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Eco-design implementation for complex industrial systems

From scenario-based LCA to the definition of an eco-innovative R&D projects portfolio

Mise en œuvre de l'éco-conception pour des systèmes industriels complexes

De l'ACV par scénarios à la définition d'un portefeuille de projets de R&D éco-innovants

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devant un jury composé de :

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Abstract

Face to the growing awareness of environmental concerns issued from human activities, eco-design aims at offering a satisfying answer in the products and services development field. However when the considered products become complex industrial systems, there is a lack of adapted methodologies and tools. These systems are among others characterised by a large number of components and subsystems, an extremely long and uncertain life cycle, or complex interactions with their geographical and industrial environment. This change of scale actually brings different constraints, as well in the evaluation of environmental impacts generated all along the system life cycle (data management and quality, detail level according to available resources…) as in the identification of adapted answers (management of multidisciplinary aspects and available resources, players training, inclusion in an upstream R&D context…). So this dissertation aims at developing a methodology to implement eco-design of complex industrial systems. A general methodology is first proposed, based on a DMAIC process (*Define, Measure, Analyse, Improve, Control*). This methodology allows defining in a structured way the framework (objectives, resources, perimeter, phasing…) and rigorously supporting the eco-design approach applied on the system. A first step of environmental evaluation based on Life-Cycle Assessment (LCA) is thus performed at a high systemic level. Given the complexity of the system life cycle as well as the exploitation variability that may exist from one site to another, a scenario-based approach is proposed to quickly consider the space of possible environmental impacts. Scenarios of exploitation are defined thanks to the SRI (Stanford Research Institute) matrix and they include numerous elements that are rarely considered in LCA, like preventive and corrective maintenance, subsystems upgrading or lifetime modulation according to the economic context. At the conclusion of this LCA the main impacting elements of the system life cycle are known and they permit to initiate the second step of the eco-design approach centred on environmental improvement. A multidisciplinary working group perform a creativity session centred on the eco-design strategy wheel (or Brezet wheel), a resource-efficient eco-innovation tool that requires only a basic environmental knowledge. Ideas generated during creativity are then analysed through three successive filters allowing: (1) to pre-select and to refine the best projects; (2) to build a R&D projects portfolio thanks to a multi-criteria approach assessing not only their environmental performance, but also their technical, economic and customers' value creation performance; (3) to control the portfolio balance according to the company strategy and the projects diversity (short/middle/long term aspect, systemic level…). All this work was applied and validated at Alstom Grid on electrical conversion substations used in the primary aluminium industry. The methodology deployment has allowed initiating a robust eco-design approach recognized by the company and finally generating a portfolio composed of 9 eco-innovative R&D projects that will be started in the coming months.

Key-words: Eco-design, Life-Cycle Assessment (LCA), Eco-innovation, Complex industrial system, Scenario-based LCA, Exploitation scenario, Eco-ideation, R&D projects portfolio, AC/DC conversion substation.

Résumé

Face à l'émergence des problématiques environnementales issues des activités humaines, l'éco-conception s'attache à offrir une réponse satisfaisante dans le domaine de la conception de produits et services. Cependant, lorsque les produits considérés deviennent des systèmes industriels complexes, caractérisés entre autres par un grand nombre de composants et sous-systèmes, un cycle de vie extrêmement long et incertain, ou des interactions complexes avec leur environnement géographique et industriel, un manque évident de méthodologies et d'outils se fait ressentir. Ce changement d'échelle apporte en effet des contraintes différentes aussi bien dans l'évaluation des impacts environnementaux générés au cours du cycle de vie du système (gestion et qualité des données, niveau de détail de l'étude par rapport aux ressources disponibles…) que dans l'identification de réponses adaptées (gestion de la multidisciplinarité et des ressources disponibles, formation des acteurs, inclusion dans un contexte de R&D très amont…). Cette thèse vise donc à développer une méthodologie de mise en œuvre d'une démarche d'éco-conception de systèmes industriels complexes. Une méthodologie générale est tout d'abord proposée, basée sur un processus DMAIC (*Define, Measure, Analyse, Improve, Control*). Cette méthodologie permet de définir de manière formalisée le cadre de la démarche (objectifs, ressources, périmètre, phasage…) et d'accompagner rigoureusement l'approche d'éco-conception sur le système considéré. Une première étape d'évaluation environnementale basée sur l'Analyse du Cycle de Vie (ACV) à haut niveau systémique est ainsi réalisée. Etant donnée la complexité du cycle de vie considéré et la variabilité d'exploitation d'un système industriel d'un site à l'autre, une approche par scénario est proposée afin d'appréhender rapidement l'étendue possible des impacts environnementaux. Les scénarios d'exploitation sont définis à l'aide de la matrice SRI (Stranford Research Institute) et intègrent de nombreux éléments rarement abordés en ACV, comme la maintenance préventive et corrective, la mise à niveau des sous-systèmes ou encore la modulation de la durée de vie du système en fonction du contexte économique. A l'issue de cette ACV les principaux postes impactants du cycle de vie du système sont connus et permettent d'entreprendre la seconde partie de la démarche d'éco-conception centrée sur l'amélioration environnementale. Un groupe de travail multidisciplinaire est réuni lors d'une séance de créativité centrée autour de la roue de la stratégie d'éco-conception (ou roue de Brezet), un outil d'éco-innovation peu consommateur de ressources et ne nécessitant qu'une faible expertise environnementale. Les idées générées en créativité sont alors traitées par trois filtres successifs, qui permettent : (1) de présélectionner les meilleurs projets et de les approfondir ; (2) de constituer un portefeuille de projets de R&D par une approche multicritère évaluant leur performance environnementale, mais également technique, économique et de création de valeurs pour les clients ; (3) de contrôler l'équilibre du portefeuille constitué en fonction de la stratégie de l'entreprise et de la diversité des projets considérés (aspects court/moyen/long terme, niveau systémique considéré…). L'ensemble des travaux a été appliqué et validé chez Alstom Grid sur des sous-stations de conversion électrique utilisées dans l'industrie de l'aluminium primaire. Le déploiement de la méthodologie a permis d'initier une démarche solide d'éco-conception reconnue par l'entreprise et de générer au final un portefeuille de 9 projets de R&D éco-innovants qui seront mis en œuvre dans les prochains mois.

Mots-clés : Eco-conception, Analyse du Cycle de Vie (ACV), Eco-innovation, Système industriel complexe, ACV par scénarios, scénario d'exploitation, Eco-idéation, Portefeuille de projets de R&D, Sous-station de conversion AC/DC.

A mes parents, qui m'ont permis de parcourir sans encombre ces premières phases du cycle de ma vie,

A Lucie, Eleanor, Adam & Valentine, la fameuse génération future de Brundtland…

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List of abbreviations

AC/DC	Alternative Current/Direct Current
DMAIC	Define, Measure, Analyse, Improve, Control
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PEM	Power Electronics Massy
POEMS	Product-Oriented Environmental Management System
R&D	Research & Development
SD	Sustainable Development

Foreword

This PhD thesis dissertation formalizes my work performed at Ecole Centrale Paris and Alstom Grid (formerly Areva T&D) under a CIFRE (*Conventions Industrielles de Formation par la REcherche*) contract between May 2009 and May 2012.

The dissertation is presented as a series of scientific papers published or submitted for publication in international journals. General chapters ensure introductions and logical links between the papers.

The following paper included in the dissertation has been published:

- Cluzel F., Yannou B., Leroy Y., Millet D., 2012, “Proposition for an Adapted Management Process to Evolve from an Unsupervised Life Cycle Assessment of Complex Industrial Systems Towards an Eco-Designing Organisation”, *Concurrent Engineering: Research and Applications*, 20 (2), pp 111-126.

The following papers included in the dissertation have been submitted for publication:

- Cluzel F., Yannou B., Millet D., Leroy Y., “Exploitation scenarios in industrial system LCA”, submitted to *the International Journal of Life Cycle Assessment*.

- Cluzel F., Yannou B., Millet D., Leroy Y., “Eco-ideation and eco-selection of R&D projects portfolio in complex systems industries”, submitted to *Technovation*.

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Résumé étendu (extended summary in French)

L'humanité est aujourd'hui plongée dans une crise multidimensionnelle dont l'aspect écologique n'est qu'une des multiples facettes. Les activités humaines ont pour la première fois dans l'histoire de l'humanité un tel impact sur l'environnement que celui-ci est peut-être irrémédiablement touché. Cependant, cette crise apparaît également comme une opportunité extraordinaire pour initier une transition vers une société durable (Morin, 2011). Cette transition, nommé par Rifkin *troisième révolution industrielle* (Rifkin, 2010) doit bien sûr être initiée par des décisions politiques, mais le secteur industriel y occupe une place prépondérante et peut dès maintenant engranger le processus.

L'équation *I=PAT*, issue des travaux de Ehrlich et Holdren (Ehrlich and Holdren, 1971), illustre parfaitement cette problématique. Dans cette équation, *I* représente les impacts des activités humaines sur l'environnement, *P* la population humaine, *A* l'abondance matérielle, associée au revenu moyen par habitant, et *T* la technologie. Ainsi, *I* dépend directement des trois autres variables, et l'étude de différents scénarios à l'horizon 2050 montre que la société actuelle, centrée sur la croissance économique, est difficilement compatible avec la limitation des effets du réchauffement planétaire (Kempf, 2011; Da Costa and Iacona, 2012). Mais l'évolution des impacts des activités humaines est également directement liée à l'évolution des technologies, et un levier particulièrement intéressant pour limiter ces impacts consiste à accélérer l'amélioration de l'efficacité des technologies humaines. Ce constat touche donc directement au domaine de l'innovation dans la conception de produits.

Dans cette perspective, l'éco-conception, c'est-à-dire l'intégration de la dimension environnementale dans la conception de produits, apparaît comme une réponse pertinente à cette problématique. Par ailleurs, et en dehors de ces considérations, les réglementations – Européennes en particulier – évoluent peu à peu vers cette prise en compte de l'environnement dans la conception, et de nombreuses entreprises sont maintenant convaincus de la nécessité de l'intégrer dans leurs processus pour préserver leur compétitivité face aux marchés globalisés.

Cependant les démarches d'éco-conception existantes sont bien souvent conçues pour et appliquées sur des produits de grande consommation, de taille et complexité limitées. Les systèmes industriels complexes ont ainsi été rarement considérés, ou du moins les méthodologies et outils existants ne leur sont pas particulièrement adaptés. Cela est particulièrement valable pour l'Analyse du Cycle de Vie (ACV), dont les limites habituellement rencontrées sont amplifiées lorsque de tels systèmes sont considérés. Cette thèse s'intéresse donc au développement d'une méthodologie d'éco-conception adaptée aux systèmes industriels complexes, incluant à la fois une phase d'évaluation environnementale et une phase d'amélioration environnementale.

Positionnement de recherche

Cette recherche a été financée par Alstom Grid et réalisée dans le cadre d'un contrat CIFRE (*Conventions Industrielles de Formation par la REcherche*) entre Alstom Grid et le Laboratoire Génie Industriel (LGI) de l'Ecole Centrale Paris, entre mai 2009 et mai 2012. Les préoccupations industrielles occupent donc une grande place dans ces travaux. C'est pourquoi cette recherche est bâtie sur un protocole de Recherche Action, ce qui signifie que nous sommes intervenus directement et activement dans l'entreprise. Ce positionnement apparaît comme un bon compromis entre les besoins industriels exprimés par Alstom Grid et le développement de méthodologies et outils génériques du côté académique.

L'objectif de cette thèse est de développer une méthodologie adaptée à la mise en œuvre d'une démarche d'éco-conception de systèmes industriels complexes. Elle a été réalisée en suivante les 4 étapes proposées par Yannou et Petiot dans le cadre de la Recherche Action (Yannou and Petiot, 2011) :

1. *Observation des pratiques de conception industrielles pour réaliser un diagnostic terrain :* pour cela, nous avons été pleinement intégrés au département R&D de l'unité Power Electronics Massy d'Alstom Grid, ainsi qu'au groupe de travail en éco-conception d'Alstom Grid. Nous avons ainsi pu observer les pratiques industrielles en place chez Alstom Grid, ainsi que le cadre réglementaire et normatif, les méthodologies et outils d'éco-conception utilisés dans l'industrie.

2. *Généralisation du diagnostic terrain à des problématiques scientifiques et réalisation d'états de l'art :* à l'issue du diagnostic terrain, trois questions de recherche ont été définies, qui ont permis de définir différents terrains de recherche sur lesquels des études bibliographiques ont été réalisées.

3. *Proposition d'un nouveau modèle :* à l'issue de la précédente étape, trois axes de recherche ont été définis et mis en œuvre pour répondre aux questions de recherche à la lumière des études bibliographiques.

4. *Déploiement et validation dans le cadre industriel :* enfin, les objets théoriques développés lors de l'étape précédente ont été appliqués dans le contexte industriel d'Alstom Grid, ce qui a permis de tirer des conclusions, d'identifier les limites de notre approche et les futurs développements possibles.

A la lumière du diagnostic terrain et de l'étude des pratiques actuelles d'éco-conception en entreprise, les trois questions de recherche sont les suivantes :

- *Question de recherche n°1 :* **Comment gérer avec un temps et des ressources limités le déploiement d'une démarche d'éco-conception d'un système industriel complexe, sans compétences et connaissances environnementales**

préalables ?

- *Question de recherche n°2 :* **Comment réaliser une ACV fiable d'un système industriel complexe à un haut niveau systémique et avec des ressources et un temps limités ?**
- *Question de recherche n°3 :* **Comment générer et sélectionner un portefeuille adapté de projets de R&D éco-innovants pour des systèmes industriels complexes ?**

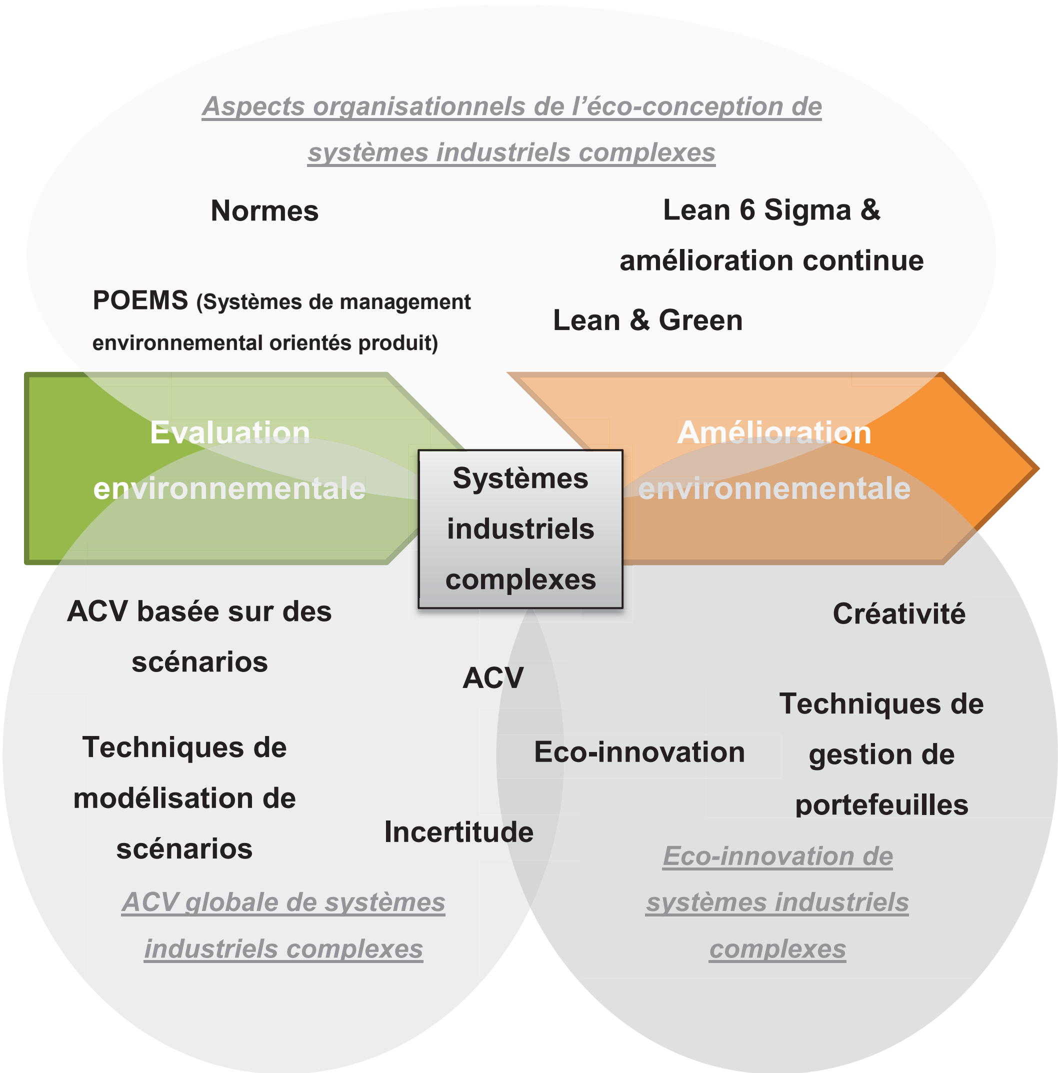

Figure 1. Positionnement des domaines bibliographiques explorés

La définition de ces questions de recherche a permis d'identifier et d'investiguer différent domaines bibliographiques, représentés sur la Figure 1. A l'issue de cet état de l'art, trois axes de recherche ont été définis.

Trois axes de recherche

Les trois axes de recherche sont interdépendants et complémentaires. Ces liens sont explicités dans la Figure 2. Le premier axe permet de mettre en place, de suivre et de gérer de manière rigoureuse un processus complet d'éco-conception, comprenant une étape d'évaluation de la performance environnementale du système et une étape d'amélioration de cette performance. L'axe 2 s'intègre dans la phase d'évaluation environnementale en proposant un modèle d'ACV adaptés aux systèmes industriels complexes. A partir de l'identification des principaux postes impactants issus de l'ACV, l'axe 3 se positionne dans la phase d'amélioration environnementale en proposant un modèle d'éco-innovation adapté. Le contenu des modèles développés au sein de ces axes est résumé ci-dessous.

