco-design 'ambassadors' in their respective departments.

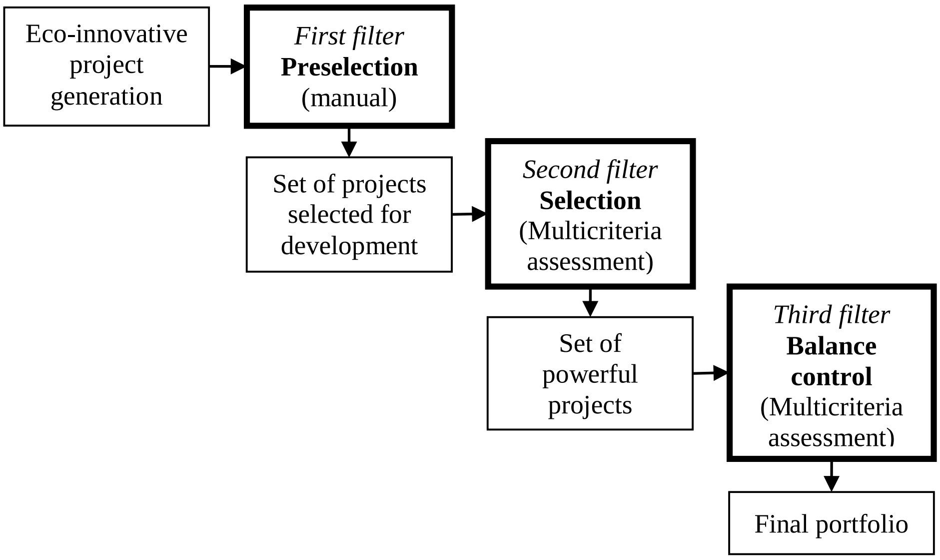

Figure 2. Overview of the global process including the three filters

Once the working group has been defined, the eco-innovation consists of two main steps: eco-ideation, and eco-innovation R&D projects evaluation and selection. The building of an adapted portfolio of eco-innovative projects is performed through three successive filters that cover these two steps. This process is described in Figure 2 and also mentioned in Figure 7 to clearly position them in the whole process, and it is detailed below.

3.2 Eco-innovative projects generation and preselection

The eco-ideation phase is divided into three sessions, supported by the eco-design strategy wheel from (Brezet and Van Hemel, 1997).

The first session is called the 'introductory session'. As the members of the working group are predominantly unfamiliar with environmental concerns and eco-design principles, this session aims at introducing the main eco-design concepts, previous environmental assessments, as well as the eco-innovation approach (including the eco-design strategy wheel). As Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010) state, the diffusion of 'soft' environmental information is favored. They have in fact highlighted a contradiction between the need for environmental information to focus on the impacting elements and the creativity limitation induced by data being too precise. Adding to this statement that most of the working group members are not experts in the environmental field, only general LCA data and high-level eco-innovation principles are communicated to them during a short meeting (1 to 2 hours). This first session allows a common language between group members to be shared.

The second session is called the 'creativity session' and may be performed as a half-day meeting. A short introduction is first necessary to recall the objectives and the scope of the study. It also permits a short icebreaker game to foster a creative atmosphere. Then a divergent creativity phase is launched, following the classical creativity rules. During this phase, only environmental considerations are taken into account (technical, economic or customer aspects are voluntarily omitted). Each of the eight axes of the eco-design strategy wheel is considered separately during a short workshop (15 to 30 minutes) in a two-step approach:

- A brainwriting phase, where each participant individually generates a maximum number of ideas in accordance with the considered axis (for example 'Optimization of initial lifetime') answering the following issue: *"Improving the environmental performance of the system considering stimuli provided by Axis XX"*,
- Following this, there is a common phase where all ideas are read by the animator and grouped. The participants are encouraged to orally propose new ideas. All the ideas are stuck on the wall on pre-defined supports.
- The divergent phase is followed by a convergent phase, where all ideas are discussed and sorted out. Technical, economic or customer aspects are now considered. The objective of this phase is to identify a first set of promising ideas or idea groups which are from now called eco-innovative projects. This transition from ideas to projects is performed by grouping closed or complementary ideas dealing with the same R&D theme.

This convergent phase is illustrated in Figure 3. It represents the first filter that permits preselection of the most promising projects, thus building a powerful R&D project portfolio. Each project is discussed. If at least one working group member is opposed to project rejection, it is selected for the next step. If the selected projects are too numerous (i.e. their number exceeds the number of projects N that can reasonably be developed according to the available resources) they are analysed once more to consensually reject the least powerful ones. This first filter is based solely on the members' expertise and experience to quickly identify a reasonable set of projects that will be developed. The rejected projects are capitalized for future use.

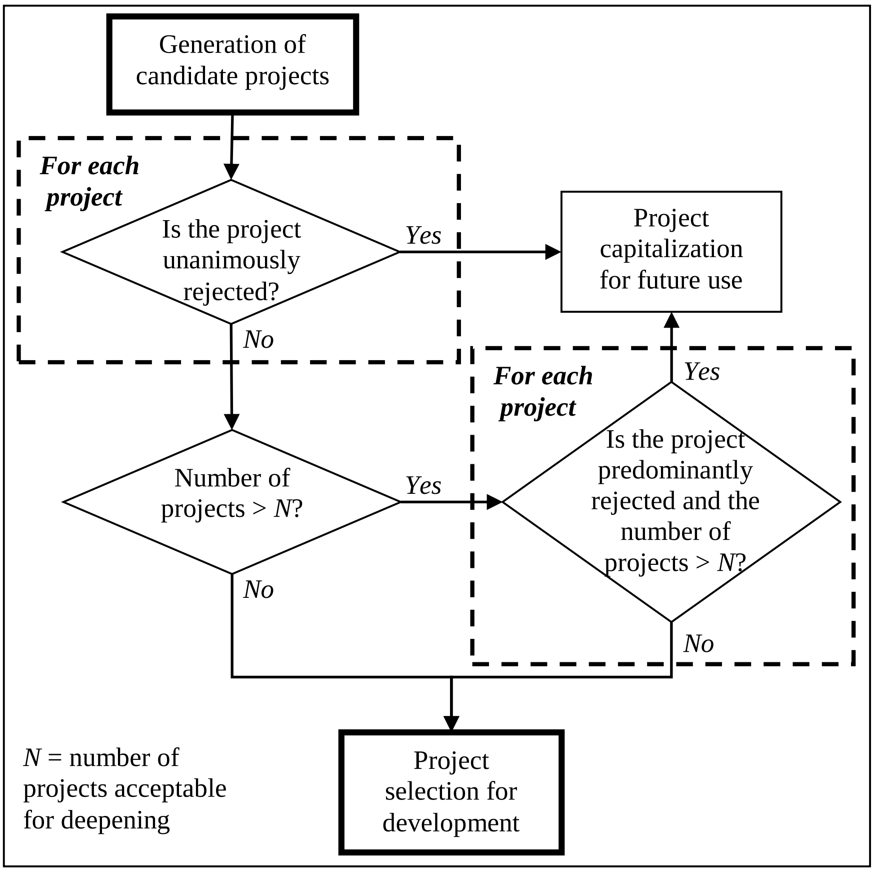

Figure 3. First filter: preselection of projects

The selected eco-innovative projects are then synthesised on standardized sheets that include:

- a description of the project,
- the objectives of the project,
- the potential environmental benefits,
- technical feasibility,
- economic feasibility.