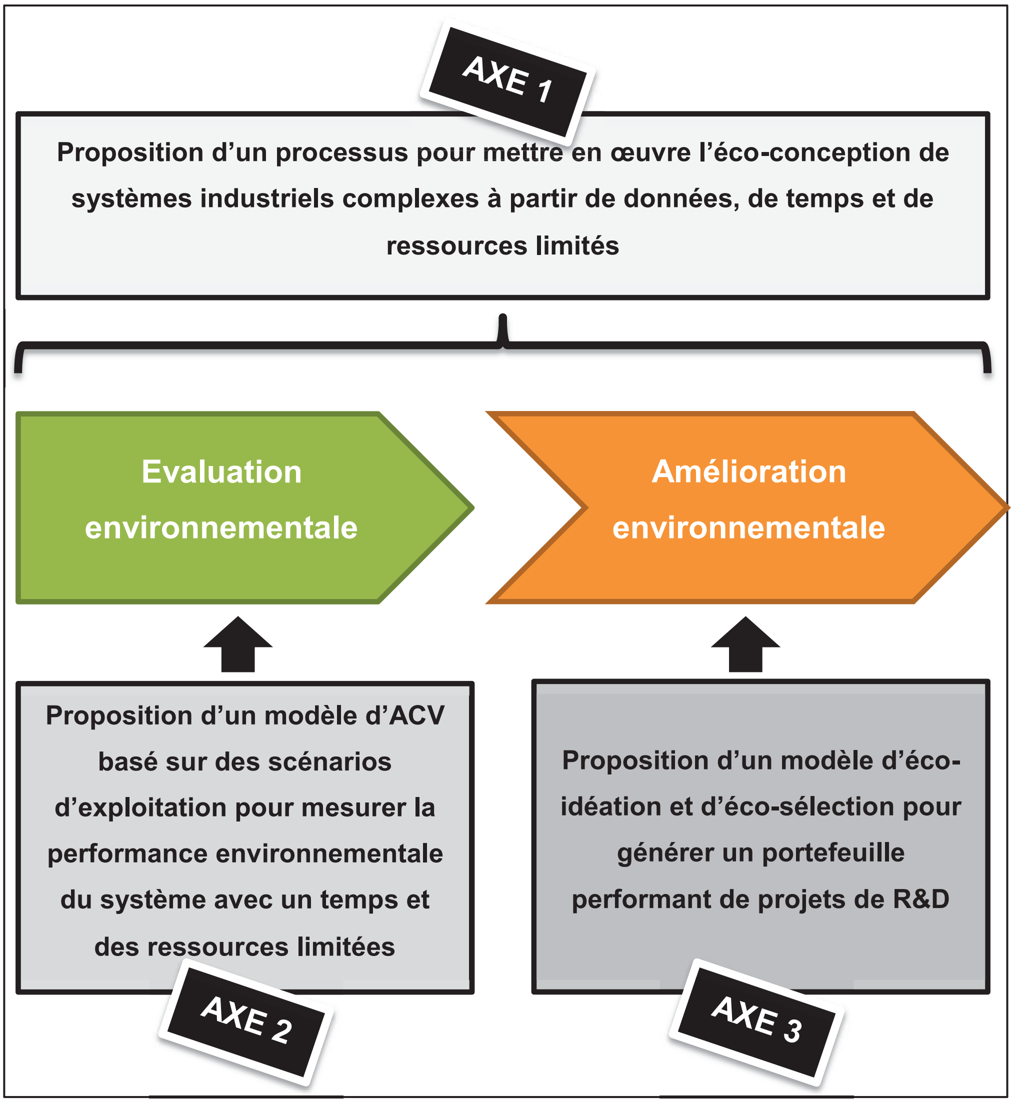

Figure 2. Positionnement des trois axes de recherche dans un processus simplifié d'éco-conception

- *Axe 1 :* **développement d'une méthodologie de gestion de la mise en œuvre d'une démarche d'éco-conception pour des systèmes industriels complexes**

Cette méthodologie est basée sur un processus DMAIC (en français : Définir, Mesurer, Analyser, Améliorer, Contrôler) issu du domaine du Lean 6 Sigma. Ce processus offre un cadre rigoureux et structuré pour gérer l'éco-conception de systèmes industriels complexes, de la réalisation d'une ACV à un haut niveau systémique à l'identification et la réalisation de projets d'amélioration. Ce processus est organisé autour de phases et livrables prédéfinis permettant d'optimiser la gestion de la complexité liée au système considéré.

Cette méthodologie a fait l'objet d'une publication dans la revue *Concurrent Engineering: Research and Applications*, reproduite dans le chapitre 3.

- *Axe 2 :* **développement d'un modèle d'ACV basé sur des scénarios d'exploitation de systèmes industriels complexes**

Les systèmes industriels complexes sont caractérisés entre autres par un grand nombre de sous-systèmes et composants, ainsi qu'un cycle de vie extrêmement long et incertain. La réalisation d'une ACV, nécessitant des données fournies et précises, et donc rendue difficile. Pour pallier à cela, nous proposons un modèle d'ACV basé sur la modélisation de scénarios d'exploitation, permettant d'identifier des postes impactants du cycle de vie du système, habituellement rarement considérés en ACV, comme la maintenance, la mise à niveau ou la modulation de la durée de vie. Différents scénarios d'exploitation sont ensuite bâtis à partir d'une approche qualitative, et les impacts environnementaux associés à ces scénarios sont ensuite mesurés. Ce modèle offre un bon compromis entre la qualité des résultats obtenus et le temps et les ressources engagés sur l'étude. Il permet à la fois de fournir des informations précieuses en phase d'amélioration et de configuration du système dans un contexte donné, mais également d'engager avec les clients des échanges en vue d'optimiser conjointement l'exploitation du système.

Ce modèle fait l'objet d'un projet de publication, soumis dans la revue *the International Journal of Life Cycle Assessment* et reproduit dans le chapitre 4.

- *Axe 3 :* **développement d'une démarche d'éco-innovation basée sur l'identification d'un portefeuille de projets de R&D éco-innovants pour des systèmes industriels complexes**

A partir des résultats d'ACV, l'identification de projets d'amélioration performants est une étape cruciale du processus d'éco-conception. La conception de systèmes industriels complexes est caractérisée par une organisation de la R&D amont sous forme de nombreux projets conjointement menés pour améliorer ou concevoir une partie précise d'un système. Les connaissances et compétences techniques sont donc détenus par de nombreux experts qui n'ont pas forcément l'habitude de collaborer. Nous proposons un processus d'éco-innovation basé sur un groupe de travail multidisciplinaire d'experts. Ce groupe est réuni lors de séances de créativité autour de la roue de la stratégie d'éco-conception, un outil d'éco-innovation ne nécessitant que peu de connaissances environnementales. Les idées générées sont ensuite triées et évaluées grâce à trois filtres successifs et une grille d'évaluation multicritère, intégrant des critères environnementaux, mais également de faisabilité technique et économique ou de valeurs des clients. A l'issue de ce processus, un portefeuille équilibré de projets de R&D est identifié et proposé à la direction de l'entreprise.

Ce modèle fait l'objet d'un projet de publication, soumis dans la revue *Technovation* et reproduit dans le chapitre 5.

Applications chez Alstom Grid

Les trois axes de recherche ont fait l'objet d'une application dans le contexte industriel de l'unité Power Electronics Massy (PEM) d'Alstom Grid, sur des stations de conversion AC/DC utilisés pour convertir l'énergie à l'entrée des usines d'aluminium primaire.

Ces stations électriques sont composées de nombreux sous-systèmes conçus par des unités différentes (transformateurs, redresseurs, génie civil…), qui représentent environ 3000 tonnes de matière pour une durée de vie souvent supérieure à 30 ans. Ces stations sont implantées dans le monde entier, dans des conditions climatique et d'alimentation électrique très différentes. Il n'existe pas de conception standard, mais chaque sous-station est bâtie sur une architecture de base commune. La phase d'exploitation est caractérisée par de nombreux évènements difficilement prévisibles (pannes, accidents, mise à niveau ou allongement de la durée de vie en fonction du contexte économique…) et la fin de vie est extrêmement incertaine car temporellement très éloignée et à la charge des clients.

La méthodologie générale issue de l'axe 1 a été déployée chez PEM. Elle a permis d'initier et d'organiser rapidement et rigoureusement le processus d'éco-conception dans l'unité avec peu de ressources et de temps disponibles. La réalisation de l'ACV a permis d'identifier dans les mêmes conditions et avec une précision satisfaisante les principaux postes impactants du cycle de vie d'une sous-station. Ces résultats ont ensuite servi de support à la démarche d'éco-innovation mise en œuvre autour d'un groupe de travail réunissant 9 experts. 109 idées ont été générées, puis groupées, et triées. L'évaluation multicritère de ces projets par le groupe de travail et 4 experts en éco-conception externes aux groupes a permis d'identifier finalement un portefeuille de 9 projets éco-innovants qui seront réalisés dans les prochains mois.

Apports et perspectives

A l'issue de ces travaux de thèse, les principales contributions de nos travaux sont les suivantes :

- Une méthodologie générique et générale de mise en œuvre de l'éco-conception de systèmes industriels complexes, bâtie autour de phases et livrables prédéfinis.

- Un modèle d'ACV générique basée sur la modélisation de scénarios d'exploitation pour acquérir une meilleure connaissance des impacts environnementaux générés au cours du cycle de vie du système dans un contexte donné.

- Un processus d'éco-innovation générique basé sur un outil reconnu et mettant en jeu un groupe de travail multidisciplinaire. La principale contribution sur ce processus est un protocole de tri de projets éco-innovants bâti autour de trois filtres structurés et une grille d'évaluation multicritère.

- L'application et la validation de ces contributions théoriques sur un cas d'étude industriel dans une grande entreprise internationale. Cette application a permis de souligner le caractère robuste et généralisable de nos travaux.

Ce travail de recherche apparaît finalement comme une étape satisfaisante pour développer l'éco-conception de systèmes industriels complexes. Cependant, nous considérons qu'il s'agit d'une première contribution dans ce contexte particulier, et qu'une grande quantité de travail est cependant encore nécessaire afin de déployer cette approche à grande échelle dans de nombreuses entreprises.

La principale perspective de nos travaux consisterait ainsi à déployer cette approche dans d'autres entreprises et sur d'autres systèmes afin de la tester dans d'autres contextes industriels. Par ailleurs, il serait également intéressant de tester la méthodologie sur le long-terme, c'est-à-dire en y intégrant la réalisation des projets d'amélioration et plusieurs réitérations du cycle complet. Enfin, une plus grande automatisation des aspects techniques de nos travaux (liés à l'ACV et à l'évaluation multicritère des projets) permettrait de déployer plus facilement et plus rapidement notre approche.

General introduction

Eco-design and complex industrial systems

The current multidimensional crisis is a decisive period in human history. From an ecological point of view and for the first time in history, the human activities have so strong impacts on the ecosystems than his long-term future becomes very uncertain. But this crisis is also an extraordinary opportunity to initiate a total metamorphosis of our society towards a more moral, ethical, fair and ecological – in one word, sustainable – world (Morin, 2011). This hard transition, called *Third Industrial Revolution* by Jeremy Rifkin (Rifkin, 2010) needs of course to be initiated by political decisions, but the industrial sector is particularly involved in this challenging process.

This point view is remarkably highlighted by the *I=PAT* equation, issued from the work of Ehrlich and Holdren in the 1970's (Ehrlich and Holdren, 1971). In this equation, *I* represents the impacts of human activities upon the environment, *P* the world population, *A* the affluence, associated to the world income per human being, and *T* the technology. This equation shows that *I* strongly depends on the three other variables. However, *P* and *A* may hardly be modified at a short-term perspective, whereas *T* is directly linked to the innovation potential of the world industry, and its ability to develop more sustainable technologies.

In this perspective, eco-design appears as a powerful answer to initiate this transition from an industrial point of view. The improvement of technologies needs of course to be combined with strong changes in the current mass consumer model, but the integration of environmental issues in product design becomes a real necessity. Out of these purely humanist considerations, the European regulations evolve more and more towards the deployment of eco-design in the industrial sector, and eco-innovation is now seen as a powerful way for companies to improve their competitivity in the globalized market.

However the eco-design approaches performed in the last years are mainly focused on mass consumer products, and large industrial installations have not been deeply considered. The existing eco-design methodologies and tools are thus not particularly adapted to complex industrial systems. This statement includes in particular Life Cycle Assessment (LCA), whose limits are amplified when considering such systems. That is why this PhD thesis focuses on the development of an eco-design methodology for complex industrial system, including both the environmental evaluation and environmental improvement stages.

Research positioning

This research has been granted by Alstom Grid through a collaboration between Alstom Grid and the Industrial Engineering Laboratory (*Laboratoire Génie Industriel*, LGI) at Ecole Centrale Paris. It is thus based on industrial issues and the applicative steps take up an important place. For these reasons this research is built on an Action Research protocol, meaning that we have been actively intervening in the industrial context. O'Hare offers an interesting state-of-the-art concerning research methodologies in design (O'Hare, 2010). He highlights the main characteristics of an Action Research methodology:

- Suitability for studying industrial practice,
- Supports active intervention within a research setting,
- Participatory nature,
- Participants as co-inquirers,
- And cyclical nature of the research process.

This protocol is indeed fully adapted to the industrial requirements expressed by Alstom Grid and the development of generic methodologies and tools from the academic side.

The aim of the thesis is to develop methods and tools to implement eco-design in a company providing complex industrial systems. This approach has been performed following the four steps of an Action Research approach proposed by Yannou and Petiot (Yannou and Petiot, 2011):

1. Observation of design practices leading to a diagnostic analysis
2. Generalization of the diagnosis to scientific issues and realization of state-of-the-art assessments
3. New model proposition
4. Deployment and validation in the industrial context

Table 1 gives an overview of the actions that have been performed according to these four steps. The realization of such an approach offers excellent opportunities in terms of industrial validation. However one main risk is to provide too specific methodologies and tools that can hardly be generalized for other context. Following the different applications, this point is treated in the general discussion section.

The realization of the first actions described in Table 1 gave us the possibility to define three research questions that are the basis of the model developments proposed in this dissertation. From both the results of the industrial diagnosis performed at Alstom Grid and the study of the scientific context about eco-design in companies, the three questions are expressed as:

- *Research question 1:* **How to manage with limited time and resources the deployment of an eco-design approach in a complex system industry with no pre-existing knowledge and competences?**

- *Research question 2:* **How to perform a reliable LCA of a complex industrial system at a high level and with limited time and resources?**

- *Research question 3:* **How to generate and select an adapted portfolio of eco-innovative R&D projects for a complex industrial system?**

Table 1. Overview of the research according to the Action Research protocol

Action Research step	Actions performed within this research
1. Observation & diagnosis	• Integration in the R&D department of Alstom Grid PEM • Involvement in the eco-design working group at the corporate level • Observation of industrial practices at Alstom Grid • Identification of the regulation and normative context, of existing methodologies and tools
2. Identification of scientific issues	• Identification of three research questions • Realization of state-of-the-art studies according to the identified research fields
3. New model proposition	• Identification of three research axes and their interdependencies • Development of a generic and general eco-design methodology for complex industrial systems • Development of an adapted scenario-based LCA model • Development of an adapted eco-innovation process
4. Deployment & validation	• Application of the three research axes at Alstom Grid • Conclusions and identification of limits and new possible developments

Three research axes

From this context and this research positioning, three research axes have been identified. They are represented in Figure 3. Each of these axes answers to one of the three research questions.

In the first axis an adapted model has been developed to implement eco-design in complex system industries. This process is based on a DMAIC (Define, Measure, Analyse, Improve, Control) process, issued from the continuous improvement field. It offers a rigorous and structured framework from the management of eco-design for complex industrial systems through the realization of a LCA at a high systemic level and with limited time and resources, to the identification and the realization of improvements projects. So it covers the whole eco-design process.

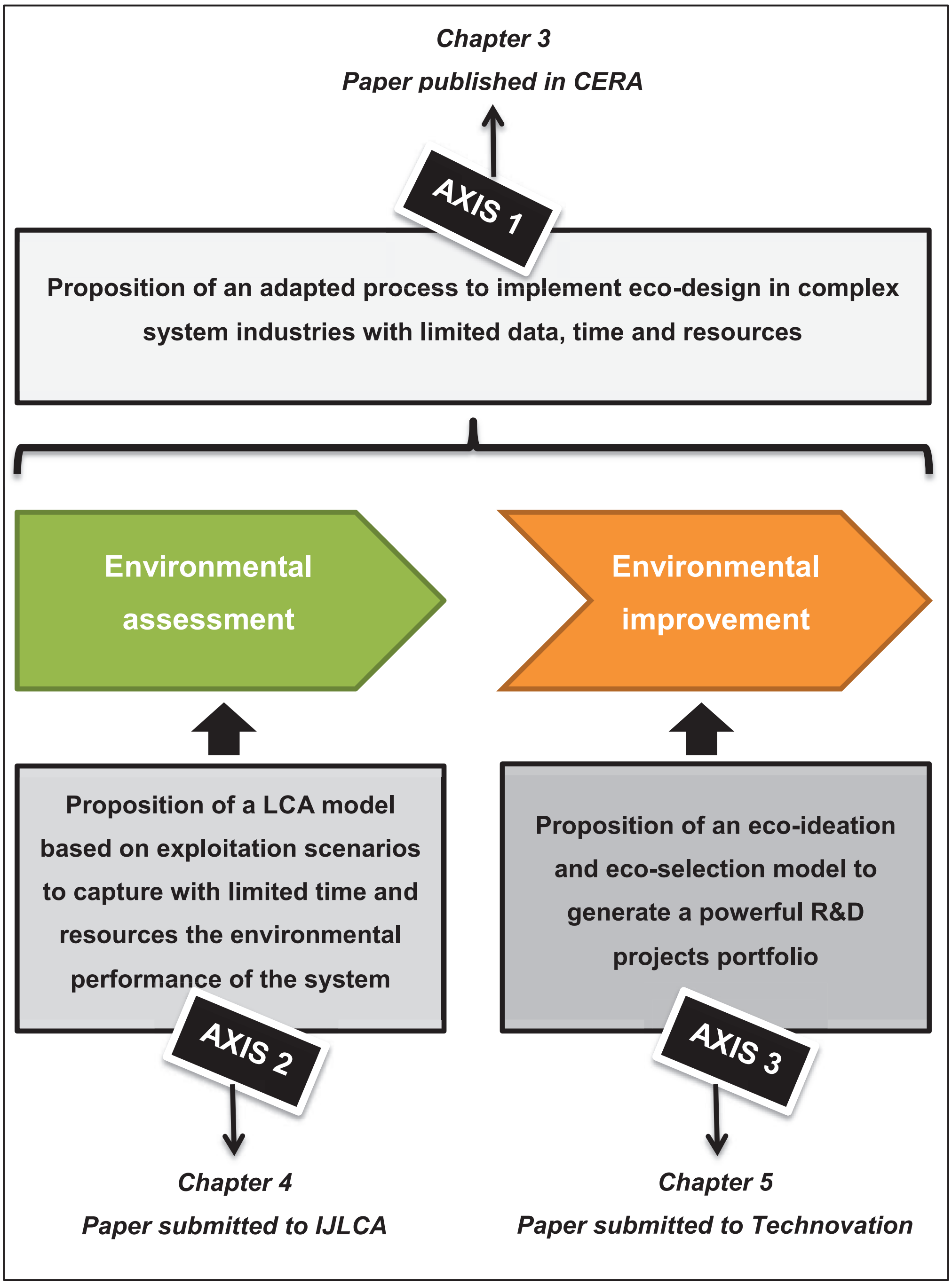

Figure 3. Positioning of the three research axes and links with the dedicated chapters and papers

The two other axes are centred on specific aspects of this methodology. Axis 2 focuses on the environmental evaluation stage. A scenario-based LCA model is proposed to assess to environmental impacts generated all along the system life cycle, which is often extremely long and characterised by great uncertainties. This LCA approach considers relevant parts of the life cycle of an industrial systems, such maintenance, life time or updates, to model a set of possible exploitation scenarios and thus to limit the resources and the time used to perform the study with acceptable results.