Such a sheet may be completed in a few hours based on expert knowledge and a short documentary study. This information remains unknown at this step, so only qualitative or estimated data are available. The standardized sheets are then developed over a few weeks by sharing them out between the working group members according to their own competencies. The standardized sheets are then updated with the new information.

The last session is called 'synthesis session'. It consists of a discussion on each eco-innovative project in order to clarify the different design aspects and to ensure that a common vision emerges for each project.

At the end of this eco-ideation process, a first set of promising eco-innovative projects has been identified. But they are generally too numerous for all of them to be considered as R&D projects, due to a lack of resources. Moreover, and even if some qualitative elements have been synthesised in the standardized sheets, it remains hard to compare the projects to make an optimal choice. Thus the next step of the eco-innovation approach concerns the prioritization of the projects thanks to a multi-criteria assessment.

3.3 Project selection based on a multi-criteria assessment

This paragraph proposes an assessment grid based on four dimensions, that is assimilated to a simple scoring model without any prioritization of the projects and where no global score is calculated. Two other dimensions are taken into account in the decision process, but as they are not judged debatable and inherent in the contents of each project, they are not included in the assessment grid. As Bitman and Sharif (2008) showed that a two-level structure is preferable, each of these dimensions is divided into several indicators. They come from different literature or company sources:

- **Potential environmental benefits:** the environmental benefits of the project are compared to the environmental performance of the existing solution thanks to the eco-design strategy wheel (Brezet and Van Hemel, 1997) on a six-level qualitative scale (0 to 5, see Table 1). The existing solution is arbitrarily positioned at 2 on each wheel axis and the relative position of the eco-innovative project is determined by the user thanks to the qualitative scale. A final score on 20 points is then calculated (average score on the eight axes), but the detail of the 8 axes is preserved, as the average score may hide important benefits on a particular life cycle aspect.

Score	Description
0	The project highly deteriorates the environmental performance of the current solution.
1	The project significantly deteriorates the environmental performance of the current solution.
2	The project does not bring any benefit or damage compared to the current solution.
3	The benefits brought by the project are minimal.
4	The benefits brought by the project are significant.
5	The benefits brought by the project are very important.

Table 1. Example of a qualitative scale to measure potential environmental benefits on each axis of the eco-design strategy wheel. (The scales used for the other dimensions are based on the same principle but not detailed in this paper)

- **Feasibility:** this dimension explores both the technical and the economic feasibility with the use of 4 indicators proposed by an expert discussion at Alstom Grid: ease of implementation in terms of time and resources, financial return of investment, technical feasibility in terms of knowledge, internal level of control (is the company able to internally manage the entire project?). Each indicator is assessed using a six-level qualitative scale (0 to 5) that permits to obtain a final feasibility on 20 points, calculated as the sum of the four scores.
- **Customers' value:** this dimension assesses the benefits for the customers associated with each project. It uses 4 indicators proposed by (Kondoh et al., 2006): cost reduction, avoidance of risks, improvement of service quality, improvement of image. Each indicator is assessed using a six-level comparative and qualitative scale (0 to 5), where 2 is a neutral score (the existing and the new solutions are equivalent). The final customers' value on 20 points is calculated as the sum of the four scores.
- **Time horizon:** this fourth dimension gives information concerning the term timescale of the studies associated to each project (and so the term where the potential benefits could be perceived), which is often considered as important to get a balanced project portfolio (Cooper et al., 1999). It simply consists of a four-level textual indicator: short term, middle term, long term and prospective (i.e. at a very long term and with high uncertainties).
- **Project perimeter:** this dimension concerns the system level considered in each project. It also consists of a four-level textual indicator inspired by Carrillo-Hermosilla et al.'s typology (Carrillo-Hermosilla et al., 2010): component, subsystem, system, super system (involving more than the system considered in the project). This dimension is not included in the assessment grid as it is assumed that each project is clearly linked to one level without ambiguity.
- **Project nature:** this last dimension allows the nature of projects to be identified: methodological, organizational, and/or technological, as a project may have several natures. This dimension is not included in the assessment grid as it is assumed that each project is clearly linked to one level without ambiguity.

Moreover for each project an expertise level indicator, self-evaluated by the users, has been added with four possible levels (from non-expert to expert). The first four dimensions are represented in an evaluation sheet, and each member of the working group evaluates each eco-innovative project. By weighting each evaluation with the member's level of expertise, greater value is given to the assessments performed by an expert rather than by a non-expert. Finally an average score is obtained on the five dimensions and for each project. The process to calculate the global thematic (environmental, feasibility, customers' value) scores is detailed in the appendix. The assessment grid involving the four first dimensions is filled in by the working group members. Once the assessments have been performed, Figure 4 proposes a second selection filter based on the obtained scores. Threshold values are identified for each dimension according to the assessment scale, and the projects are examined dimension by dimension in the following order:

1. Feasibility, as it is unfruitful to consider unfeasible projects for longer,
2. Customers' value, as it is useless to consider a project that deteriorates these values for longer,
3. Environmental benefits: the global score is first considered, but also the detail of each Brezet wheel's axis. Indeed a project may have for instance excellent benefits on end-of-life aspects and at the same time not bring benefits to the other axes, resulting in a poor global environmental score.

This process results in a justified choice of a set of eco-innovative projects. However a good balance of the overall portfolio is not ensured. That is why a final step is proposed in the next paragraph.

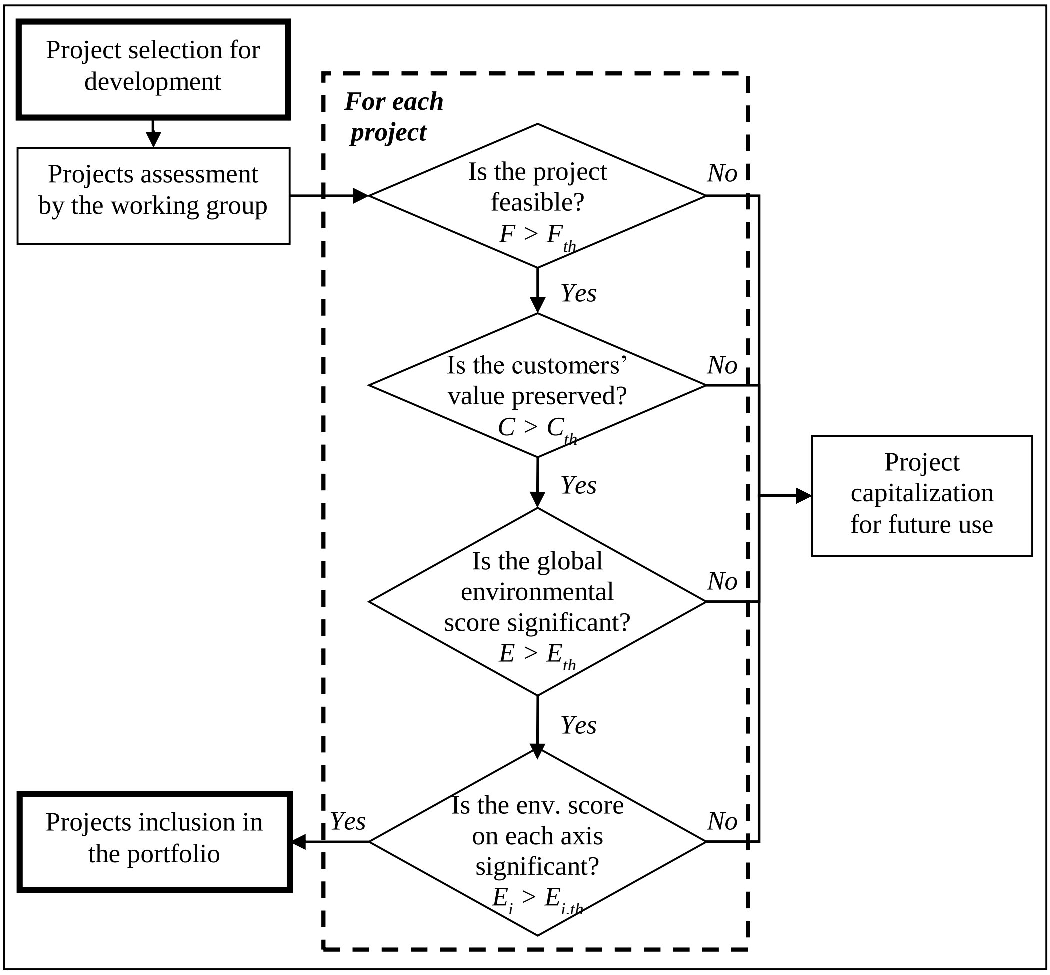

Figure 4. Second filter: selection of projects

3.4 Portfolio balance control

The individual selection of R&D projects enables a portfolio to be built. However it does not ensure that the combination of these projects is optimal. It has indeed been shown in a previous part of this paper that the balance of such a portfolio is essential to ensure the success of the approach and to offer strong and sustainable improvements.

As this eco-innovation approach aims at being easily applicable, a third and final filter based on a qualitative assessment of the overall portfolio is proposed. This filter is described in Figure 5. The last three dimensions expressed in section 3.3 are used to check that the combination of projects is well balanced. First the temporal horizon dimension is considered, as an ideal portfolio includes short-, middle- and long- term projects. Secondly the project nature is considered, in order to progress on the three axes of the dimension: organizational, methodological and technological. Finally, the distribution of the projects according to their perimeter is observed, in order to work on different levels: component, subsystem, system, and even super system.

For each dimension it is necessary to ask whether or not the portfolio is well balanced. It is assumed that this questioning clearly depends on the strategic positioning of the company and that there is neither a good nor bad answer. That is why no general rule is proposed.

If the portfolio is considered to be poorly balanced on some aspects, a new one needs to be found by returning to the previous stages of the approach, with different and adjusted threshold values. If it is not possible to define a best portfolio, the current one is validated with its weakness borne in mind.

The final steps of the approach then consist in identifying the time and the resources that need to be associated with the R&D projects, as in a classical project management methodology. The final portfolio is proposed to the top-level managers for a final validation, and then planned and realized.

The management may of course limit the number of projects according to the available resources and the strategy of the company, and different graphical representations, from classical mapping models to more specific diagrams, may be useful. It is indeed necessary to give the right information to the decision-makers to ensure the best choices can be made upstream.

At this step, the descriptive project sheets are transmitted to the decision makers. The presentation of the overall performance of the portfolio is performed through different possible diagrams. Two of them are presented in Section 4:

- Monodimensional diagrams including the uncertainty ranges are also useful to easily visualize the positioning of the projects and its eventual overlaps.
- Finally, partial ordering graphs allow easy identification if a project is outranked by another on the three dimensions (considering the uncertainty ranges). This is an alternative to the previous monodimensional diagrams, and has the advantage of being easier to read but the disadvantage of losing quantitative information.

These different diagrams present essentially the same information. Furthermore propositions 3 and 4 include uncertainty aspects, but several graphs are necessary.

In the current approach, it is proposed to show these different visualization possibilities to the decision-makers, as they all present pros and cons, and they may be more or less adapted to some people and situations.

Considering these synthesis graphs and the project sheets, the decision-makers should have the right amount of data to make the right decisions.