The last axis focuses on the environmental improvement phases. As the knowledge of the complex industrial system is owned by company experts, they are involved in a creativity approach. After a short training, ideas are generated thanks to the eco-design strategy wheel (Brezet and Van Hemel, 1997). These ideas are then sorted out and assessed with an original qualitative and multi-criteria grid. The positioning of the candidate projects on the different dimensions (environmental benefits, technical and economic feasibility, customers' values…) allows identifying a portfolio of powerful R&D projects for the company.

An application is proposed for each axis at Alstom Grid, on large electrical stations used in the aluminium industry.

Dissertation structure

This PhD dissertation is structured as a series of three scientific papers, complemented by several introducing and concluding chapters.

The first chapter presents the general context of the work by focusing on the Sustainable Development perspective to introduce eco-design. The research and industrial contexts are then explored to define three research questions.

Chapter 2 introduces the main lines of the literature review that has been performed to define the three research axes answering to the three questions. Each of these axes is then briefly exposed, as well as the applicative field at Alstom Grid.

Chapter 3 reproduces a scientific paper recently published in *Concurrent Engineering: Research and Applications*, about the general methodology to implement eco-design in complex systems industries.

Chapter 4 reproduces a scientific paper submitted in *the International Journal of Life Cycle Assessment*. This paper proposes a scenario-based LCA model to evaluate the environmental impacts associated with the exploitation of complex industrial systems.

The last paper is proposed in Chapter 5. It has been submitted to *Technovation*, and it presents an eco-innovation approach adapted to complex industrial systems through the identification of a powerful portfolio of R&D projects.

Chapter 6 proposes a general discussion about these three research axes, while conclusions and perspectives are drawn in a last section.

Chapter 1. Context and research questions

This first chapter introduces the context of the thesis. The general context centred on the Sustainable Development perspective is presented to introduce the eco-design research field. Industrial considerations then allow highlighting some problems linked to the implementation of eco-design for complex industrial systems. Three research questions are finally proposed.

1.1. General context

1.1.1. The Sustainable Development perspective

The human society undeniably meets a global crisis. The main aspects of this crisis are economic, social, environmental, but also political or moral (Morin, 2011). From the second part of the 20^{th} century and the coming of the mass-consumer society, new research fields have appeared face to the awareness of upcoming and hardly solvable difficulties. This awareness is well illustrated by the *I=PAT* equation, issued from the work of Ehrlich and Holdren in the 1970's (Ehrlich and Holdren, 1971).

The *I=PAT* equation is expressed in Formula (1):

$$I = P \times A \times T \quad (1)$$

Where *I* represents the human impacts on the environment, *P* the size of the human population, *A* the affluence, associated to the world income per human being, and *T* the technology. An interesting analysis of this equation is proposed by Kempf (Kempf, 2011) and Da Costa (Da Costa and Iacona, 2012). This analysis is synthetized below.

If we simplify this equation by associating *I* with the worldwide CO_2 emissions, and *T* with the CO_2 intensity, i.e. the quantity of CO_2 emission necessary to produce 1 \$, it becomes possible to easily simulate some evolution scenarios.

In 2010, 33 billion of CO_2 tons were emitted, while the world population was 6.84 billion of inhabitants. The theoretical portion of gross national income was 9,136 \$ and the CO_2 intensity was 530 g/\$. These figures may be represented as in Formula (2):

$$33 = 6.84 \times 9.1 \times 0.53 \quad (2)$$

The question is now to study how these figures could evolve and what value they could reach in 2050. Several scenarios are highlighted below.

First scenario: no change in the CO_2 emissions

This first scenario consists in preserving the actual CO_2 emissions and studying the evolution of the average income. If we consider that the technology evolution follows the same trend as in the last decades, *T* becomes 0.22, while *P* becomes 9 according to an UNO scenario. Following these hypothesis, the average income *A* becomes 16,700 $ in 2050, i.e. much higher than today, but still less than the 2010 European level (34,000 $). But the main hypothesis of this scenario, the preservation of the CO_2 emissions, is too high to limit global warming according to the IPCC experts, leading to the second scenario.

Second scenario: limitation of global warming

If we try to limit global warming to 2°C according to the pre-industrial era, CO_2 emissions need to be divided by two. Keeping the same hypothesis for *T* and *P*, *A* becomes 7,600 $, which is less than today…

Third scenario: limitation of global warming and preservation of the average income

Finally, if we try to limit global warming and preserve the current average income with the same hypothesis for *P*, *T* becomes 0.18, which require much more efforts to improve human technologies.

These three simple scenarios highlight the difficulty to solve this equation. In all cases, some dead-ends appear:

- It seems extremely hard to reach in 2050 and at a worldwide level the current European average income while at least preserving the current CO_2 emissions. This is in contradiction with the humanist vision stating that every world inhabitant has the right to reach the same prosperity level than the others. Except of course if the richest countries accept to decrease their average income, which is clearly not topical as long as political decision-makers associate progress with economic growth.

- The number of world inhabitants in 2050 is variable from one study to another, but it seems not very probable that it reaches less than 9 billion in 2050.

- Another solution to this equation consists in increasing the income by increasing the CO_2 emissions. This hypothesis is considered by Kempf as intolerable for the world environment (Kempf, 2011), and the consequences on human activities would be disastrous.

- Finally the last parameter concerning the human technologies seems to be the easiest to improve. But the questions raised by Da Costa concerning the third scenario are the following: what would be the conditions to reach $T = 0.18$? What would be the required political decisions to reach this level? Da Costa underlines the need to completely review the national R&D policies, as the current economic system does not offer sufficient incentives to innovation and technological changes.

Anyway the solution – if it exists – would probably emerge from a global compromise on these different aspects. In this particular context, the notion of Sustainable Development (SD) appeared in the late 1980s. It is defined in the Brundtland report as a *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (World Commission on Environment and Development, 1987). Beyond this classical definition, the Sustainable Development notion aims at ensuring the development of the human society while preserving the natural resources and respecting the people. In other words, it consists in rationalizing the economic dimension by considering the social and environmental ones.

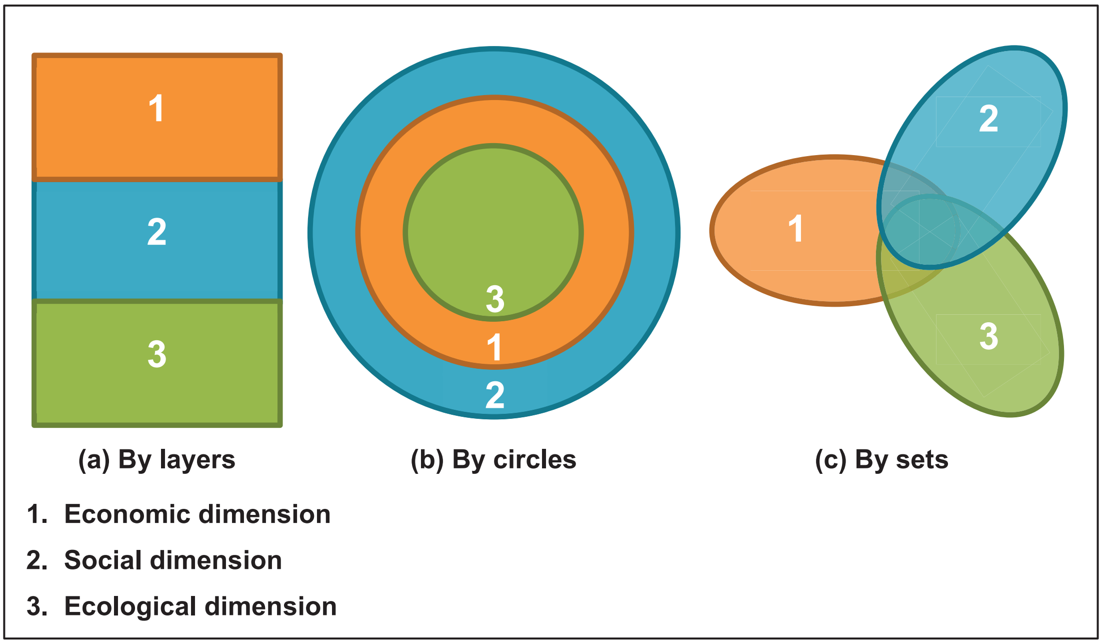

Figure 4. Three graphical representations of Sustainable Development (Bürgenmeier, 2004)

The classical graphical representation of SD appears in Figure 4.c. It shows interaction zones between the economic, social and ecological dimensions. The SD concept is illustrated by the common and central zone. However, other graphical representations exist (Figure 4.a. and b. from (Bürgenmeier, 2004)). In the first one, the three dimensions are represented by stacked layers, where the economic dimension is preceded by the social one, itself preceded by the ecological one. In this vision, the economic relations exist only because social relations exist, and these social relations are part of the global ecosystem. The deterioration of the ecological dimension would necessarily impact the two other dimensions. For Morin, the ecological crisis becomes more marked with the increasing damage on the biosphere, leading to more economic, social and political crisis (Morin, 2011). This is also the point of view developed by the representation by circles, where the environment is at the heart of the graph.

The difficulty to reach such a compromise between the three dimensions is obvious. We have shown that a particular lever to contribute to this compromise is the improvement of human technologies. If this improvement follows the same trends than in the last decades, it has been shown that it would probably not be sufficient to limits the impacts on the environment. It is thus mandatory to go further by promoting specific approaches centred on environmental considerations. This observation brings us directly to the product development field. However this transition toward a more sustainable paradigm is only possible if the current mass-consumer model is also deeply modified.

1.1.2. Towards a reasoned consumption

It is now admitted that if all the human beings follow the Western mass consumption model, there would not be enough resources on Earth to support it (Kempf, 2011). This is particularly problematic as the emerging countries such China and India represent several billions of people. But on the other hand these people have the right – and they want it – to pretend to better living conditions, which is often perceived as a right to consume more. This evolution is unavoidable, and trying to restrain it would be inequitable (as it would favour some people to the detriment of the others). But it would also be very dangerous, as it would probably be the source of generalized social troubles.

It is thus mandatory to define and deploy a reasoned consumption model based on two key aspects. First, the population of the Western countries needs to quickly converge from the current mass-consumption model towards the new reasoned model. And second, the population of the emerging countries, representing – as said previously – several billions of people, need to converge directly towards this new model.

Table 2. Example of proven reserves for some critical chemical elements (figures taken from (Sciences & Vie, 2012))

Chemical elements	Proven resources (millions of tons)	Annual production (millions of tons)	Reserve (years)
Copper	630	16	38
Phosphorus	65,000	191	340
Uranium	2.5	0.054	46
Gold	0.051	0.0025	20
Zinc	250	12	20

If we focus on environmental concerns, the current situation is characterised by several main issues that are closely intertwined:

- *Natural resources are over-exploited:* renewable resources (animals, plants or water) or non-renewable resources (for example metal and fossil resources) are for number of them over-exploited by human activities. In the first case it means that the human needs on these resources exceed their natural regeneration power, while these resources are by essence limited in the second case. In the two situations, the process leads to endangered or depleted resources. Table 2 illustrates this critical situation with some resources.

- *Human activities are more and more impacting soils, air and water:* the pollutions generated by the human activities have direct effects on the environment (see Figure 5). The anthropological greenhouse gases emissions leading to an accelerated climate change are the most popular and worrying aspect of this issue. However it hides other aspects that may also have strong negative effects. Impacts on air concern for example the ozone layer depletion or particulate matter formation. Impacts on water concern for example eutrophication phenomenon. Impacts on soils concern for example soils acidification phenomenon, or the use of land due to human activities (through deforestation, urban sprawl…). Other aspects like the emission of ionising radiations (for example after the Fukushima disaster) may also concern air, water and soils.

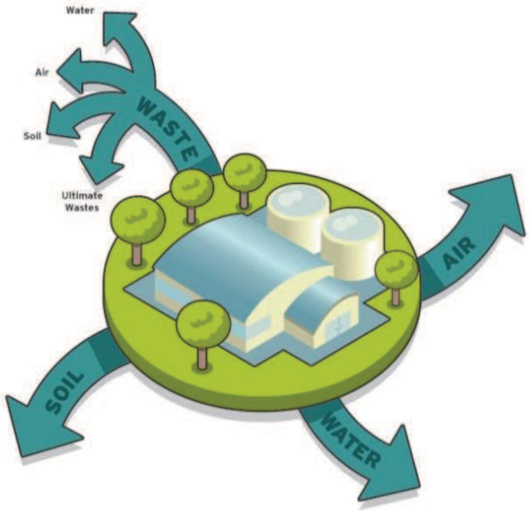

Figure 5. Impacts of human activities on air, water and soils

- *Human activities have negative effects on the biodiversity and the human health:* the over-exploitation of animal and vegetal resources directly causes the disappearance of numerous species. But the environmental pollution also leads to decrease the biodiversity through ecotoxicity phenomenon. It also have negative effects on human health, for instance by the development of numerous diseases like cancers.

The transition from the current consumption model towards a more reasoned approach taking into account all these impacts requires a radical questioning. It becomes obvious that an end-of-pipe approach is limited and that the problems need to be solved at source. That is why the field of product development is particularly concerned.

1.1.3. Environment versus new product development: the legitimacy of eco-design

New product development is the process of bringing a new product (good, service or process) to market. It is closely linked to the notions of ideation and innovation, that need to be conciliated with the quality, time and cost dimensions. In its traditional form the product development process includes technical and economic aspects, but no particular focus is made on environmental aspects. Eco-design gives an answer to this lack.

Eco-design (also named Environmentally Conscious Design (ECD), Design for Environment (DfE), green design or sustainable design) is defined as the *"integration of environmental aspects into product design and development with the aim of reducing adverse environmental impacts throughout a product's life cycle"* (ISO, 2011). Moreover the Areva definition of eco-design specifies that this integration is performed *"along with design parameters (technical feasibility, cost, quality, etc.)"* (AREVA, 2006). The main mission of eco-design consists in considering environment as soon as possible in the design process in order to minimize the environmental impacts generated by the products all along its life cycle. This sharply contrasts with classical design methodologies where the life cycle phases incumbent upon the customers are not considered.

Eco-design aims at designing new products that offer better environmental performance compared to the previous or equivalent ones. It is closely linked with the innovation field. In this way an eco-innovation is defined as *"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"* (Carrillo-Hermosilla et al., 2010). This definition includes in particular radical and incremental innovations. The deployment of an eco-design approach appears today as the best way to generate eco-innovative products in a systematic manner. It is the best way to take into account the environmental concern previously expressed, and thus it represents the most powerful driver from an environmental point of view to support the transition of product development towards a more sustainable model.

By considering more economic aspects, the necessity for the Western countries to preserve their employment and their competitivity is obvious face to the global crisis and the emergence of developing countries. That is why the ability to innovate becomes more than ever a key driver for companies in France, but also more generally in Europe. A recent study performed by a French think tank about innovation highlights these problems to promote innovation (Association des Centraliens - Think Tank Innovation, 2011). It proposes some priorities, like the need to integrate long-term visions, to invest in R&D or to improve innovation processes or creativity methods. The inclusion of environmental concerns in the companies' innovation programs is then a strategic choice, but the elements previously given in this dissertation clearly show that it becomes beneficial for their competitivity as well as mandatory for the human society.

The present dissertation focuses on these aspects by considering in particular complex industrial systems. The next sections explore these fields in terms of research and industrial context, in order to define the research questions that are treated from Chapter 2.

1.2. Research context

1.2.1. Eco-design

Eco-design has become in the last decades an entire research field, at the crossroad between product design, project management and ecology. From the 1990s, several standards have been published to harmonize the different existing visions (see for example ISO 14006 (ISO 2011), ISO 14062 (ISO 2002) or IEC 62430 (IEC 2009)). Regulations are also little by little set up to promote eco-design deployment in companies, in particular in the European context with the WEEE, RoHS or EuP directives (European Union, 2003a, 2003b, 2005) or the REACH regulation (European Union, 2006).

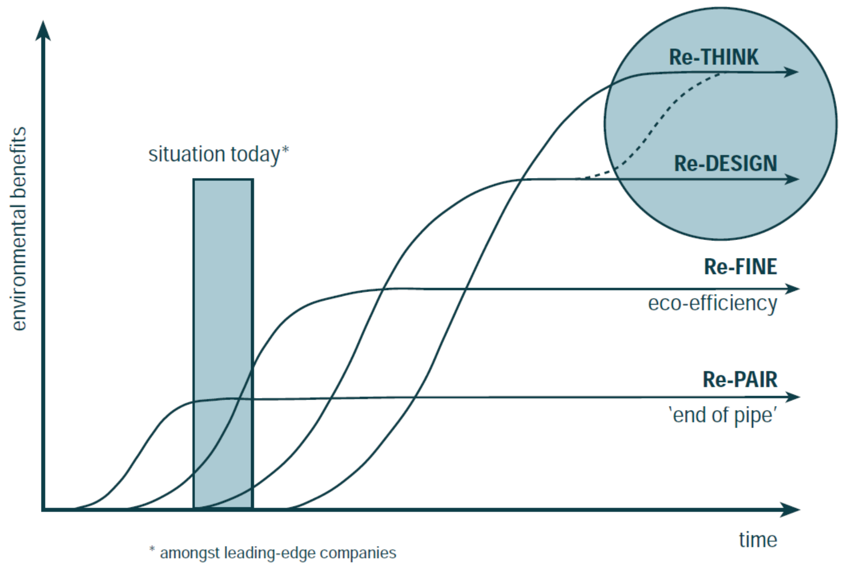

Figure 6. The "four steps" model of eco-design (Charter and Chick, 1997)

One main aspect of eco-design concerns the fact that multiple approaches exist. It can be initiated from different objectives, and it can be deployed at different levels. Charter and Chick distinguish for example four eco-design steps on Figure 6 that are more or less innovative according to the resulting environmental benefits and the time spent on the product (Charter and Chick, 1997). Brezet proposes a similar approach with different designations (Brezet, 1997). The Re-PAIR, Re-FINE, Re-DESIGN and Re-THINK steps respectively corresponds to a product improvement, a product redesign, a function innovation or a system innovation. These models show that a full eco-innovation approach is a long-term process, and it requires an important investment for companies, associated with the full support of the top management (McAloone, 1998).