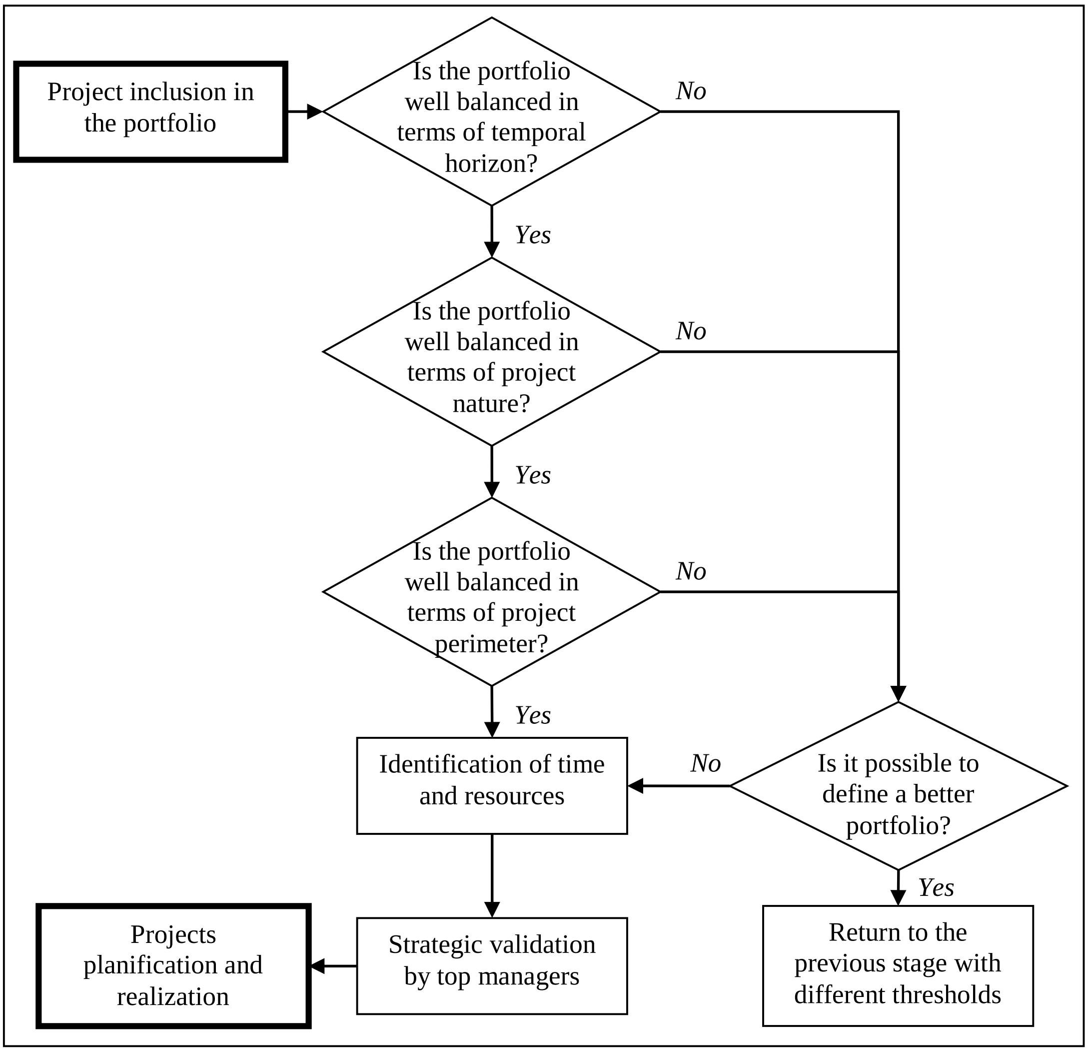

Figure 5. Third filter: balance of the project portfolio

3.5 Project realization

Once the project portfolio has been selected by the decision-makers, and the projects planned as usual, they may be realized following the general eco-design process for complex industrial systems proposed in (Cluzel et al., 2012).

The project realization may be spaced out over several months or years. Once the whole portfolio or the selected projects have been performed, the full approach may be reiterated by considering the new system as the system of reference.

3.6 Validation criteria

The validation of such a process is not easy, because it involves subjective and qualitative elements.

The four criteria proposed by Shah et al. (2003), who add *variety* and *novelty* to *quantity* and *quality* of generated ideas, are of interest here. *Novelty* concerns what is unusual or unexpected. *Variety* measures the size of the explored solution space. *Quantity* is the total number of ideas generated. Finally, *quality* corresponds to the feasibility of an idea and its proximity to the initial requirements. To validate the eco-innovation approach, we propose associating the following indicators with these criteria:

- ***Novelty:*** two questions are added in the assessment grid given for each project to the members of the working group: 1) Do you think that this project has already implicitly existed, before the introduction of the eco-innovation approach, in the mind of one or several persons in the company? 2) Do you think that this project would have emerged, been formalized and seriously considered by the decision-makers without the eco-innovation process?
- ***Variety:*** different indicators are considered: the balance between short/middle/long term and prospective projects, the balance between component/subsystem/system/super system related projects, and the balance of the nature of the projects (technical, organizational, methodological projects, etc.).
- ***Quantity*** is assessed by the total number of ideas generated during the divergent creativity phase and the total number of eco-innovative projects proposed after the convergent phase. The time spent on the different phases of the eco-innovation process is also taken into account.
- ***Quality*** is assessed thanks to the three dimensions: potential environmental benefits, feasibility and customers' value.

These four criteria will facilitate assessment of the global performance of the eco-innovation process proposed in this paper. In the next section, a case study performed at Alstom Grid on a complex industrial system is proposed.

4. Results

The methodology outlined above was applied at Alstom Grid on AC/DC conversion substations for the aluminium industry. This case study is described in the next paragraphs.

4.1 AC/DC conversion substations for the aluminium industry

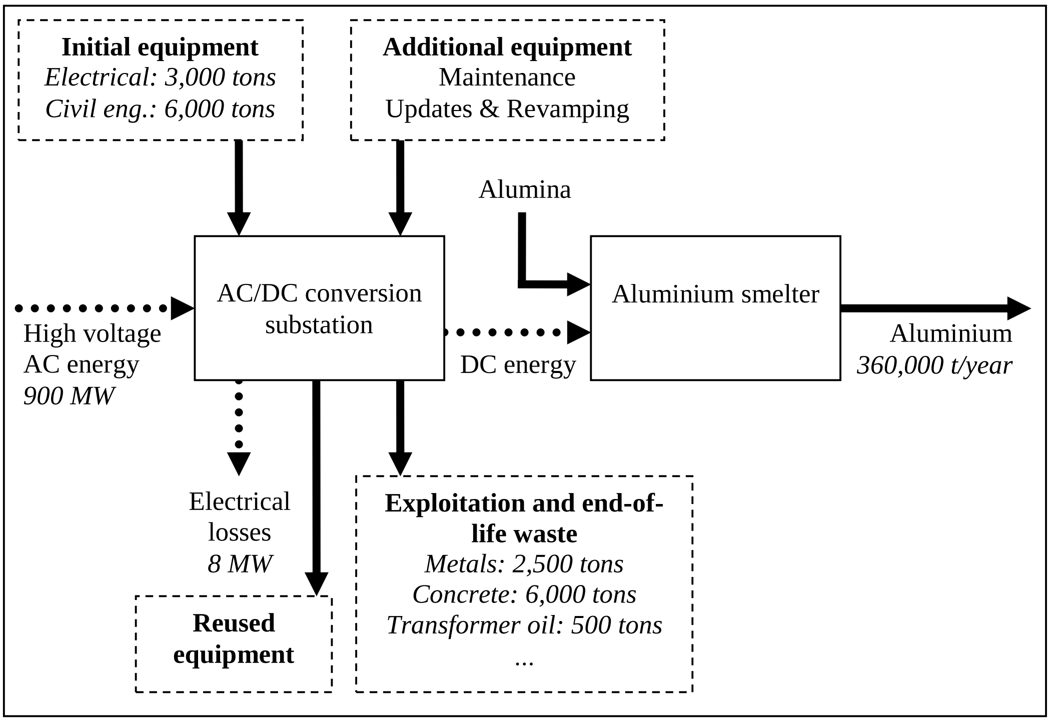

Figure 6. Overview of the flows associated with a substation life cycle. (Figures rounded off for confidentiality reasons)

Alstom Grid PEM (Power Electronics Massy) designs, assembles and sells substations for the electrolysis of aluminium worldwide. These are electrical stations designed to convert energy from the high voltage network to energy that can be used for aluminium electrolysis, which for the environment is a particularly high-impact and energy-consuming activity. An electrolysis substation represents thousands of tons of power electronics components and transformers, costing tens of millions of Euros.

It is made up of several groups that are composed of a regulating transformer, a rectifier transformer and a rectifier. The groups are connected on one side to the high voltage network through an electrical substation and on the other side to a busbar that is directly connected to the electrolysis potline. All the groups are supervised by control elements that are connected to the electrolysis pots to regulate the process. The amount of energy consumed by a recent primary aluminium plant is comparable to the amount of energy delivered by a nuclear plant unit (more than 1 GW). Key elements of such a substation life cycle are given on Figure 6.

These substations are considered to be complex industrial systems because:

- The number of subsystems and components is considerable. Some subsystems could themselves be considered as complex industrial systems (like transformers or rectifiers).

- The lifetime of a substation is considerable, up to 35 or 40 years. Many uncertainties exist for the use and end-of-life phases. No end-of-life scenario is clearly known.
- The substation is only a part of the aluminium plant. Their processes are closely connected and interdependent.
- No standard design exists: the substation is tailor-made for each customer, even though the general design is often the same. Substations are considered as a product family.

In this context, Alstom Grid PEM wishes to minimise the environmental impacts of its products to conform to Alstom's environmental policy and to be differentiated from competitors. A first global Life Cycle Assessment has already been performed on an entire substation (Cluzel et al., 2012). This LCA is the basis for the eco-innovation process described below.

4.2 Eco-innovation process deployment

The eco-innovation approach was deployed at Alstom Grid following the time line described in Figure 7. The whole process lasted about 10 weeks.

The working group included two persons from the R&D department, one person from the Engineering department, one person from the Commercial department, two persons from the R&D department of another Alstom Grid unit providing the transformers of the substations, and one academic eco-design expert. These persons were chosen in coordination with the department managers in order to have a complete knowledge of a substation. They are mainly junior experts on one specific substation aspect, or senior experts with a global vision of the system life cycle. These persons are not familiar with creativity tools and session and they were chosen according to their expertise and their motivation. Support was given by the R&D department and by the other departments, which authorized involvement of their experts in the process.

The animation was managed by two junior eco-design experts, who did not propose ideas during the creativity session. So the eco-innovation process involved in total 9 persons.

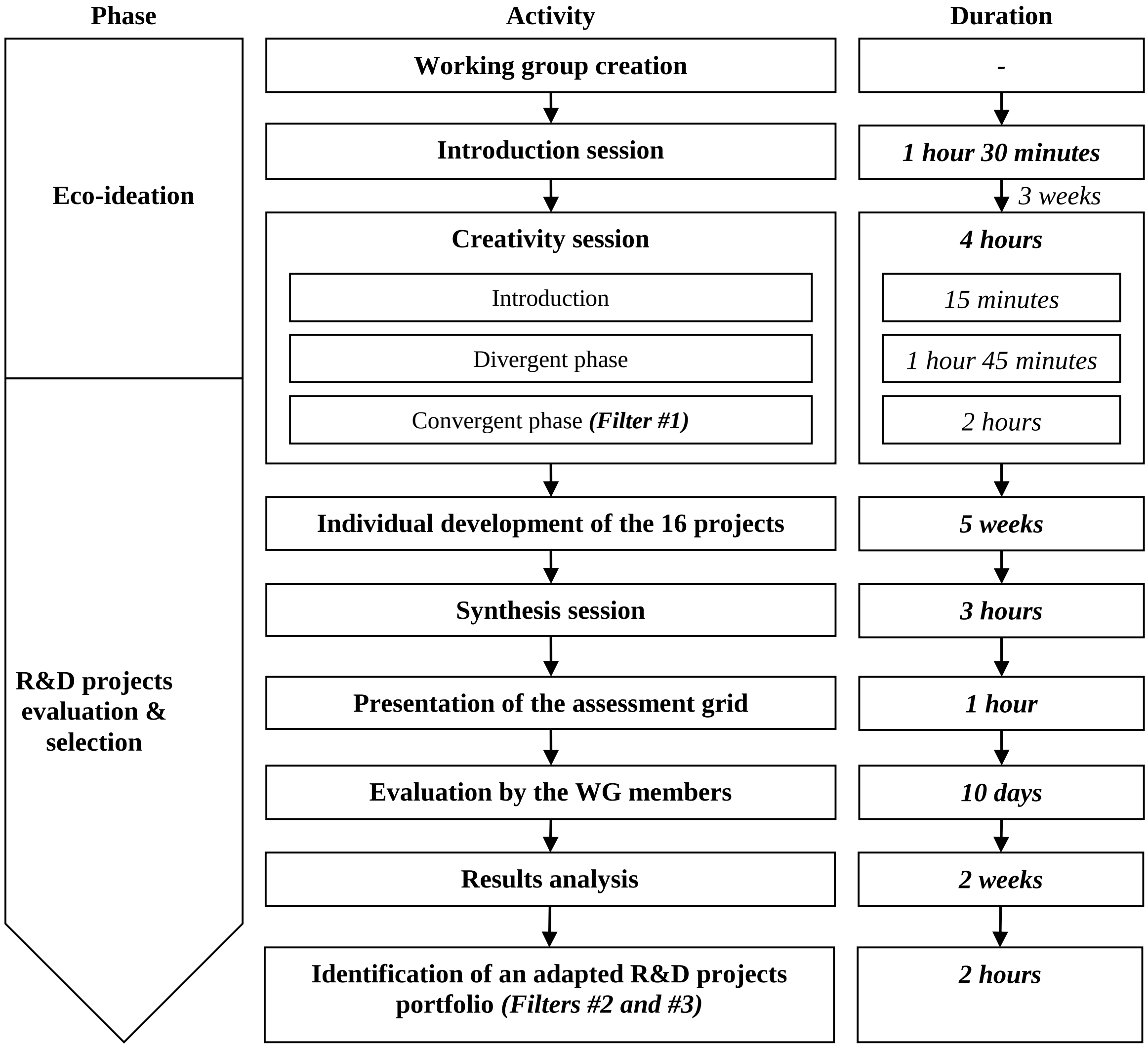

Figure 7. Time line of the eco-innovation process at Alstom Grid PEM

Soft environmental information was given to the working group during the introduction session, in the form of a short description of the main environmental issues, certain eco-design principles and examples, and the main conclusions of the first LCA study on substations. Three weeks were then given to the working group to ‘assimilate the information.

The creativity session was divided into three parts. First, some reminders of the introduction session, the creativity rules and the eco-design strategy wheel were presented during a short introduction

Then during the divergent phase each axis of the eco-design strategy wheel was considered during a 15-minute session. Two axes of the eco-design strategy wheel were not processed during the creativity session (‘Optimization of production techniques’ and ‘Optimization of distribution system’) as the members did not have competencies in these fields, and production is carried out by subcontractors.

16 eco-innovative projects were then selected at the conclusion of the convergent phase, where each idea was reconsidered according to Figure 3. These projects were developed over a five-week period and synthetized in predefined sheets during the synthesis session. Projects deal for example with a long-term optimization of transformers (200 tons of metals and mineral oil each), heat loss recovery or material substitution.

The final step of the approach consisted in assessing and selecting the most promising projects in order to build an adapted eco-innovative R&D project portfolio. This process in described in greater detail in the next section.

4.3 Choice of an optimized eco-innovative R&D project portfolio

At this stage 16 projects were selected, as shown in Figure 8. Then they were assessed by the working group members in order to restrict the portfolio to the most promising ones, some of them appearing indeed limited concerning some dimensions after development. The assessment grid was filled out and the competence weights associated with each member and each project were calculated to obtain the final thematic average scores for each project. The diagrams presented in section 3.4 were drawn to support the decision-making.

By running with consensual threshold values the second filter described in section 3, a short process resulted in twelve projects being selected that were considered as the best compromises between environmental performance, feasibility and customer values. Figure 9 and Figure 10 show some graphical results from the same results, used to assist the decision-makers is the company. Figure 9 represents the global environmental score with the associated uncertainty range for each project, while Figure 10 is another way of representing the same data. When two uncertainty ranges overlap, there is undecidability. For example, Project 7 dominates, while it is not possible to determine if Project 14 is better than Project 5.

Once this portfolio including twelve projects was identified, the last step consisted in controlling the balance of the portfolio. The projects were judged as well balanced with regards to their time horizon (short/middle/long term), as well as their nature (organizational/methodological/technological). However regarding their perimeter, it was noticed that no project concerned component aspects. But in the initial set of preselected projects, only one concerned a component and it was clearly not feasible. That is why the proposed portfolio was deemed satisfactory by the decision-makers and it was proposed to the company management for further planning and implementation.