An eco-design approach is basically made of two main stages (Le Pochat, 2005). The first one concerns the evaluation of the environmental performance of the system, while the second one aims at identifying improvements according to this environmental performance. This simplified vision is considered in the next chapters to structure the research axes.

Numerous eco-design tools have been developed through research works or industrial projects. We do not pretend to give an exhaustive overview of these existing tools. However some interesting references propose a classification of the main tools. For example, Janin distinguishes two main categories (Janin, 2000):

- Environmental evaluation tools, that can be divided into two sub-categories:
    - Quantitative tools, such as Life Cycle Assessment (LCA), simplified LCA, eco-indicators, Material Input Per Service unit (MIPS) or Life Cycle Costing (LCC)…
    - Qualitative tools, like matrices, regulation-based assessments, check-lists, material lists…
- Environmental improvement tools, such as standards, guidelines, check-lists, ecolabel approaches, software… We also include to these improvement tools the eco-innovation field, which aims at identifying new eco-friendly concepts and products.

To these two main categories, Janin also adds other tools, i.e. strategic tools, awareness tools and communication tools (Janin, 2000).

All these existing tools show that there is not one single eco-design process, but a multiplicity of eco-design tools and methods to perform the two general stages of evaluation and improvement. Standards exist to propose some guidelines to implement eco-design, but they stay at a theoretical level of recommendations and they are hardly applicable at an operational level.

This tools classification also shows that environmental evaluation tools are a key element of an eco-design process. Life Cycle Assessment is today the most recognized and used in industry. Next section focuses on it.

1.2.2. Life Cycle Assessment

Life Cycle Assessment is defined in the ISO 14040 standard as a *"compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle"* (ISO, 2006a).

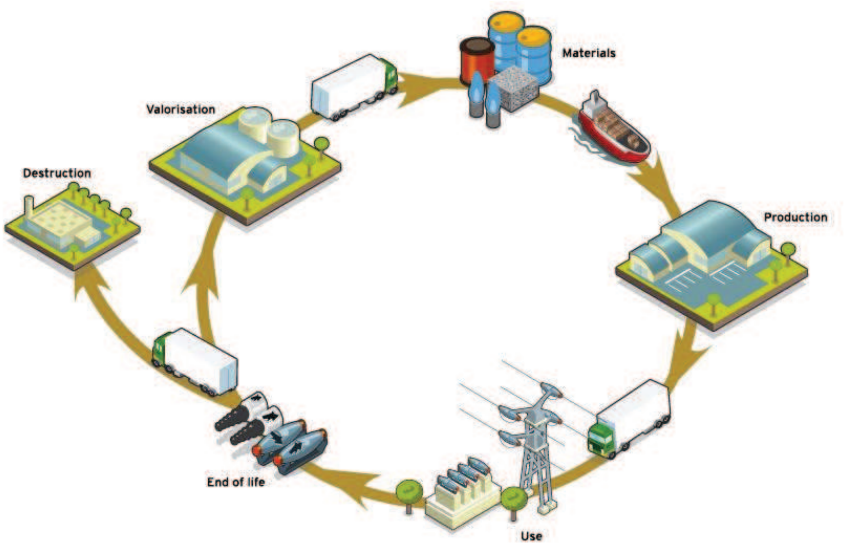

Figure 7. A typical life cycle of an industrial product

A typical life cycle of an industrial product is presented on Figure 7. Raw materials are extracted and manufactured to assemble the final product. This product is then transported to its exploitation site. At the end of its life, the materials may have different paths, for example recycling, reuse or landfilling.

A LCA process is divided into four main phases clarified in ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b). These four phases that are represented in Figure 8:

- **Goal and scope definition:** the objectives of the study (application, reasons for carrying out the study, audience…) are clarified, and the scope (considered system, functions, functional unit, perimeter, data quality…) is defined. This stage requires a particular attention as it conditions the entire study, and the results are extremely dependent on the chosen hypotheses.

- **Life Cycle Inventory (LCI):** this second stage aims at characterising the system life cycle and collecting all the data required to model this life cycle. Data are then related to the reference flow of the functional unit. Allocation of flows is also treated at this stage. Data quality management is a key aspect of the LCI stage.

- **Life Cycle Impact Assessment (LCIA):** the impacts generated by the system life cycle are evaluated from the LCI data by considering environmental impact categories associated with relevant indicators.

- **Interpretation:** the interpretation stage is inter-related with the three previous one. Results of the LCI and LCIA stages are analysed according to the goal and scope definition, and conclusions and recommendations are drawn to support for example an improvement process.

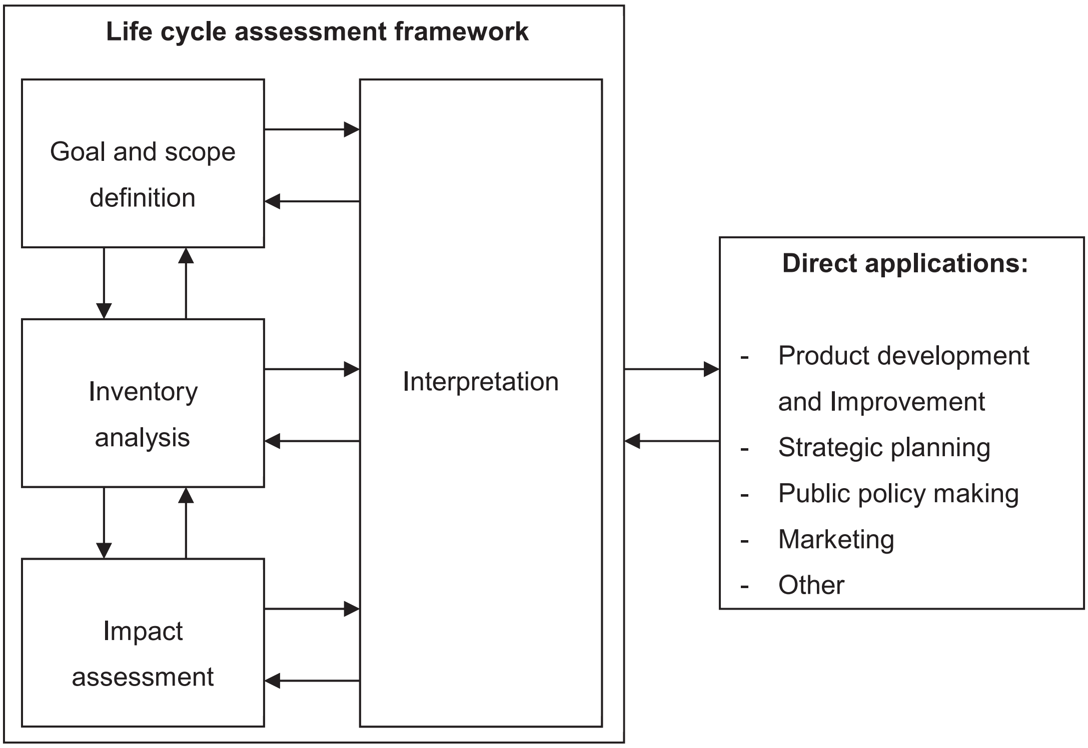

Figure 8. Stages of an LCA (from (ISO, 2006a))

Despite some limitations (see Section 1.3), LCA is certainly the most advanced environmental evaluation tool. As shown in Figure 9 taken from (Dewulf, 2003), it is the only eco-design tool that is able to feed all the other evaluation and improvement tools. However, it is also known that LCA can hardly be applied in the early design process, as it requires accurate data to provide acceptable results (Millet et al., 2007).

Life Cycle Assessment has been mainly applied in the last years on mass-consumer products. But large industrial systems have been poorly considered. Several reasons may be expressed to explain that, like the lack of specific eco-design regulations or the lack of environmental awareness in the design departments of complex systems industries. The next paragraph focuses on these systems to then introduce particular problems when eco-designing them.

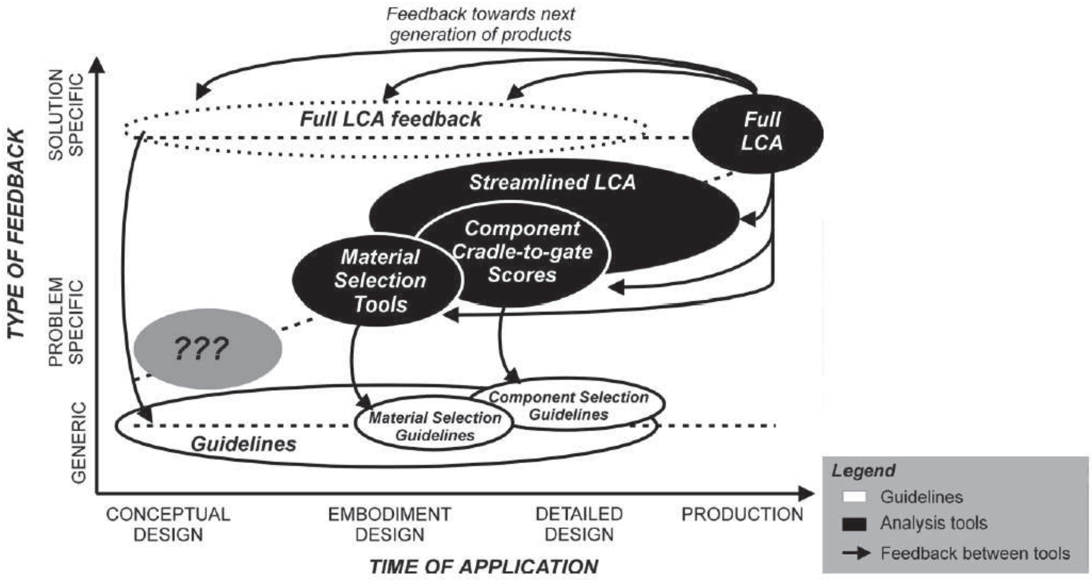

Figure 9. Categorisation of eco-design tools according to type of feedback and time of application (Dewulf, 2003)

1.2.3. Complex industrial systems

This section focuses on complex industrial systems whose specificities have not really been taken into account by eco-design and Life Cycle Assessment: these are industrial systems where complexity induces major issues in terms of modelling, prediction or configuration. If we consider the systems engineering domain, Blanchard and Fabrycky (Blanchard and Fabrycky, 2011) characterise engineered systems as systems that achieve operational objectives; that operate over a complete life cycle; that are composed of a combination of resources (humans, materials, equipment, money…); that are composed of subsystems and components that interact with each other; that are influenced by external factors from larger systems and in interaction with the natural world. Adding an environmental dimension, we define a complex industrial system in the sense of eco-design as:

- A large-scale system in terms of subsystems and components, mass and resource usage,
- A system whose life cycle is hardly predictable at the design level in the long-term, in particular its lifetime, upgrades, maintenance and end-of-life ,
- A system whose subsystems may have different life cycles and different obsolescence times,
- A system in close interaction with its environment (super system, geographic site…),
- A system supervised by human decisions and management.

Examples of such systems are Alstom Grid AC/DC conversion substations considered all along this dissertation (see in particular section 1.3.3).

These systems have not been particularly considered in eco-design and LCA. Some complex systems companies like Alstom Grid have indeed initiated eco-design approaches, but they are mainly focused on products and they do not consider systemic aspects. However some of these companies now want or need to consider environmental concerns at a systemic level in their product development. This industrial context is explained in the next section.

1.3. Industrial context

1.3.1. Eco-design and LCA implementation in companies

More and more companies integrate eco-design and LCA practices in their design processes. This implementation may be justified by two main visions:

- A proactive vision: the company is aware of environmental concerns and its environmental policy has planed the deployment of eco-design to its products and systems. Out of pure environmental considerations, eco-design is often perceived also as an effective way to promote innovation through eco-innovation, and thus to gain a competitive advantage (AFNOR, 2008).

- A reactive vision: the company implements eco-design to answer to new regulations, to customer needs or simply to follow its competitors developing a proactive approach (Janin, 2000; Le Pochat, 2005).

In the same vein the success of eco-design implementation is conditioned by some factors, like top management commitment (McAloone, 1998), a clear strategic environmental vision and the deployment of an adapted approach (Le Pochat, 2005).

The realization of such a successful eco-design approach offers numerous substantial benefits to the company (AFNOR, 2008), like:

- Brand image improvement,
- Competitive advantage,
- Market share increasing,
- Internal costs decreasing,
- Future regulations compliance,
- …

Numerous examples of successful eco-design deployment in France are given in (AFNOR, 2005). However the actual regulations do not concern complex industrial systems such as large electrical stations. Eco-design integration in the concerned companies is thus often initiated with a proactive perspective, or to follow proactive competitors. But in reality a large majority of complex system industries are not involved in eco-design deployment. Some reasons may be contradictory economic drivers, or a poor environmental awareness (Le Pochat, 2005). Another one is the lack of adapted eco-design and LCA methods and tools for complex industrial systems. The next section focuses on this point.

1.3.2. Limits related to complex industrial systems

Numerous literature references highlight the limits associated with LCA. Reap et al. offer a pertinent literature review on this subject (Reap et al., 2008a, 2008b). Table 3 lists the main problems according to the LCA phases.

When complex industrial systems are considered, some of these problems are amplified because of the amount of data to manage, the multiple possible perimeters, the uncertainties associated with the system life cycle, and so on. However, in many cases, such systems are simply considered as "classical" products (Macharey et al., 2007; Schmidt and Thrane, 2009), but no particular reflection is proposed to adapt the granularity of the study (the detail level to consider) to its objectives.

The problems that seem for us the most important when specifically considering complex industrial systems appear in bold in Table 3:

- Boundary selection: as previously explained, multiple boundaries exist and their choice needs to be carefully made;
- Alternative scenario considerations: the uncertainties associated with the system life cycle make possible numerous life cycle scenarios;
- Spatial variation and dynamics of the environment: the uniqueness of complex industrial systems (like the Alstom Grid substations), their worldwide geographical implantation and their customized exploitation management imply spatial and temporal variation from one site to another, while limited time and resources limit the ability to perform specific LCAs.
- Data availability and quality: the system complexity clearly amplified this classical problem, and the question of the granularity of the study becomes essential.

More generally when considering the entire eco-design process, it appears as essential to guide the designer from the LCA results to the identification of environmental improvements. Among the multiple eco-design approaches proposed in the literature, no particular attention is given to the specific requirements of complex industrial systems, characterised by a global design process performed during a long cycle and in an upstream R&D context. Standards like ISO 14062 (ISO, 2002) propose some specifications, for example to involve a multidisciplinary team, but no operational procedure is given.

Table 3. LCA problems by phase (Reap et al., 2008a)

Phase	Problem
Goal and scope definition	• Functional unit definition • **Boundary selection** • Social and economic impacts • **Alternative scenario considerations**
Life cycle inventory analysis	• Allocation • Negligible contribution ('cutoff') criteria • Local technical uniqueness
Life cycle impact assessment	• Impact category and methodology selection • **Spatial variation** • Local environmental uniqueness • **Dynamics of the environment** • Time horizons
Life cycle interpretation	• Weighting and valuation • Uncertainty in the decision process
All	• **Data availability and quality**

We propose to illustrate some of these limits in the next paragraph by considering the Alstom Grid context.

1.3.3. The Alstom Grid example

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 is a particularly environmentally impacting and energy-consuming activity (Schmidt and Thrane, 2009). An electrolysis substation represents thousands of tons of power electronics components and transformers, costing tens of millions Euros.

It is made up of several modules (four in Figure 10) 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).

Figure 10. Example of an Alstom Grid AC/DC conversion substation (Aluar, Argentina)

In this context, Alstom Grid PEM wishes to minimise the environmental impacts of its products to answer to the environmental policy of the company and to be differentiated from competitors.

Such a substation is considered as a complex industrial system 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 really long, up to 35 or 40 years. Many uncertainties exist for the use and end-of-life phases, which depend on the plant management and the political and economic context. No end-of-life scenario is clearly known as it is supported by the clients.
- 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. We consider substations as a product family.

No eco-design approach was performed at PEM before the application of the work presented in this PhD dissertation. It also implies that no-one was really trained in eco-design and environmental considerations. A pre-existing eco-design group was however already present at a corporate level, but it had no settling in the PEM unit and its work was clearly more focused on products aspects than systems aspects.

The PEM design process is characterised by two main design departments. The R&D department is in charge of the global architecture of substations, the development of technological innovative bricks and the upstream research to these technological developments. The Engineering department is in charge of the instantiation of the global architecture for each projects and the detailed design.

As the most efficient environmental improvements need to be performed very early in the design process (McAloone, 1998), the R&D department rapidly appeared to be the best place to act and to first implement eco-design. This department generally jointly performed projects that are then combined to propose new architectures and technologies for the designed systems. This portfolio-based approach is thus considered in the next sections and chapters.

From this industrial context the main requirements were to introduce eco-design in a unit that has never considered environmental issues, with limited time and resources and benefiting from scarce and uncertain life cycle data. Combining the research and industrial contexts, three research questions have been defined. They are presented in the next section.

1.4. Research questions and methodology

The industrial and research context show methodological lacks about eco-design applied to complex industrial systems. From these observations three research questions have been defined.

1.4.1. How to manage eco-design for complex industrial systems?

We have highlighted the lack of an operational methodology to implement eco-design in complex systems industries. Specificities associated with complex industrial systems amplify the classical limitations of Life Cycle Assessment. Moreover the time and resources available in companies limit the ability to perform in-depth environmental evaluation and improvement processes. For these reasons we define the first research question as:

Research question 1
How to manage with limited time and resources the deployment of an eco-design approach in a complex system industry with no pre-existing knowledge and competences?

1.4.2. How to assess the environmental performance of

complex industrial systems?

Considering the problems specifically linked with the deployment of LCA for complex industrial system, one main question concerns the granularity level to choose in order to reach the best compromise between results quality and available time and resources. It has been noticed that performing a complete and in-depth LCA of such a system would probably take several years. However is it really necessary to perform this type of LCA to feed an internal environmental improvement process? We are actually convinced that the identification of the main impacting elements of the system life cycle is sufficient for that use. Consequently a detail level that permits distinguishing the subsystems and the main components seems to be a good compromise. However some difficulties quickly appear, like the modelling of the system life cycle, which is very long and uncertain. That is why we formulate the second research question as:

Research question 2

How to perform a reliable LCA of a complex industrial system at a high level and with limited time and resources?