The next section provides elements to validate the eco-innovation process according to the four criteria defined by Shah et al. (2003).

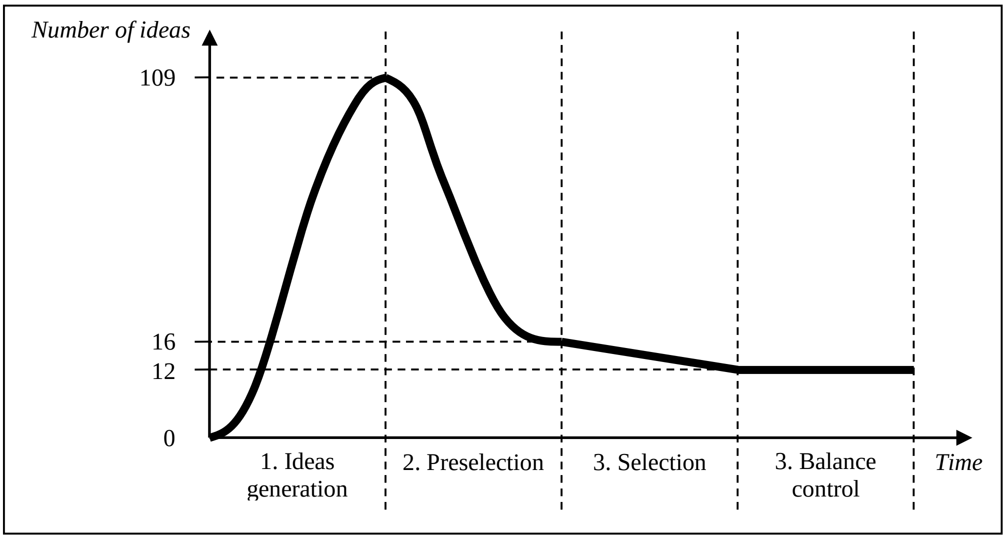

Figure 8. Evolution of the ideas number according to the process stages

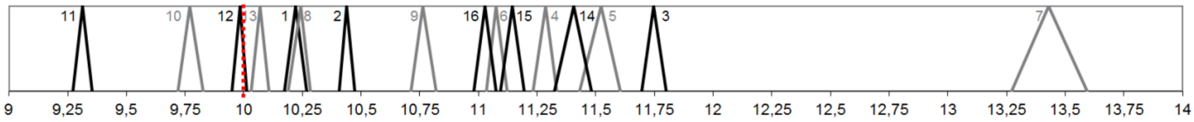

Figure 9. Positioning of the 16 projects and their uncertainty grade according to their global environmental score. The threshold value was fixed at 10 according to the strategy of the company and the global distribution of the projects.

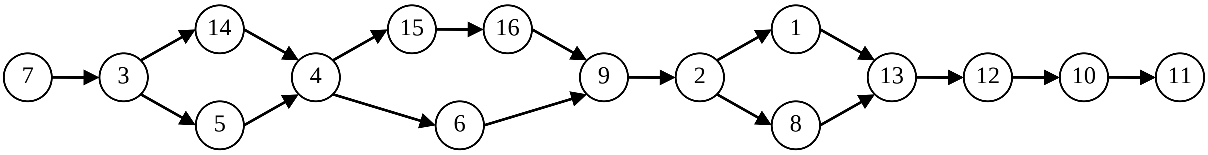

Figure 10. Outranking diagram of the 16 projects according to their global environmental score.

4.4 Methodology validation

4.4.1 Quantity

109 ideas were generated during the creativity sessions. Each axis of the eco-design strategy wheel provided between 10-23% of these ideas. Each active member of the working group proposed between 8 and 35 ideas. Relative to the time spent in the divergent session (1 hour and 45 minutes), this result is considered as highly satisfactory.

After the convergent session, 16 eco-innovative projects were identified, and a final portfolio comprised of 12 projects was proposed to the top management of the company. These numbers were consistent with company requirements and it was also judged as satisfactory.

4.4.2 Variety

Table 2. Synthesis of the time horizon, project perimeter and project nature aspects of the 12 final selected projects. For the project nature, M means methodological, T technological and O organizational.

Project No.	Time horizon	Project perimeter	Project nature
3	Long term	Subsystem	M, T, O
4	Middle term	System	T
5	Short/middle term	Subsystem	T
6	Long term	Subsystem	T
7	Middle term	System	M, O
8	Short term	Subsystem	M
9	Short/middle term	System	M, T
12	Middle term	System	M, T
13	Short term	System	M
14	Long term	System	M, T
15	Middle/long term	Subsystem	T
16	Middle/long term	Super-system	M, T

The variety of the final portfolio is ensured through the portfolio balance control step (third filter, see Figure 5). Table 2 shows that the twelve selected projects are well balanced in terms of time horizon and project nature. Concerning the project perimeters, only projects dealing with systems, subsystems or super-systems are represented. No project concerns component aspects, which may be associated with the fact that the eco-innovation process considers the whole system at a high level, and it is therefore hard to manage component aspects at this stage. But the realization of these projects may allow the emergence of component-related environmental issues that may be considered in the future.

These results are considered as highly satisfactory, as the portfolio including the 12 projects is relatively well balanced on all three criteria. All categories are represented. A consensus is almost always found for the 'time horizon' criteria, which was the only one evaluated by the working group.

4.4.3 Novelty

For 7 of the 16 projects, a majority of the working group considered that they did not have the projects in mind before initiating the eco-innovation process, whereas 7 other projects were predominantly considered as already present in their mind, but in an unstructured way, i.e. neither shared with other people nor written down somewhere. For the three last projects it was not possible to determine the answer.

Concerning the answer to the second question, 11 projects would not have emerged without the eco-innovation process, even if they were present is some people's mind. Only 2 projects would have emerged without the process, and for 3 projects it was not possible to determine the answer.

These results clearly show that new ideas may emerge from the proposed eco-innovation process. They also show that this process seems to be an excellent way to formalize preexisting ideas that would not have emerged otherwise. The approach is thus satisfactory on the novelty potential too.

4.4.4 Quality

The quality of the process is assessed using the designer's evaluation of the 16 projects according to three criteria (environmental benefits, feasibility, client's value).

The results for the environmental benefits show that the average score is 10.8 (out of 20), but with a low standard deviation (0.98). This means that the 16 projects propose environmental improvements on some axes of the eco-design strategy wheel, but no generalized environmental improvements. This clearly characterizes incremental eco-innovations. But it also shows that the environmental qualitative scales are not sensitive enough to accurately assess the differences between the projects.

For the feasibility criteria, the average score is 12.1 and the standard deviation is considerably higher (2.76). The projects show a good range on the scale (from 4.1 to 15.9) showing that the proposed qualitative indicators are sufficient to distinguish the projects.

Finally, the results for the client's value criterion show that the average score reaches 11.0 with a standard deviation at 1.42. As for environmental benefits, it is more difficult to distinguish between the 16 projects. But considering that only incremental eco-innovations have been identified, it could be explained by the fact that the projects would only bring little benefit for the client's value.

5. Discussion

The definition and the use of the third formalized filters thus appear relevant to ensure good performances of the process according to the four criteria proposed by Shah et al. (2003): quantity, variety, novelty and quality. But beyond the previous validation of the proposed eco-innovation process, it is useful to go further by testing the robustness of the model.

Concerning the first filter, the discussion may concern the number of projects to preselect for the second filter. In the case study presented in this paper, if 32 projects had been selected instead of 16, the amount of work to develop these projects would have been too large for the capacity of the working group. The number of projects clearly needs to be defined by the company from the available resources and to be aligned with its strategy. This is the best way to adjust the process to its organization. On the contrary, if only 8 projects had been selected when about

15 projects were required by the company, the problem would again have been different. Indeed it means that no consensus has been identified in the working group, and it shows the poor quality of the initial ideas. One possible answer here consists in adopting a more adapted and specific, but maybe more complex ideation tool than the eco-design strategy wheel, meeting one previous comment made in section 3.

A second assessment of the environmental performance of the projects (corresponding to the second filter) was performed with a group of four eco-design experts that were not part of the working group. They are Alstom Grid experts from units other than PEM, working on other large electrical systems and products. One of these experts is the sustainable development director of Alstom Grid, and another one the eco-design director of Alstom Grid. The two other experts are eco-design engineers. These four experts only assessed the environmental aspects of the 16 preselected projects as they do not have a lot of available time and the assessment of the feasibility and customer aspects would have required a lot of additional information.

Contrary to the first experiment with the working group, where the results obtained on the environmental dimension do not clearly rank the projects, the distribution of the 16 preselected projects with the external experts is much more readable. The average score is 11.1, with a standard deviation reaching 1.95. The order of the projects is different from the working group results, but global tendencies are shared. The external experts have good eco-design skills but no specific knowledge of the technical aspects of substations. This is another point of view, which adds a richer dimension to the initial results.

By running the third filters with the environmental assessments of the external experts instead of the assessments of the working group, with the same rules, a portfolio of 9 projects is obtained. These 9 projects are included in the first portfolio of 12 projects defined in section 4.4 from the working group results. For the other three projects, significant differences were noticed between the two groups, but these projects were clearly not included in the first ones. As a conclusion to this test, the multi-criteria model shows a satisfactory robustness concerning the evaluation of the environmental performance of the project, which is the key objective of the eco-innovation process. But as the assessment of the environmental benefits of the project with the working group could be improved (see section 4.4.4), it was suggested to the company to combine the evaluations of the working group with the evaluations of the external experts, leading to a final portfoli of 9 projects. The eco-innovation process has thus been improved with the contribution of an expert point of view. The environmental pertinence of the selected projects is justified by both internal and external decision-makers, with a significant robustness of the approach.

As a conclusion, the proposed methodology brings to complex systems industries the ability to develop and plan an ambitious R&D program based on eco-innovative projects. Contrary to existing eco-innovation methods and tools, this methodology is not centred on the identification of eco-innovative solutions. It aims at identifying promising areas to investigate in order to develop a balanced eco-innovative R&D projects portfolio, when the system complexity implies long term developments and knowledge and skills broken up between numerous people and departments. One main limitation of this work concerns the relatively weak ability of the eco-design strategy wheel to generate radical eco-innovations. More powerful tools do exist, but the constraint is to keep the same level of simplicity to make the process accessible for non eco-design experts. The application of the methodology in only one industrial context is another limitation that should be considered for future research.

6. Conclusions and perspectives

Starting from the statement that eco-innovation methods are not adapted to complex industrial and technological systems, an adapted eco-innovation process based on a simple tool has been proposed. This process includes two main stages:

- An eco-ideation phase involving a multidisciplinary working group and a creativity session based on the eco-design strategy wheel proposed in (Brezet and Van Hemel, 1997).
- A multi-criteria assessment phase performed by the working group, considering not only environmental aspects, but also technical and economic feasibility, client's value, project perimeter and time horizon.

This process was applied at Alstom Grid on large electrical substations. The results were very satisfactory as this method enabled a high number of ideas with limited time and resources to be obtained. From these ideas, a balanced eco-innovative R&D project portfolio was identified, mainly composed of ideas that would not have emerged without the method, but also of some new ideas. The assessment grid seems satisfactory for the feasibility and client aspects. However, the sensitivity of the environmental indicators was not sufficient to assess the projects, as the constraints associated with complex industrial systems favored incremental eco-innovations.

Further work has been completed, taking into account the contribution of external eco-design experts in order to obtain more accurate results for environmental aspects. A final portfolio of 9 projects was proposed to the company management, and the first projects will probably be implemented in the coming months.

Two perspectives may be considered for future work:

- This paper focused on the overall eco-innovation process and how to assess and select the best ideas, rather than on the ideation phase itself. The eco-design strategy wheel offers acceptable performance, but it is not particularly adapted for radical innovations. Further research could, for example, apply the proposed eco-innovation process with other eco-ideation tools, like Eco-ASIT (Tyl, 2011).
- It could also be interesting to develop the robustness analysis by applying the approach in different companies and on a different complex industrial system, for example in the aeronautic, automotive or energy generation industries.