1.4.3. How to generate and select a powerful eco-innovative R&D projects portfolio for complex industrial systems?

Once an effective environmental evaluation of the system has been performed, the question is now to provide environmental improvements based on LCA results. In the particular context of complex systems industries, the global system architecture is designed in the R&D department. The size and the complexity of the system does not permit simply identifying some improvements and performing them in a linear process. Thus it becomes necessary to introduce the notion of "R&D projects portfolio". However this notion is rarely considered in the eco-design field. And the third research question is formulated as:

Research question 3

How to generate and select an adapted portfolio of eco-innovative R&D projects for a complex industrial system?

1.4.4. Synthesis

The three research questions are synthesized in Figure 11. The first question deals with the entire eco-design approach, including both the environmental assessment and environmental improvement stages, while the second and third questions are focused respectively on the first and second eco-design stages.

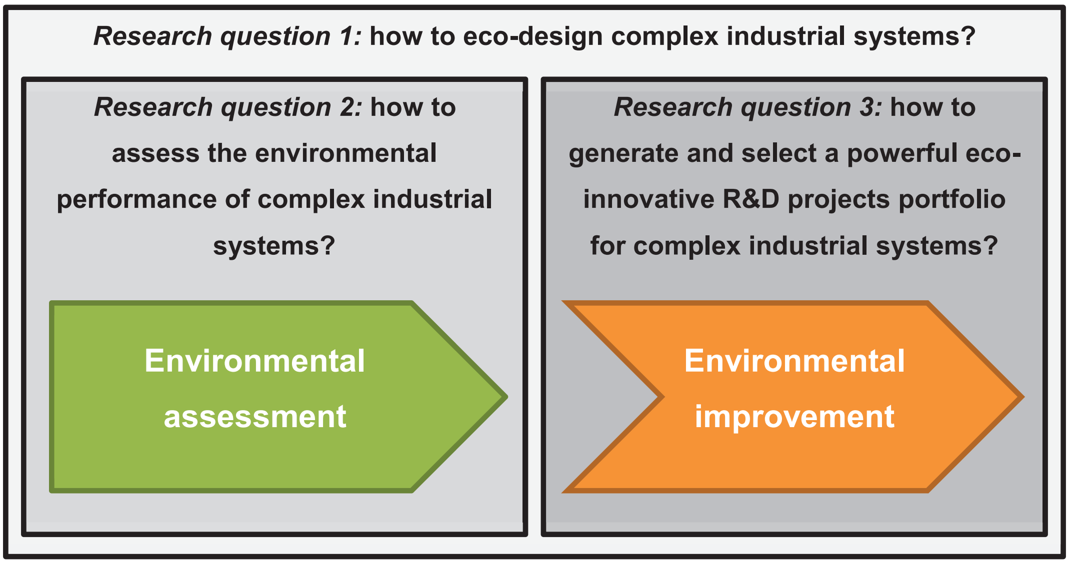

Figure 11. Positioning of the three research questions in a general eco-design process

So the first questions aims at identifying a general methodology in which the answers to the two other questions will be inserted. These three questions are treated in the next chapter, first by performing a literature review of the main associated research fields, and secondly by proposing adapted methods and tools.

Chapter 2. Proposition of a general methodology

From the context and the research questions expressed in the previous chapter, an overview of the literature in the different concerned research fields is proposed in Section 2.1 to introduce the general methodology in Section 2.2. The applicative steps performed at Alstom Grid are presented in Section 2.3. The three main aspects of the methodology are treated in detail in Chapter 3, Chapter 4 and Chapter 5 as papers published or submitted in international journals.

The role of this chapter is not to give detailed information and results, but to structure and to link in a logical way the research fields and axes treated in the three journals papers presented in the following chapters.

2.1. Literature review overview

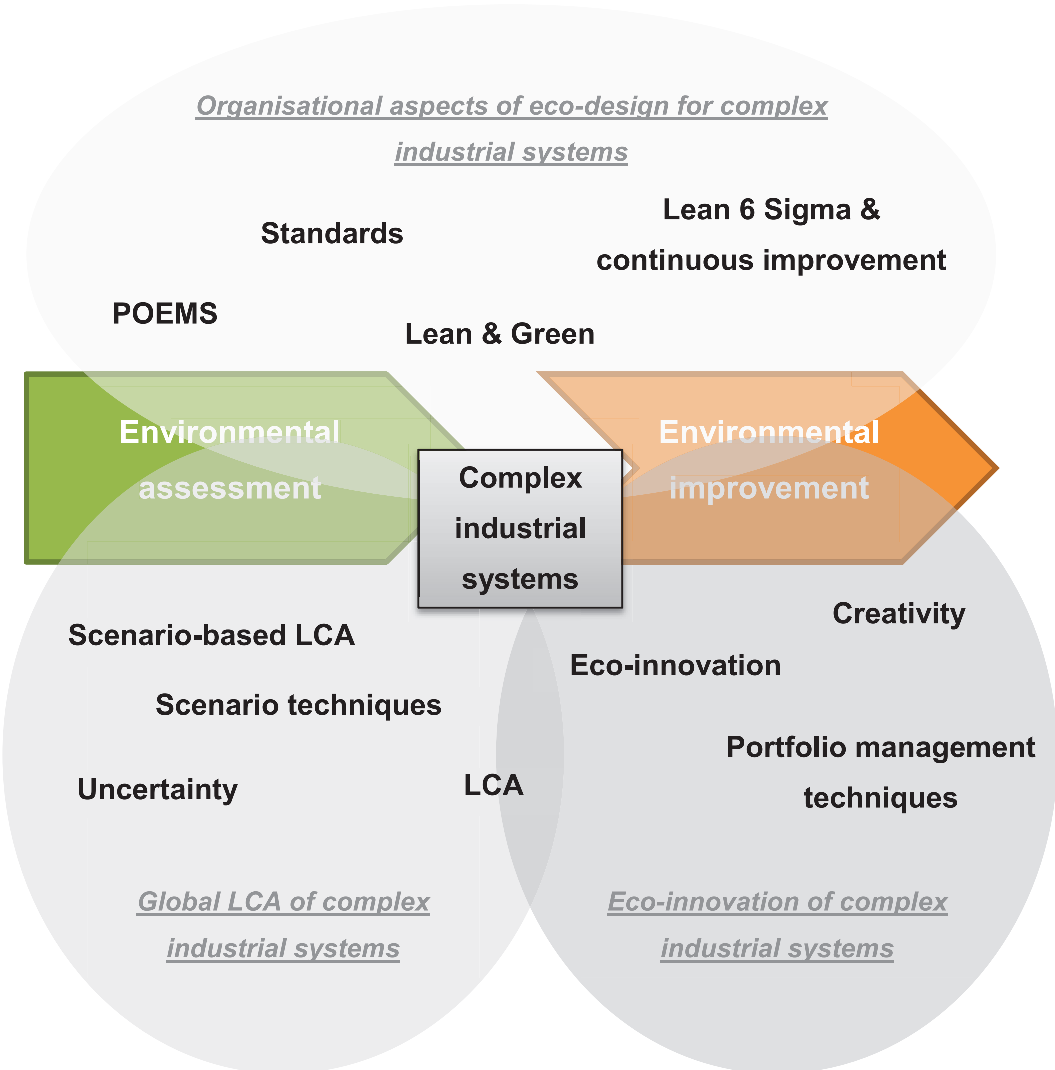

Figure 12. Positioning of the three explored literature fields with the main associated concepts

With regard to the research questions, three main research fields have been defined and explored. They are represented in Figure 12. The main key elements of these three literature domains are given in the next paragraphs to introduce the methodology in section 2.2.

2.1.1. Organisational aspects of eco-design for complex industrial systems

Concerning the first research question that deals with organisational aspects of eco-design, related standards have been studied (the main one being the recent ISO 14006 standard (ISO, 2011)), as well as the research field known as Product-Oriented Environmental Management Systems, or POEMS. (Wuppertal Institute for Climate, Environment, Energy, 2008) offers an interesting overview of the associated literature. Another interesting field that has been studied concerns Lean 6 Sigma and continuous improvement, and more particularly some works mixing environmental concerns and Lean 6 Sigma under the term Lean and Green (see for example (US Environmental Protection Agency, 2000)).

This first literature axis is deepened in Chapter 3.

2.1.2. Global LCA of complex industrial systems

The second research question aims at offering environmental evaluation tools and methods adapted to complex industrial systems. We have chosen to only focus on Life Cycle Assessment as:

- It is currently the most accurate environmental evaluation method,
- It is standardised (ISO, 2006a, 2006b) and well recognized worldwide,
- It is already deployed in other Alstom Grid unit,
- The quantitative results were really useful in the Alstom Grid context.

In the LCA field we have favoured qualitative approaches to consider uncertainties due to the lack of data and the complexity of the system life cycles. That is why we have rapidly converged toward scenario-based LCA (Pesonen et al., 2000; Weidema et al., 2004; Höjer et al., 2008; Zamagni et al., 2008) , and more generally scenario techniques (Tietje, 2005; Börjeson et al., 2006; Bishop et al., 2007).

This second literature axis is deepened in Chapter 4.

2.1.3. Eco-innovation of complex industrial systems

Finally, the third research question deals with eco-innovation in an upstream R&D context. The field of eco-innovation has of course been explored, including eco-ideation and creativity

(Brezet and Van Hemel, 1997; Fussler and James, 1997; Jones et al., 2001; Pujari, 2006; Carrillo-Hermosilla et al., 2010; Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010; O'Hare, 2010; Bocken et al., 2011; Tyl, 2011). However we have also focused on portfolio management techniques that appeared as really adapted to the industrial needs for complex industrial systems (Cooper et al., 1999; Mikkola, 2001; Apperson et al., 2005; Coldrick et al., 2005; Lawson et al., 2006; Bitman and Sharif, 2008; Henriksen and Palocsay, 2008).

This third literature axis is deepened in Chapter 5.

2.2. General methodology

2.2.1. General overview

According to the three research questions and the three literature fields previously presented, three research axes have been defined to answer to the research questions. These axes are presented in Figure 13. Each axis is materialized by a scientific paper, reproduced in Chapter 3, Chapter 4 and Chapter 5.

Within the first axis an adapted process to implement eco-design in complex system industries in proposed. The second axis concerns the development of a scenario-based LCA model to consider uncertainties and variabilities related to the system life cycles. Finally an eco-innovative process is proposed within the third axis to define a promising portfolio of R&D projects for complex industrial systems.

An overview of these propositions is performed in the next paragraphs. Moreover the coordination between the three axes is clarified in the next paragraph. But basically, as shown in Figure 13 the global methodology proposed in the first axis offers a complete framework to the eco-design of complex industrial systems, whereas the two other axes focus on more specific aspects, concerning respectively the environmental evaluation stage and the environmental improvement stage.

The whole process is designed to be applied in a company producing complex industrial systems, with no particular eco-design or environmental prerequisites. A special attention is made to the saving of time and resources in the company, i.e. to define the best compromise between environmental gain and the ability of the organisation to absorb this new dimension without reviewing the usual design rules.

So the inputs of the process are:

- A company or a company unit designing complex industrial systems,
- With only few environmental or eco-design competences and knowledge,

- But with a real ambition to introduce eco-design in its practices, which includes both the management support and the ability to occasionally mobilize technical experts for some hours to contribute to the data inventory or the eco-innovation process,

- And an eco-design leader supporting the process deployment, who may come from the company or not (from a university or a consulting company for example).

Once the process has been deployed and realized in the company, the expected outputs are:

- A portfolio of eco-innovative R&D projects. These projects offer substantial environmental benefits, deal with different aspects of the system and the company (organisational, technical or methodological; short, middle, or long term…) and some elements are known to prove their feasibility from an economic and a technical point of view,

- Eco-design is implemented in the company, meaning that people are aware of eco-design, and some people are trained and act as eco-design ambassadors in their department,

- The company knows the environmental performance of the studied systems, and may orient some design choices even out of the improvement projects,

- And finally the company has the possibility to communicate about its eco-design organisation and results to promote ecological values and to improve its competitivity and its brand image.

However the proposed methodology covers the steps from the introduction of eco-design into the company to the development of a set of eco-innovative R&D projects, but it does not cover the realization of these projects. In fact the time line of such an entire process would be too long for an industrial PhD thesis, and that is why we have preferred focusing on the details of the first steps. We estimate indeed that reliable and validated basis are essential to integrate eco-design on a long-term vision. However some guidelines are given for the realization of the projects, in particular through a structured framework in the first research axis.

From these considerations, we can estimate that the benefits for the company would be much more substantial after the realization and the capitalization of the improvement projects, which implies a successful implementation of the steps leading to these projects. A quick introduction of the three research axes is proposed in the next paragraph, with some complementary information compared to the scientific papers, in order to clarify their links.

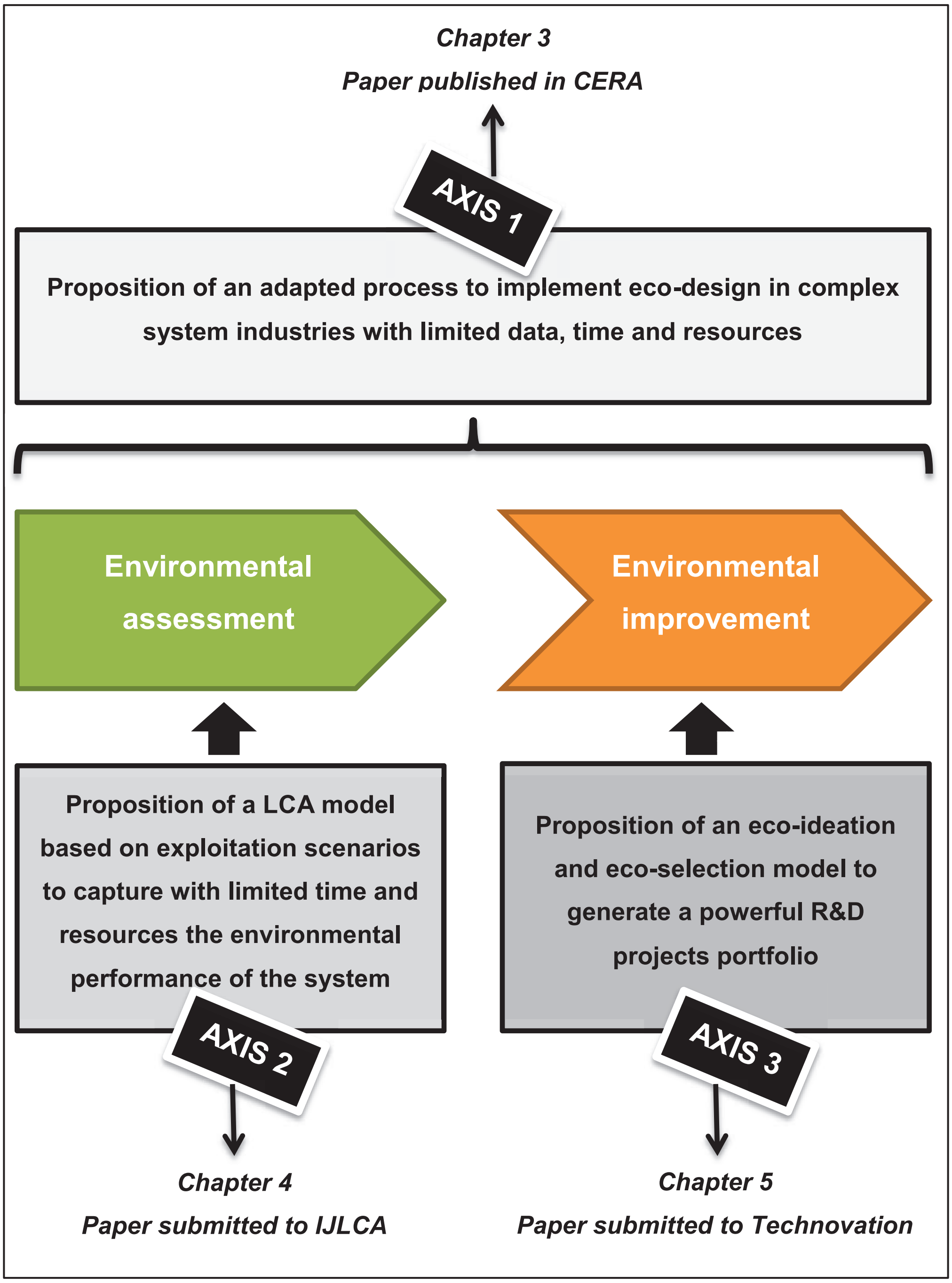

Figure 13. Positioning of the three research axes and links with the dedicated chapters and papers

2.2.2. Axis 1: an adapted eco-design process for complex industrial systems

Axis 1 answers to the first research question: *how to manage eco-design for complex industrial systems?* It is materialized by the scientific paper reproduced in Chapter 3, which has been recently published in *Concurrent Engineering: Research and Applications*.

From the literature review, an original methodology has been developed to support in a reliable way the implementation of eco-design in complex system industries. This methodology considers the DMAIC (*Define, Measure, Analyse, Improve, Control*) approach from the Lean 6 Sigma field to structure the different steps of a classical eco-design approach centred on LCA.

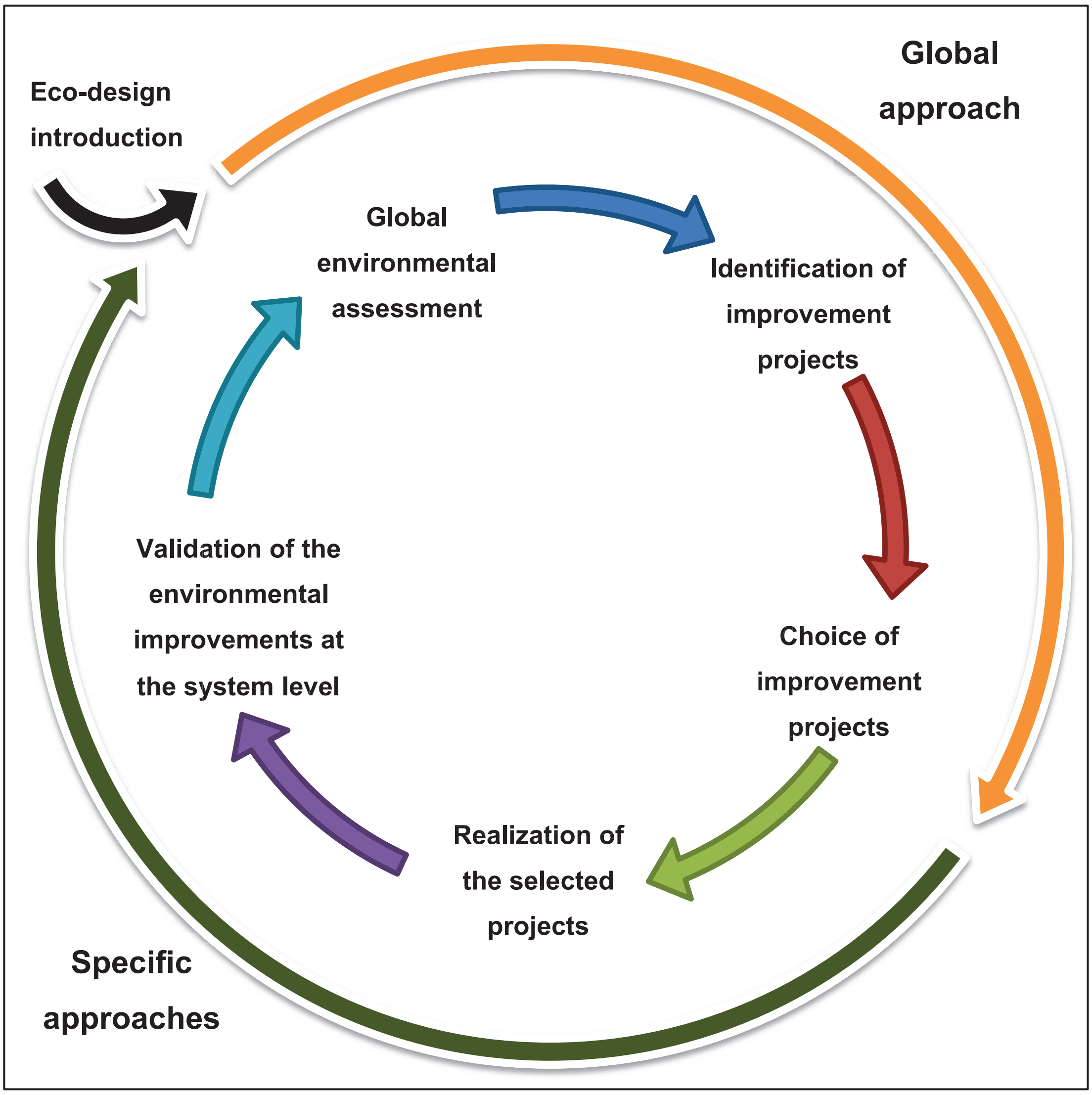

Figure 14. Overview of the main steps of the proposed eco-design process for complex industrial systems

A first global approach is proposed to support a global environmental assessment of the system through the *Define*, *Measure* and *Analyse* steps. Then improvement projects are identified and selected during the *Improve* and *Control* steps. These projects are realized and validated separately in specific approaches supported by another DMAIC scheme.

Once the projects have been realized, the whole process may be reiterated, in a continuous improvement perspective. The initial reference system is at that time replaced by the new system including the improvements validated at the conclusion of the projects. As complex industrial systems are considered, an entire loop may take some years.

As said previously, the application of this methodology only covers the global approach. The whole process is illustrated in Figure 14.

Figure 13 illustrates the positioning of the three research axes on a classical and simplified eco-design approach (environmental evaluation followed by environmental improvements). Figure 15 illustrates, with the process previously described, the positioning of the second and the third research axes within the first axis. These two axes are quickly described in the next paragraphs.

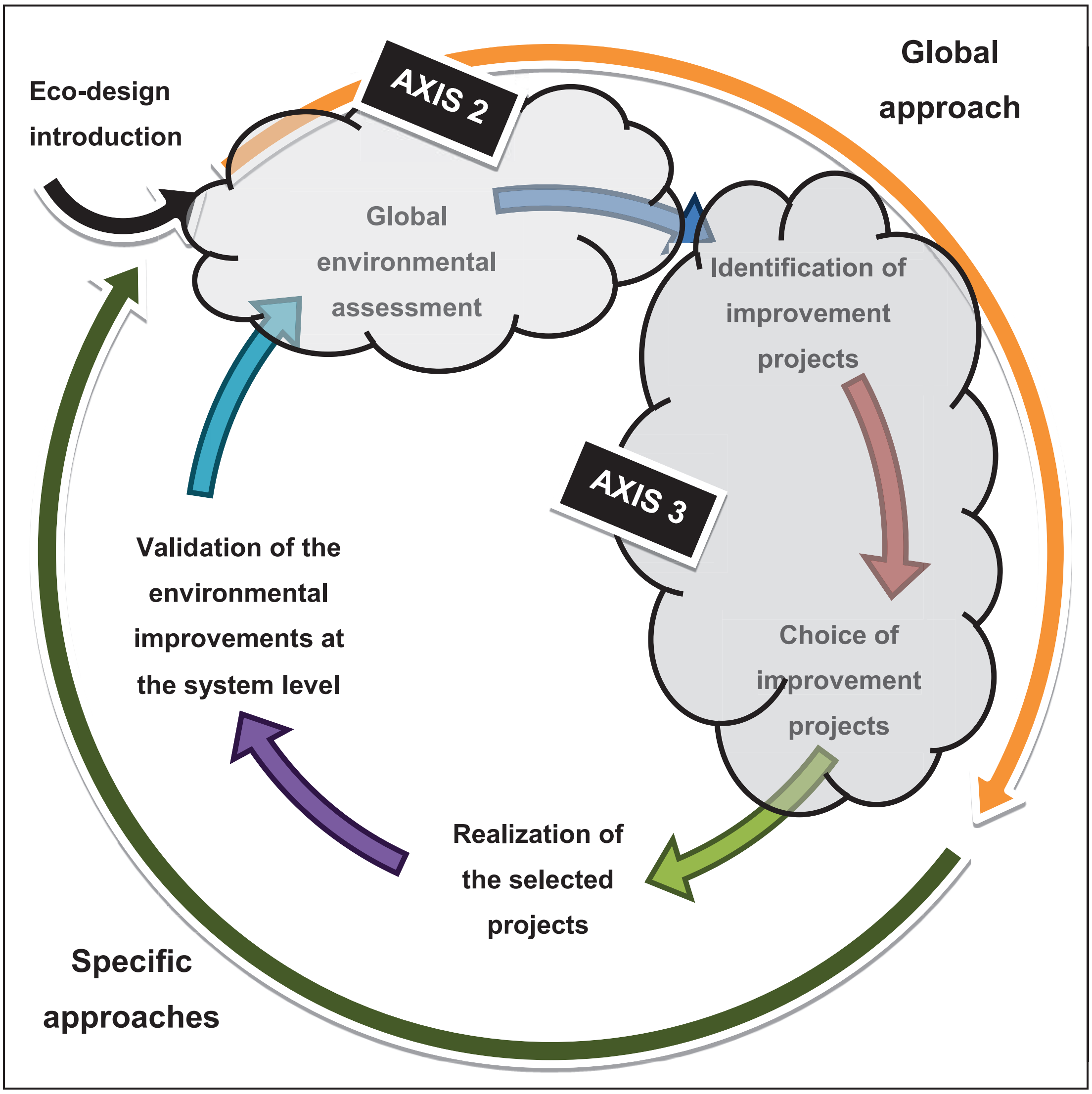

Figure 15. Positioning of research axes 2 and 3 in the global eco-design process (research axis 1)

2.2.3. Axis 2: a scenario-based LCA model for complex industrial systems

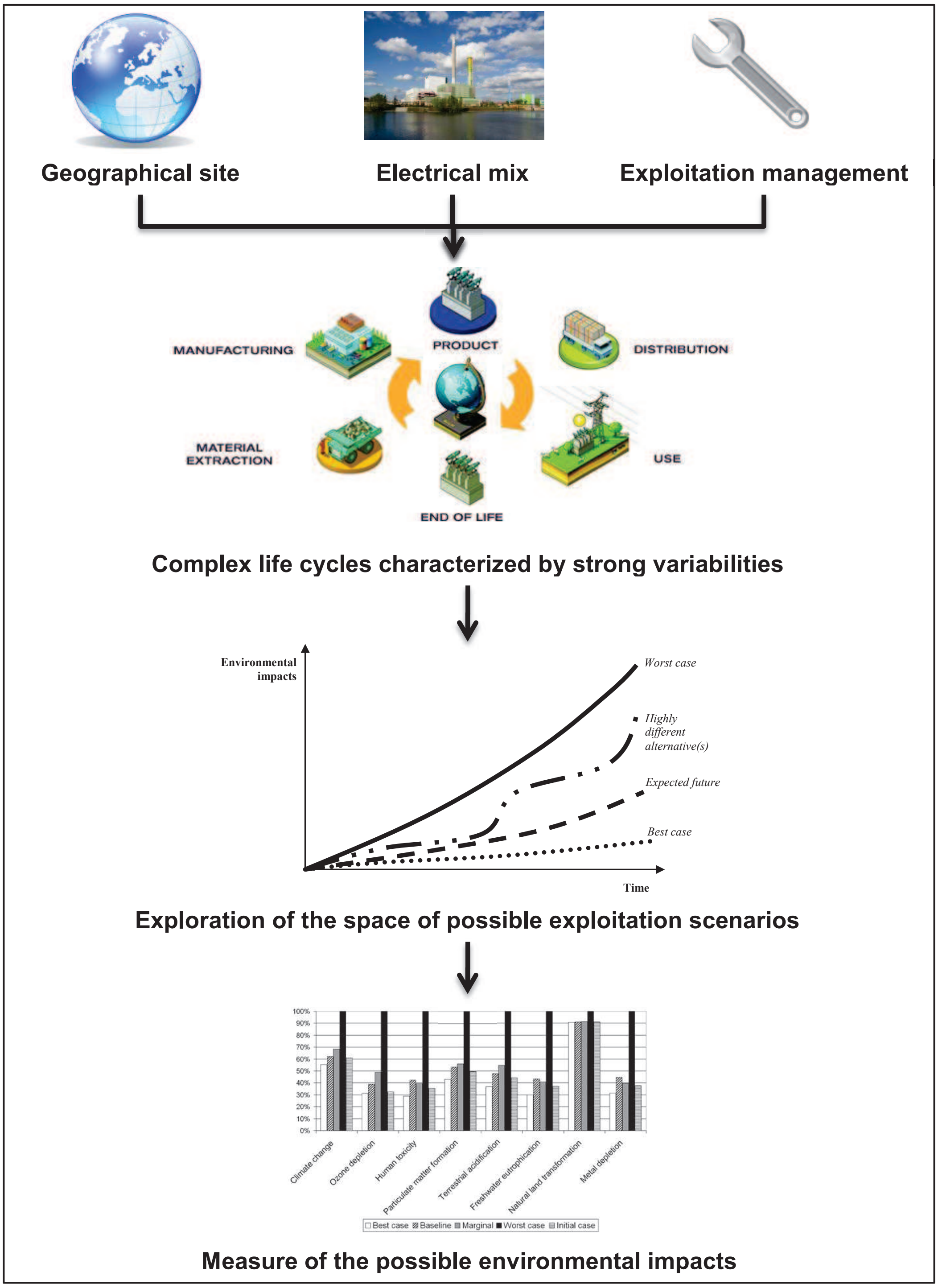

Figure 16. Overview of the proposed scenario-based LCA model for complex industrial systems

Axis 2 answers to the second research question: *how to assess the environmental performance of complex industrial systems?* It is materialized by the scientific paper reproduced in Chapter 4, which has been submitted in *the International Journal of Life Cycle Assessment*.

When performing a first global LCA of an Alstom Grid electrical substation as an application of the methodology proposed in the first research axis, it has been noticed that the methodology is helpful to rigorously define the objectives and the perimeter of the study, and to support the different steps of an LCA approach with a high amount of data. However it has also been noticed that the LCA methodology in itself hardly permits taking into account in a simple way the variabilities that may exist from one industrial site to another. To avoid tedious inventories of the system exploitation phase while the system in itself is almost the same from one project to another, it would be useful to have at one's disposal an adapted LCA model.

As only mainly qualitative, partial and uncertain data (without associated probabilities) are often available for complex industrial system like Alstom Grid substations, formal uncertainty methods have been quickly dismissed. Scenario-based LCA has on the other hand been carefully studied, as it encompasses all the needed characteristics.

From the first LCA we have identified the key elements that were not or badly taken into account to integrate them into the scenario-based approach. So relevant elements such as preventive and corrective maintenance, updates and revampings, or life time modulation have been identified and compiled into coherent exploitation scenarios.

From the geographical site, the electrical mix and the exploitation management associated to the system, scenarios are built to explore the space of possible environmental impacts, making the decisions issued from the LCA results more reliable. This process is represented in Figure 16. This scenario-based LCA model appears as being a good solution to make the eco-design decisions more reliable according to the possible exploitation scenarios. It is also a good way to initiate a dialog with the clients to generate good practices and recommendations in order to promote more cooperation and higher environmental benefits.

2.2.4. Axis 3: an eco-innovation process based on R&D projects portfolio for complex industrial systems

Axis 3 answers to the third research question: *how to generate and select a powerful eco-innovative R&D projects portfolio?* It is materialized by the scientific paper reproduced in Chapter 3, which has been submitted in *Technovation*.

LCA results from the previous research axis provide useful environmental information for decision-makers. However it does not ensure any environmental improvement, as LCA is mainly an evaluation tool. In the continuity of the general methodology developed in the first axis, the *Improve* phase aims at identifying improvement solutions to answer to the environmental problems detected thanks to the LCA results.

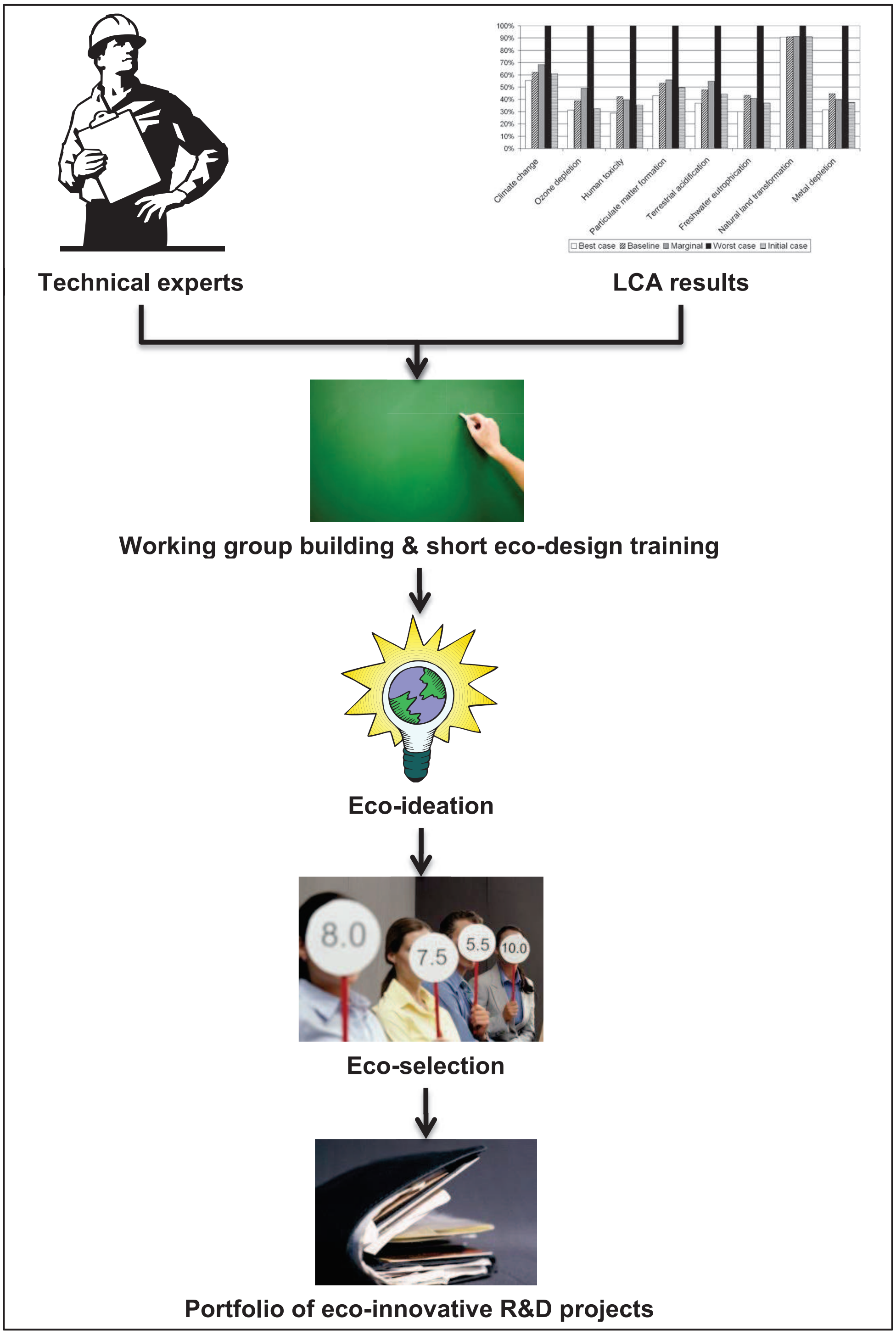

Figure 17. Overview of the proposed eco-innovation process for complex industrial systems

Considering the complexity of the studied systems, the identification of powerful improvement solutions is a hard task, and numerous design dimensions need to be considered. But the knowledge and the competences covering these dimensions are owned by numerous technical experts. That is why the intervention of technical experts of the company appears as an essential success factor to the environmental improvement phase. Moreover their participation to the deployment of eco-design in the company is also a key aspect to ensure a long-term implementation of eco-design practices.

From these considerations we propose an original eco-ideation and eco-selection methodology based on a working group of technical experts. The methodology is illustrated in Figure 17. A short eco-design training is performed and the main LCA results are communicated to prepare a creativity session based on a simple and resource-efficient eco-innovation tool, the eco-design strategy wheel (Brezet and Van Hemel, 1997). Ideas are generated and then sorted out thanks to three structured filters and a multi-criteria assessment grid (an overview of this grid is proposed in Appendix 1, p 149). The most promising projects are selected and integrated into a R&D projects portfolio presented to the company management.

The application and the validation of these three research axes have been performed at Alstom Grid on AC/DC conversion substations used in the primary aluminium industry. Some details are given in the next section.

2.3. Applications and validation

2.3.1. Deployment at Alstom Grid

The deployment of the methodology has been realized in the PEM (Power Electronics Massy) unit of Alstom Grid, a global leader in medium and high voltage products and systems. After the first theoretical work, the different applicative steps have been realized from the beginning of 2010 to 2012.

The author of this PhD dissertation has been directly leading the deployment of eco-design at PEM, as a full member of the R&D department. The work has been directly supported by the PEM R&D director and a senior sales manager from the commercial department. Some PEM members and some people from other Alstom Grid units have also been asked to contribute in the eco-design deployment at the different stages of the approach:

- During the Life Cycle Inventory to provide data,
- During the eco-innovation approach deployment to take part in the creativity working group,
- During the eco-innovation approach deployment to assess the projects in order to identify the best projects portfolio. The assessors have been the working group members and some eco-design experts from other Alstom Grid units.