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Appendix

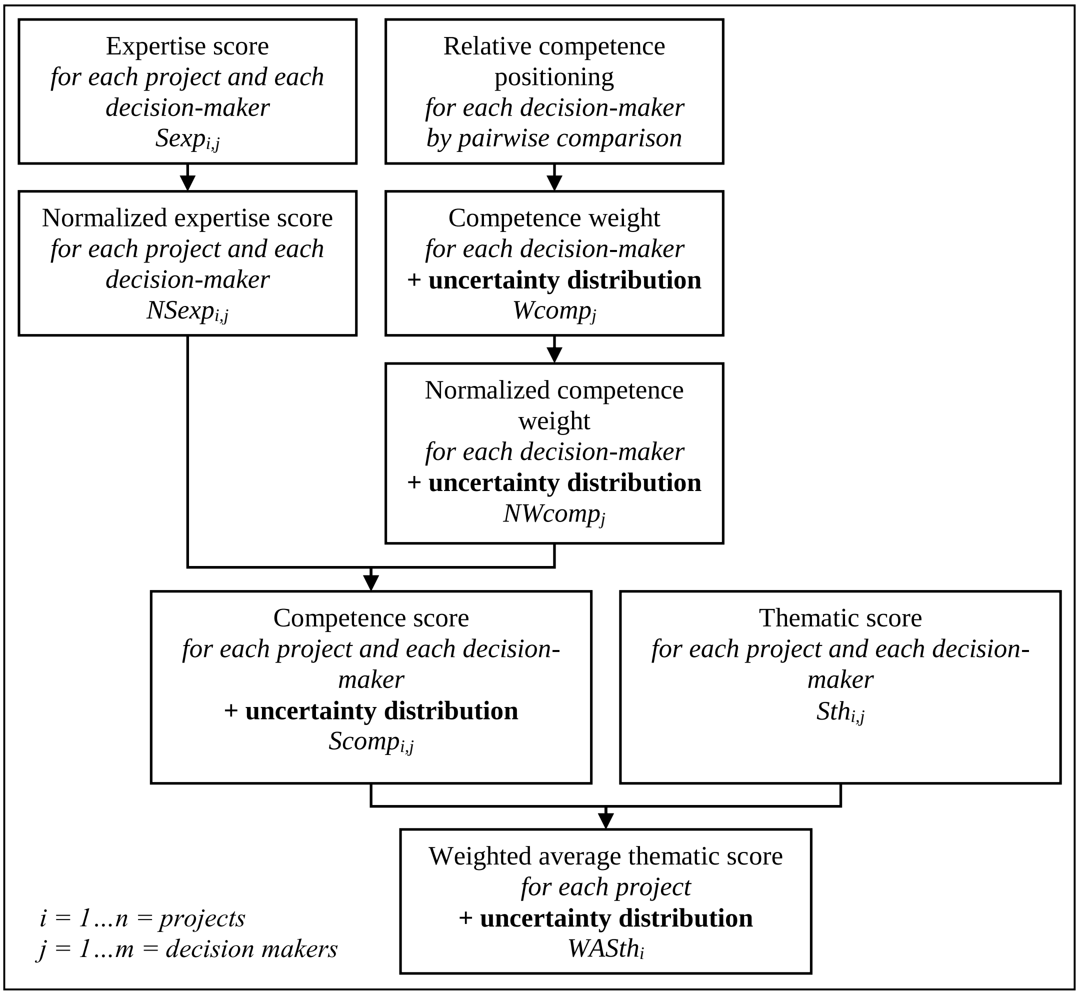

Figure 11. Calculation of the thematic (environment, feasibility, customers' value) scores in mutlticriteria assessments

The indices *i* correspond to the assessed projects, whereas the indices *j* correspond to the decision makers (members of the working group or external experts).

Each decision-maker first defines his/her expertise score (from 1 to 4) for each project, called $Sexp_{i,j}$. As all the decision-makers do not allocate the same number of expertise weights, these scores are then normalized on 50 points and they become $NSexp_{i,j}$ in formula (1):

$$NSexp_{i,j} = \frac{Sexp_{i,j} \times 50}{\sum_i Sexp_{i,j}} \tag{1}$$

Next, the decisions-makers are asked to compare themselves relative to the other working group members in terms of global competence. This assessment is performed through the use of a pairwise comparison approach. The process of pairwise comparisons (PC) starts with the completion of a PC matrix (see Figure 12a). Let us now consider that some decision-makers (corresponding to rows) are compared with themselves (corresponding to columns) for their competence level. The subjects are asked to provide a number of competence pairwise comparisons, not necessarily all of them; it is tolerated that the PC matrix be scarce. These comparisons are qualitative assessments in a 7-level scale (much less, less, slightly less, equal, slightly more, more, much more) noted (<<<, <<, <, =, >, >>, >>>) (see (Limayem and Yannou, 2002)). For instance, a "<" at the location (row #1, column #2) means "the competence of expert#1 is slightly less than the one of expert#2". In practice, this symbolic scale is indexed onto a numerical scale (10%, 25%, 40%, 50%, 60%, 75%, 90%) corresponding to the estimation of the relative part of the score of expert *i* (on row *i*) over the sum of both scores of expert *i* and expert *j* (on column *j*). Let us note c^*_{ij} such a comparison on row *i* and column *j*. Then, c^*_{ij} is an estimation of the quantity $w_i/(w_j+ w_i)$, w_i and w_j standing for the scores for expert *i* and expert *j*. Let us operate a transformation into score ratios such that (see formula (2)):

$$c_{\mathrm{ij}} \approx \frac{\mathrm{w_i}}{\mathrm{w_j}} = \frac{-1}{1-\frac{1}{\mathrm{c}^*_{ij}}} \qquad (2)$$

Then, one proceeds to a Least Squares Logarithmic Regression (LSLR) of the PC matrix such as that proposed by (De Graan, 1980) and (Lootsma, 1981). It consists in minimizing the cumulated square distance between the logarithmic terms of the estimation of the score ratio c_{ij} and of the actual score ratio w_i/w_j, The result of this process is the competence weight vector. But, as all the experts do not have the same evaluation of a given comparison between two experts, one rather considers a triangular distribution for each comparison c^*_{ij} limited by $\min_k\left(c^*_{\mathrm{ijk}}\right)$ and $\max_k\left(c^*_{\mathrm{ijk}}\right)$ and with a modal value $\overline{c^*_{\mathrm{ijk}}}$. Then, the MCPC method (Monte Carlo Pairwise Comparison) is used as in (Limayem and Yannou, 2002) to result in a competence weight distribution $Wcomp_j$ (see Figure 12b).

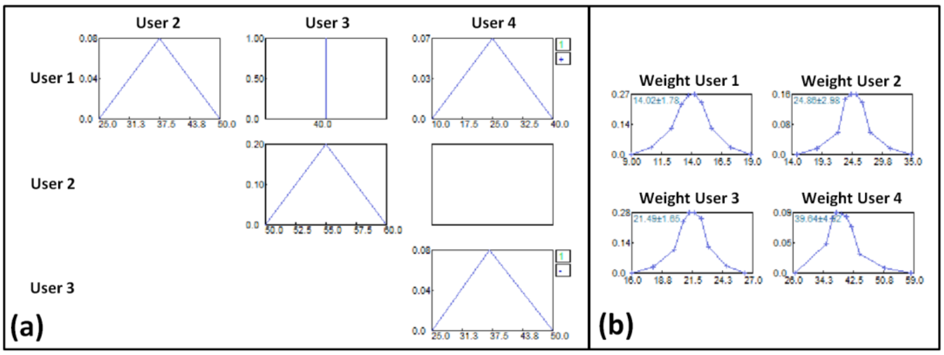

Figure 12. Example of a pairwise comparison matrix (a) and the corresponding competence weights distributions (b)

A Monte Carlo simulation is further performed with 10 000 runs to measure the uncertainty range on the thematic scores. Each Monte Carlo run is renormalized so that the sum of the weights remains 100. $NWcomp_j$ is obtained in formula (3):

$$NWcomp_j = \frac{Wcomp_j \times 100}{\sum_j Wcomp_j} \quad (3)$$

Finally a competence score $Scomp_{i,j}$ is calculated in formula (4) for each project and each decision-maker, for the 10 000 Monte Carlo runs:

$$Scomp_{i,j} = NSexp_{i,j} \times NWcomp_j \quad (4)$$

The $Scomp_{i,j}$ represent the expertise shared by each decision maker on each project. They are used to weight the thematic scores $Sth_{i,j}$ of each decision-maker on each project, from the assessment grid. Thus the weighted and average thematic scores $WASth_i$ are expressed in formula (5):

$$WASth_i = \frac{\sum_j Scomp_{i,j} \times Sth_{i,j}}{\sum_j Scomp_{i,j}} \quad (5)$$

Among the 10 000 Monte Carlo runs, the minimum and maximum $WASth_i$ are identified, as well as the score resulting from the modes of the triangular distribution (which corresponds to the most likely value), in order to rebuild the uncertainty distribution proposed in the graphical results (see for example Figure 9). So if two distributions overlap each other, there is a case of undecidability.