The eco-design methodology has been deployed on AC/DC conversion substations, i.e. on the main electrical system provided by PEM. To provide accurate data to feed the substation

LCA, we have chosen to focus on one particular project. The project chosen is a substation under construction for a Hindalco aluminium smelter in India, with a capacity of 360,000 tons of aluminium per year and supplied by a captive coal power plant. As all the data are not available for this project, data from other close projects have also been used.

The final deliverable for Alstom Grid is a portfolio including 9 eco-innovative and documented R&D projects, with the objective to implement them in the next months. Some details about this portfolio are given in the next paragraph.

2.3.2. Identification of 9 eco-innovative R&D projects

The implementation of the general eco-design methodology, the application of the scenario-based LCA model and the realization of the eco-innovation process has finally led to the identification of a 9 R&D projects portfolio. These 9 projects have been chosen thanks to the evaluation performed by technical and eco-design experts. So they have been selected for their excellent performances in terms of environmental benefits, technical and economic feasibility and benefits for the clients. The 9 projects are listed below:

1. **Transformer optimization:** this project consists in the implementation of eco-design in the design process of special transformers used in the substations. It includes organizational, methodological and technological aspects on a long term perspective.

2. **Choice of transformer oil:** this project includes an in-depth analysis of the different transformer oils to develop more eco-friendly transformers.

3. **Design guidelines and tools:** this projects aims at developing adapted design methods and tools to eco-design complex industrial systems at a more operational level (once the global architecture is fixed).

4. **Transformer oil end-of-life:** the end-of-life of transformer oils is uncertain, and this project aims at documenting and providing recommendations for this particular stage.

5. **Use of recycled materials:** the objective of this project is to promote the use of recycled materials in the substation subsystems.

6. **Components marking for the end-of-life:** the substation end-of-life being highly uncertain, the goal of the project is to study the feasibility of specific marking on substation components to facilitate the end-of-life stage.

7. **End-of-life leaflets:** in parallel with the previous project, this one aims at documenting the possible end-of-life routes for the different subsystems, to favour ecological treatments despite the high uncertainties existing at the design stage.

8. **Recyclability:** the objective of this project is to promote the use of recyclable

materials in the substation subsystems.

9. **Transformer oil diagnosis:** finally this last project deals with oil diagnosis to monitor the health of transformers and to optimize their life time.

For confidentiality reasons, only few and general details are given about these projects.

This portfolio represents the main operational deliverable for Alstom Grid. However other contributions are of course perceptible for the company. They are listed in the next paragraph.

2.3.3. Contributions for the company

The main industrial contributions of this research work and its applications at Alstom Grid are listed below:

- **A robust and iterative eco-design methodology:** this methodology may easily be implemented in other units on other system with limited time and resources.

- **An efficient capitalization of knowledge:** the last step of the adapted DMAIC process, *Control*, ensures a systematic capitalization of the produced knowledge, easily mobilizable for future projects.

- **A competitive advantage:** as no environmental regulation currently focuses on complex industrial system such Alstom Grid substations, the implementation of eco-design is voluntary and it provides a useful competitive advantage for the company. It is also particularly useful if clients ask for a guaranteed environmental performance.

- **A better knowledge of the systems:** the LCA deployment implies an in-depth analysis of the system life cycle, and it provides detailed results, that permit developing and capitalizing new expert knowledge, potentially useful in other technical fields.

- **A new R&D positioning:** the identification of the eco-innovative R&D projects portfolio offers a new vision centred on environmental concern that can feed and orient the R&D program for the next years.

- **An effective environmental communication:** scientific publications issued from this PhD thesis ensure an interesting positioning of the company based on recognized eco-design results.

- **Internal cooperation:** the eco-innovation process involves both a multidisciplinary working group and a panel of technical and eco-design experts. It is thus a stimulating tool to promote cooperation between different units, or even between members of the same unit that are not used to work together.

- **External cooperation:** the whole process highlights on many aspects the possible cooperation with clients and suppliers. The collaboration with suppliers is particularly underlined with the scenario-based LCA model to co-develop eco-friendly exploitation scenarios.

The next chapters reproduce original papers published or submitted to international journals. They detail the methodologies and applications proposed in the current chapter.

Chapter 3. Paper #1: Proposition for an adapted management process to evolve from an unsupervised Life Cycle Assessment of complex industrial systems towards an eco-designing organisation

François Cluzel, Bernard Yannou, Yann Leroy, Dominique Millet

This paper has been published in *Concurrent Engineering: Research and Applications* in June 2012, under the following reference:

Cluzel F., Yannou B., Leroy Y., Millet D., 2012, "Proposition for an Adapted Management Process to Evolve from an Unsupervised Life Cycle Assessment of Complex Industrial Systems Towards an Eco-Designing Organisation", Concurrent Engineering: Research and Applications, 20 (2), pp 111-126.

Foreword

The first paper (Chapter 3) was chronologically written before the two other ones (Chapters 4 and 5). A first LCA is proposed concerning an Alstom Grid substation. This LCA is shown in the first paper as the application of the first steps of the methodology. But it was also a way to identify weak LCA methodological elements that are the base of the second paper (Chapter 4), i.e. a scenario-based LCA model.

In a new and fictive implementation of the general methodology, the scenario-based LCA model would directly be applied instead of the classical LCA application proposed in the first paper, as it is proved to be more efficient and adapted to R&D strategic orientation than a classical LCA.

Finally, the general methodology proposed in the first paper includes a step of generation and selection of eco-innovative R&D projects. No application of this process was proposed in it, as the paper was written before this application. The detailed process and its application are thus proposed in the third paper (Chapter 5).

To synthetize, the first paper (Chapter 3) proposes a methodology in two steps: environmental evaluation and environmental improvement. The environmental improvement is applied in the first paper through a classical LCA study, but a more accurate and adapted model based on exploitation scenarios is then developed and applied in the second paper (Chapter 4). The environmental improvement step is detailed and applied in the third paper (Chapter 5).

Abstract: The integration of environmental concerns into the product design process is not trivial when dealing with complex industrial systems. Actually, environmental assessment methodologies like Life Cycle Assessments (LCA) reach, in this case, methodological and organisational limits. More generally, the complexity inherent in the design process may put off eco-design initiatives from a lack of organisational management, methods and tools. In this paper, we propose a project management methodology to facilitate the integration of eco-design into the design process of complex industrial systems. This methodology is based on continuous improvement and a DMAIC process. It is then structured around precise team definition, precise milestones, deliverables and phases. A first stage ensures a reliable environmental assessment of the full system and the identification of environmental improvement projects. A second stage allows the independent execution of the most promising improvement projects. A first application is proposed on the Alstom Grid AC/DC conversion substations for the aluminium industry. A Life Cycle Assessment has been performed with limited resources and has provided rich findings and promising perspectives. It shows in particular that the best environmental configuration of such a complex industrial system depends on external parameters like the implantation site.

Key words: Eco-design, Life Cycle Assessment (LCA), Product-oriented environmental management, Lean Six Sigma, complex industrial system, AC/DC conversion substation.

3.1. Introduction

Eco-design has become a major concern for many large companies in the last decade. Dealing first with mass consumer goods, B-to-B firms are now concerned. The constantly evolving regulations framework (particularly in the European Union with the WEEE [1], RoHS [2], EuP [3] directives or the REACH regulation [4]) and highly competitive markets are pushing the most innovative complex industrial systems producers towards a proactive eco-design approach. However, substantial limitations are slowing down this deployment in the design process of such systems. Characterised by their complex architectures, complex life cycles or large-scale scope, these systems cannot be considered as “classical” products. Actually performing a Life Cycle Assessment (LCA) on a large energy system is an extremely hard task and the lack of resources (people, time, money) as well as the lack of accurate data quickly becomes unacceptable.

It is thus necessary to find a way to perform environmental assessments of complex industrial systems with limited resources at an acceptable quality level. That is why this paper proposes an adapted eco-design project management methodology for complex industrial systems. This two-stage iterative methodology is based on a global environmental assessment of the system with a Lean Six Sigma approach, along with specific environmental improvement projects. This methodology naturally finds its place among the different environmental standards (in particular ISO 14006 [5], ISO 14062 [6] and ISO 14040 [7]) and methodologies proposed in the past, like Product-Oriented Environmental Management Systems (POEMS, see [8]). Its main force is its compatibility with these standards, while being adaptable to company constraints; it allows adapting the study to the complexity of the system, thanks to a precise project charter.

The application of the first steps of the methodology was performed on an Alstom Grid AC to DC conversion substation for the aluminium industry. This industrial system is characterised by a high level of complexity in terms of the number of components and life cycle. Its environmental impacts are extremely dependent on the implantation context and the choices made at the super system level (aluminium smelter). Thus, this is a good example of a complex industrial system.

The results of this first LCA have provided with limited resources a strong basis to deploy eco-design activities. They have also permitted the establishment of a working group to orient the future eco-design activities within the company. The application of these next steps will ensure the ability of the methodology to successfully design and configure complex industrial systems from an environmental perspective.

The original methodology has undergone major improvements since its first version (see [9]) to permit its application in accordance to the company's constraints. This paper includes the last evolutions and applicative steps, as well as a clear positioning among the standards and other existing approaches.

Section 3.2 presents a definition of a complex industrial system and highlights the limits of eco-design and Life Cycle Assessments for such systems. This permits a clear positioning of the methodology among the different standards and previous approaches. The methodology is then detailed in Section 3.3 through the description of the different DMAIC steps. Section 3.4 proposes an application on Alstom Grid AC/DC conversion substations, with a focus on the main LCA results obtained thanks to the methodology. It shows the importance of focussing the improvement projects on particular aspects (life cycle phase, subsystem, component or material) while always considering a global environmental vision of the system. Finally, some conclusions and perspectives are given, the next applicative steps are described and the concept of an 'environmental configurator' is introduced.

3.2. Methodological Positioning

3.2.1. Context of the Study

This paper focuses on complex industrial systems whose specificities have not really been taken into account by eco-design and Life Cycle Assessment: these are industrial systems where complexity induces major issues in terms of modelling, prediction or configuration. If we consider the systems engineering domain, Blanchard and Fabricky [10] characterise engineered systems as systems that achieve operational objectives; that operate over a complete life cycle; that are composed of a combination of resources (humans, materials, equipment, money…); that are composed of subsystems and components that interact with each other; that are influenced by external factors from larger systems and in interaction with the natural world. Adding an environmental dimension, we define a complex industrial system in the sense of eco-design as:

- A large-scale system in terms of subsystems and components, mass and resource usage
- A system whose life cycle is hardly predictable at the design level in the long-term, in particular its lifetime, upgrades, maintenance and end-of-life
- A system whose subsystems may have different life cycles and different obsolescence times
- A system in close interaction with its environment (super system, geographic site…)
- A system supervised by human decisions and management

Examples of such systems are, in particular, energy systems like the Alstom Grid conversion substations described in Section 3.4. In such systems, the classical eco-design limitations are amplified by the internal system complexity. In addition, complementary issues appear. These limitations are explained in more detail in the next sections.

3.2.2. Limits of Eco-Design for Complex Industrial Systems

From this definition, this part first considers LCA limits encountered in complex industrial systems. Then, wider eco-design limits are detailed to introduce the requirement definitions.

3.2.2.1. Technical LCA Limits

Life Cycle Assessments of large-scale energy systems have already been performed (see for example [11,12]). However, they are considered as 'classical' products. Local implantation in particular, due to the nature of electricity, seems crucial to approximate the real environmental impacts of these systems.

Moreover, the current eco-design limits, in particular for LCA are a recurrent discussion topic. Reap [13,14] gave a list of LCA problems by phase (see Table 4). The problems that particularly concern us in this paper are in bold in Table 4.

The boundary selection is hard to manage for complex industrial systems because the high number of subsystems and the interactions with surrounding systems make the boundaries fuzzy. Another problem concerns the inventory data granularity to choose, and more globally the data availability and quality [15]. Is it necessary to consider every screw or electrical component to obtain significant LCA results? This problem is also taken into account by Leroy, who highlights the need for quantified data [16].

Table 4. LCA problems by phase (from [13])

Phase	Problem
Goal and scope definition	• Functional unit definition • **Boundary selection** • Social and economic impacts • Alternative scenario considerations
Life cycle inventory analysis	• Allocation • Negligible contribution ('cutoff') criteria • Local technical uniqueness
Life cycle impact assessment	• Impact category and methodology selection • **Spatial variation** • Local environmental uniqueness • Dynamics of the environment • Time horizons
Life cycle interpretation	• Weighting and valuation • Uncertainty in the decision process
All	• **Data availability and quality**

The last problems raised by Reap that interest us, deal with the spatial dimensions, that means the variability that could exist for the same product on different geographical sites. Actually as it will be shown later in the paper, exogenous parameters such as electricity mix can have strong influences on the environmental impacts. We clearly need to manage the uncertainties about spatial dimensions to obtain significant results.

These technical problems are well known to LCA practitioners. We do not pretend to solve them, but we are looking for a methodology that will help us to consider them systematically.

3.2.2.2. Overall LCA and Eco-Design Limits

Apart from technical limits, other problems of the eco-design process management will be considered in our study.

The first one is that LCA is an evaluation tool and not an improvement tool. It is then only the first stage of an eco-design process. Dewulf shows in [17] that LCA is able to feed environmental improvement tools, but it needs to be based on an existing product. It is not adapted to a new product design [18].

Furthermore, ISO 14062 [6] specifies the need for a multi-disciplinary team throughout the eco-design process, but it does not specify how to build the team. The eco-design process is globally defined, but no standardised or systematic deliverables and milestones exist. As shown in the next section, the existing standards and methods stay at a requirement or guidelines level. To complete them an operational level seems necessary to manage the complexity of complex industrial systems.

Finally, there is no clear way to include the customer requirements that will orient the decisions throughout the process within the study.

3.2.2.3. Methodology Requirements

Following from the above, we need to define an operational methodology that:

- Can systematically consider the technical LCA limits concerning complex industrial systems
- Can be applied on different systems and subsystem levels
- Considers a reference product to improve
- Supports ISO standards for LCA
- Covers both the environmental evaluation and improvement phases
- Offers a rigorous framework with precise milestones and deliverables and a clearly defined team
- Can take into account customer requirements

The next section studies the pre-existing approaches in the literature to refine and position the methodology detailed in Section 3.3.

3.2.3. Literature Study

3.2.3.1. Normative Aspects

The normative framework concerning environmental management and eco-design is constantly evolving. However, standards often stay at a high level of abstraction and are often difficult to apply directly in companies. We distinguish three normative levels in Figure 18. The requirements define the scope, the objectives and the global outline of the approach. The guidelines are more precise and propose general ways to attain the requirements. Finally, the operational methodologies, based on the guidelines, are directly applicable to the studied object. These three levels are represented on the Y-axis. The X-axis distinguishes the site-oriented approaches from the product-oriented approaches. This distinction can also be made between site management and product design. The frames inside the diagram give a third dimension. The focus is on environmental management, and more precisely, eco-design.

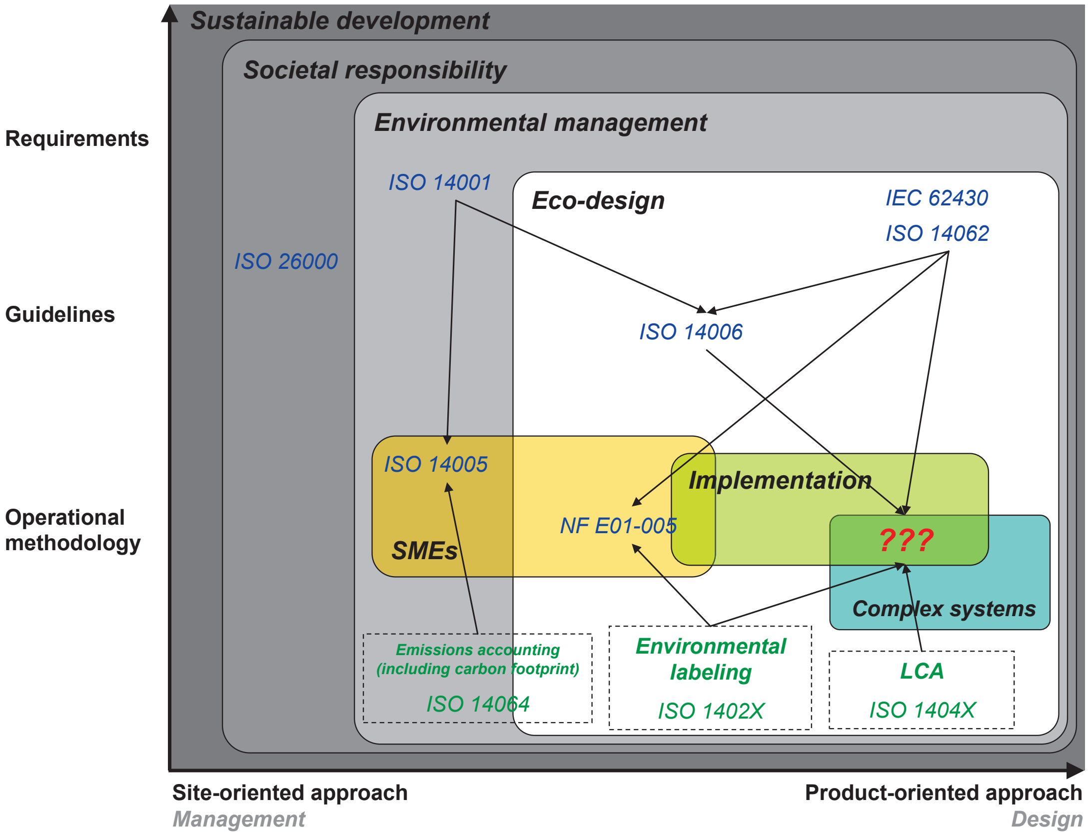

Figure 18. Positioning amongst some pre-existing environmental standards. The arrows represent the connections between the standards.

ISO 14062 [6] and IEC 62430 [19] standards are directly connected to eco-design by describing the main lines of the integration of the environment into product design. ISO 14006 [5] gives guidelines to incorporate eco-design into the more general framework of environmental management systems (ISO 14001 [20]). NF E01-005 [21] (French standard) caters to eco-design in small and medium enterprises with an operational, but simplified approach. Finally, ISO 14005 [22] permits the easy application of environmental management practices (from ISO 14001) in SMEs, but it is not focused on eco-design.

On the other hand, environmental tools like emissions accounting (ISO 14064 [23]), environmental labelling (ISO 14020 series [24–27]), or Life Cycle Assessment (ISO 14040 series [7,28]) are clearly operational but only support a part of the eco-design process deployment.

Therefore, this diagram highlights the lack of an operational eco-design methodology for complex industrial systems based on well-established standards and supported by well-known environmental tools such as LCA. In these systems, the implementation stage is a real challenge and it has to be 'precaution' driven. This is why the issue is also highlighted in the diagram.

Now that the proposed methodology is precisely positioned amongst the different environmental standards, in the next section we can focus on the multiple approaches that exist in the literature.

3.2.3.2. Product-Oriented Environmental Management Systems

Due to this lack of operational standards to support a complete eco-design process in companies, different approaches have been proposed in the past, under the acronym POEMS (Product-Oriented Environmental Management Systems). They are mainly based on the fact that the classical EMS proposed in ISO 14001 are focused on site environmental aspects and they do not easily consider environmental impacts of products. The CALCAS report (Co-ordination Action for innovation in Life Cycle Analysis for Sustainability: a project financed by the Sixth Framework Programme of the European Commission) states that *"traditional EMSs (ISO 14001, EMAS) do not encompass products in their procedures and do not answer to the needs of firms to communicate the environmental quality of products"* [8]. Moreover, classical approaches often display major weaknesses in the management aspects of eco-design [8]. Finally, a common definition of POEMS appeared recently: a POEMS is defined as "*an EMS with a special focus on the continuous improvement of a product's eco-efficiency (ecological and economic) along the life cycle, through the systematic integration of eco-design in the company's strategies and practices*" [8,29–31].

Examples of POEMS are given in [29,30,32,33]. While these methodologies stay closely connected to academic works, other approaches, at Airbus for example [34], have been developed in major industrial companies. This particularly highlights the requirements of companies, namely to adapt POEMS to their own organisations [35]. This is mandatory to drive proactive eco-design activities successfully.

From the previous section, a comparison can easily be made between POEMS and ISO 14006, as these approaches aim at adapting EMS for eco-design. However, we consider that they stay at a guideline level, because they encompass all the eco-design activities of the company, starting at the environmental policy level. With a perspective of application to complex industrial systems, a methodological layer is clearly missing.

Moreover an analogy is made in [36] between POEMS and TQM (Total Quality Management). This comparison with the fields of quality and continuous improvement is extremely interesting and will be explored in the next sections. Actually, the rigor, the organisational aspects and the adaptability of such methodologies appear promising for the application of eco-design to complex industrial systems in concrete terms.

3.2.3.3. Lean & Green

Lean & Green is a concept mixing Lean Six Sigma and environmental considerations in order to minimise the environmental impact of a product, service or process. It appeared in the last decade. Several companies or organisms propose variants on *Lean & Green* approaches.

The US Environmental Protection Agency has used this term since 2000, in a document called *The Lean and Green Supply Chain* [37]. The EPA has gone further since then and now proposes a structured and well-detailed approach called *Lean Manufacturing and the Environment* [38]. Different interesting toolkits are available:

- *Lean and Environment Toolkit* [39], which is oriented towards the identification of the environmental wastes in a supply chain,
- *Lean and Energy Toolkit* [40], whose aim is to identify energy losses in an industrial process to improve performance.

Furthermore, for several years IBM has offered a consulting offer called Green Sigma. "*This is a new solution offering, which merges IBM's deep expertise in Lean Six Sigma with other robust green initiatives, resources and intellectual capital across the company*" [41]. The Green Sigma project is divided into five stages: define key performance indicators, establish metering, deploy carbon dashboard, optimise processes and control performance - which is very close to the Six Sigma DMAIC approach (*Define, Measure, Analyse, Improve, Control*).

Other approaches based on the same principles are described in [42] and [43]. These two books show several industrial case studies of *Lean & Green* approaches. As in the previous examples, these different *Lean & Green* approaches have advantages (use of the rigorous Lean Six Sigma framework to optimise complex systems), but we consider that they stay site-oriented and are hardly applicable to products (we consider the whole product life cycle). They potentially offer powerful tools to assess the environmental quality of supply chains and organisations and, consequently, they are more oriented towards environmental management systems (see ISO 14001 [20]).

3.2.4. Synthesis

This literature study has shown that no existing methodology is really adapted to manage the eco-design of complex industrial systems. POEMS and ISO 14006 offer a promising methodological layer, but they are not easily applicable at an operational level. This could be deliberate in order to let companies customise POEMS to their own organisation. However, the specificities of complex industrial systems in terms of eco-design make it necessary to develop an additional layer. *Lean & Green* approaches are also useful to organisational aspects. That is why in the next section we will develop this additional layer on a DMAIC basis with close links to POEMS and ISO 14006.

3.3. Model description

The model proposed in this paper is based on two stages. The first is a "global approach" and is focused on environmental assessments and the identification of methods of improvement. The second includes several "specific approaches" and is more focussed on environmental improvements.

3.3.1. General Model

The main objective of the methodology is to permit an easier integration of eco-design in a company unit designing complex industrial systems, where there was no pre-existing approach. The focus is particularly on operational implementation throughout the organisation by giving a concrete and generic detailed process. It is more precise than POEMS and ISO 14006 that are focused on requirements and guidelines at a more strategic level. In the next section, we will present an application in a unit of Alstom Grid, where the strategic dimension of eco-design (environmental policy in particular) is pre-existing at the group level. The industrial needs are thus centred at the operational level in the unit. Therefore, the methodology is compatible with POEMS and ISO 14006 and complements them as a user-friendly layer.

A classical eco-design approach is divided into two main stages: environmental evaluation and environmental improvement. From an initial environmental assessment (often based on Life Cycle Assessment or simplified LCA), design recommendations emerge to improve the overall environmental performance of the product throughout its whole life cycle.

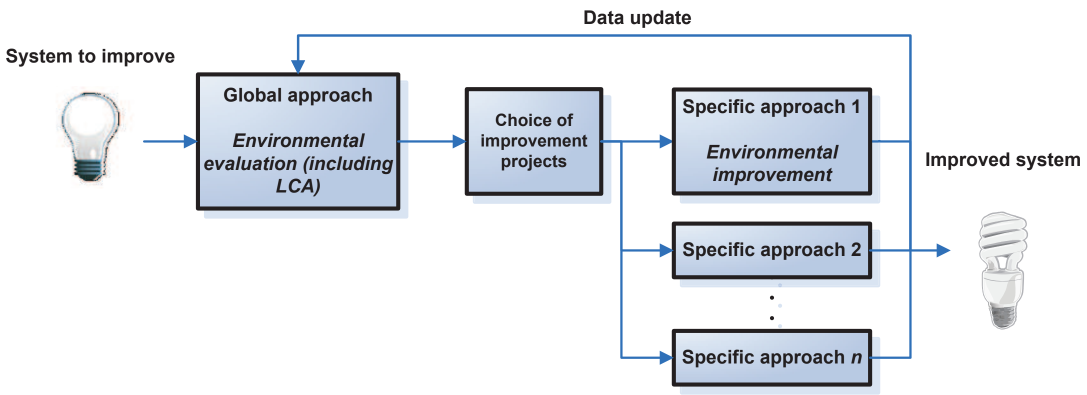

Figure 19. Global versus specific approaches to manage the eco-design of complex industrial systems

The proposed methodology maintains this global architecture, but the complexity highlighted in Section 3.2 makes the implementation of a classical eco-design process delicate. That is why the methodology is divided into a global environmental assessment on the one hand and specific improvement approaches on the other. It is designed to start from an expert approach (LCA) and evolve to an expert-assisted approach through a continuous rise in knowledge and competency and clearly defined deliverables. Figure 19 illustrates the iterative architecture of the methodology. This iterative nature ensures continuous improvement, a good capitalisation of the results as well as an effective expertise transmission. The next sections detail these different approaches.

3.3.2. About DMAIC

In order to standardise and facilitate the deployment of this methodology in companies, it has been constructed on a Lean Six Sigma basis and, more precisely, on a DMAIC process. Lean Six Sigma is a continuous improvement approach, which gives competitive advantages and creates value for the stakeholders. Historically, increasing the performance of one dimension of the *Quality, Cost, Time* triangle meant decreasing the performance of the two other dimensions. In the continuous improvement paradigm (including Lean Six Sigma), all dimensions increase together.

Lean Six Sigma is a mix of Lean Manufacturing and Six Sigma. Lean Manufacturing targets waste (waste increases costs and has no value for customers). It is a bottom-up approach. On the other hand, Six Sigma improves customer satisfaction by increasing quality and by killing variation. It is a top-down approach.

Lean Six Sigma includes two main methodologies: PDCA (*Plan, Do, Check, Act*, also known as the Deming wheel) and DMAIC (*Define, Measure, Analyse, Improve, Control*). Environmental management systems such as POEMS are based on PDCA [20] (see next section). They allow daily and continuous improvement. Contrary to the PDCA approach that increases performance thanks to successive iterations, the DMAIC approach offers an incremental performance improvement. It is based on a rigorous methodology that is adapted to complex problems whose non-solution is known. A DMAIC project is supported by a multi-disciplinary team and a project leader, who is an expert in Lean Six Sigma. It lasts from four to six months and is formalised by precise deliverables. The DMAIC project is structured in five stages:

- *Define:* starts the project and formalises the problem. The main deliverables are a project charter, the voice of the customer and the team definition.
- *Measure:* identifies the problem reference base and collects the data needed to know the fundamental causes. The main deliverables are the definition and the identification of the key factors, process flow diagrams, and measuring system analysis.
- *Analyse:* the fundamental causes of the project are identified, representing the 20% of causes that produce 80% of the effects. The main deliverables are the identification of the potential causes, the estimation of the effects on the consequences and the validation of the causes and prioritisation.
- *Improve:* allows the definition, deployment and validation of the solutions. The main

deliverables are the identification of innovative solutions, the validation of the solution impacts and the realisation of a pilot project.

- *Control:* aims to preserve the benefits and to standardise the solution throughout the company. The main deliverables are poka-yoke (fool-proofing), procedures, training, standardisation…

The methodology proposed in this paper is based on DMAIC. However, it is not an application of DMAIC to eco-design, but an adaptation of DMAIC for the eco-design of complex industrial systems. The goal is to take advantage of the forces of DMAIC to make the process of eco-design for complex industrial systems more reliable, systematic and formalised.

3.3.3. Integration in a POEMS or ISO 14006 Approach

The good integration of this methodology in the POEMS or ISO 14006 approach is necessary. This issue is studied in this section.

Actually the POEMS approach, as well as the ISO 14006 approach are based on a PDCA cycle. The content of the four PDCA stages may change from one reference to another but it globally stays the same. From the previous POEMS references [8,29–36] and the ISO 14006 standard [5], it is possible to define the general processes linked to the PDCA stages (see Figure 20).

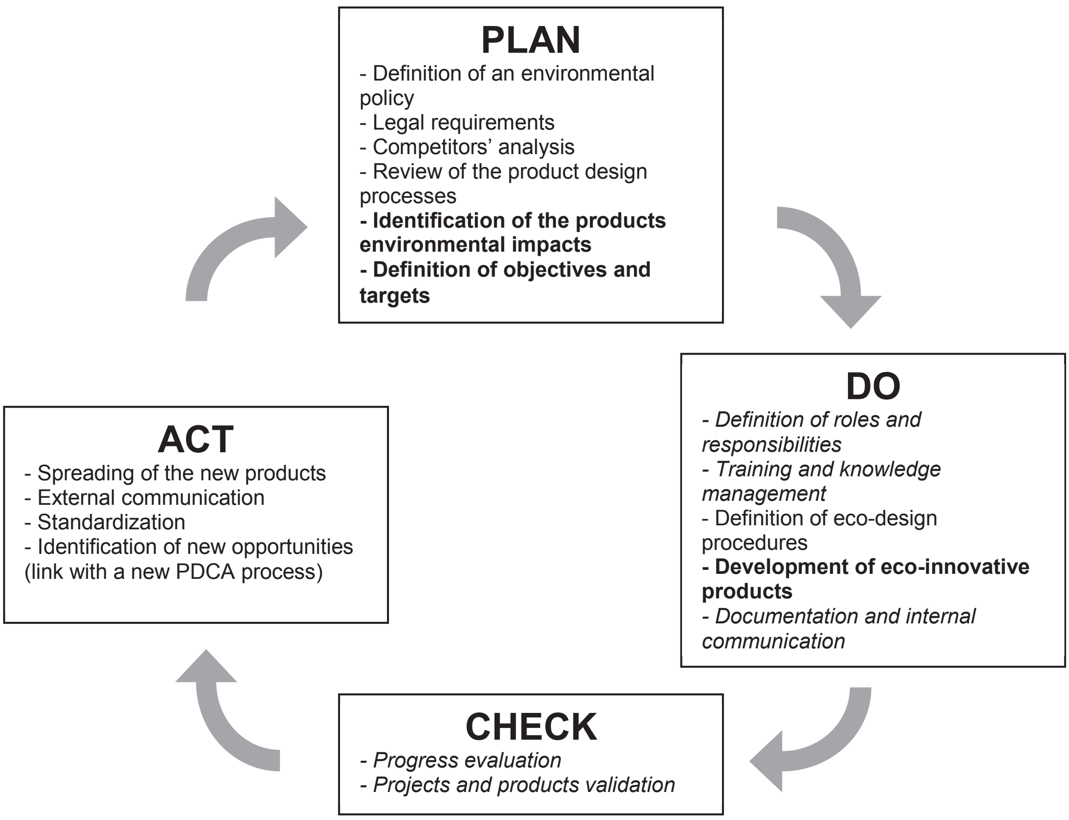

Figure 20. Generic POEMS approach

On Figure 20 the processes marked in bold represent the processes that are entirely managed by the proposed methodology, whereas the processes marked in italic are partially managed. The proposed methodology thus offered a concrete answer to the operational eco-design actions of a POEMS approach. The following sections will explain this methodology in more details.

3.3.4. Global Approach

The global approach is devoted to a global environmental assessment of the system and to the identification of ways to improve this overall environmental performance. It gives concrete actions for the two PLAN processes in bold on Figure 20. It is implemented via an adapted DMAIC approach from the Six Sigma theory:

- *Define:* via a project charter, including the goal and scope phase of LCA, the objectives, the team and sponsors, the project plan and the impacts of the project are stated. The project charter is presented in Table 5 below. It includes the information required by ISO 14040 [7] at the *Goal and Scope* stage. This charter is a fundamental document to structure the project, as it clarifies all that is often implied in classical projects. Moreover, as it is compatible with LCA standards, it is a useful tool to ensure the validity and the communication of the project.

- *Measure:* this stage includes the Life Cycle Inventory (LCI) and the Life Cycle Impact Assessment (LCIA) phases of LCA. These two stages provide the data needed to identify the fundamental causes of the problem. During the Life Cycle Inventory, data is collected to model the system life cycle in the LCA software (mass, materials, energy, manufacturing processes, transport…). The potential environmental impacts associated with this life cycle are then calculated during the LCIA phase thanks to dedicated methods in the LCA software.

- *Analyse:* this third stage includes the last LCA phase, the Life Cycle interpretation. Through an analysis of the previous phases, as well as sensitivity and uncertainty analysis, the main environmental impacts are identified.

- *Improve:* the objective of this stage is to identify technological solutions to the fundamental causes. It is performed through the setting up of an internal and multidisciplinary working group. Creativity sessions based on the eco-design strategy wheel (also known as the Brezet wheel) [44] ensure the identification of the improvement projects, as well as the evaluation of their technical and economic feasibility thanks to a dedicated evaluation process based on maturity scale (not detailed in this paper).

- *Control:* the project responsibility is then returned to the sponsors who are able to choose the best improvement projects that will lead in the specific approaches. The results of the whole DMAIC project are communicated and capitalised.

Table 5. The new project charter in line with the ISO standards dedicated to LCA.

Business impact	**Problem/opportunity statement**
The material and immaterial expected benefits are listed, as well as the efforts needed to reach these benefits. For example, the expected benefits could be: • *Environment:* decreasing the environmental impact over the whole lifecycle • *Cost:* decreasing the *Life Cycle Cost* (LCC) • *Quality:* increasing the component quality (Lifetime extension, maintenance needs limitation, energy losses decreasing…) • *Time:* extension of the product lifetime These elements need to be precise and quantified.	The environmental problem is described according to the *Five Ws (and one H)* formalism. An example applied to the electrical substations studied in Section 3.4 could be: Alstom Grid PEM (**Who?**) wishes to optimise the environmental impact of its conversion substations (**What?**) during the design process (**When?**). These substations are sold worldwide to primary aluminium plants (**Where?**) to convert energy from high voltage networks to energy that is usable for aluminium electrolysis. The study aims to minimise the environmental impacts throughout the product life cycle while still considering the technical and economic criterion (**How?**). It is a way for Alstom Grid PEM to be differentiated from the competitors (**Why?**).
Key metrics	**Project scope**
The objectives are described according to ISO 14040 [7]: • Intended application • Reasons for carrying out the study • Intended audience • Are the results intended to be used in public comparative assertions? The key indicators are the environmental indicators chosen for the study according to the objectives and the intended audience. Other indicators can be considered, such as technical or economical, or even social in a sustainable development perspective.	The expected information asked by ISO 14040 to define the scope of the study is [7]: • Studied product system • Functions of the product system • Functional unit • System boundary • Allocation procedures • Selected impact categories and impact assessment methodology • Data requirements • Assumptions • Limitations • Initial data quality requirements • Type of critical review, if any • Type and format of the report
Project plan	**Team selection**
The project milestones are defined. Each phase duration needs to be detailed.	The members of the eco-design team are selected. The different roles are: • Sponsors, who ask for the project • Champion, who vouches for the rigorous application of the methodology • Project leader (Black belt in a classical Lean Six Sigma approach), who is responsible for the progress of the project • Team members, who are the human resources allocated to the project

3.3.5. Specific Approaches and Closed Loop

Then the specific approaches allow the realisation of projects that have been chosen by the decision makers during the Control phase of the first DMAIC. These improvement projects are defined as classical R&D projects of the companies with an added environmental follow-up at the different gate reviews. It answers to the DO and CHECK processes highlighted on Figure

20.

The aim of such specific approaches is to classify the main and complex problems into sub-problems with a more precise scope and lower complexity. The specific approaches are designed to give the company a high level of freedom to adapt the environmental considerations to its processes. The idea is not to bring a new design constraint, but to consider the environment as a new opportunity to improve products and processes, to improve the brand image and finally to be differentiated from competitors.

In terms of implementation, a DMAIC approach also seems adapted to these projects. Nevertheless, it has to be differently adapted. Its objective is not to support the full project, but to ensure an environmental follow-up for the classical R&D projects of the company. The five stages are:

- *Define:* a new project charter is defined based on the same model as Table 5. The difference with the global approach mainly concerns the scope and the objectives of the project.

- *Measure:* the LCI and LCIA stages are extended according to the project charter (the focus is on the subsystem or life cycle phase targeted by the project objectives).

- *Analyse:* the LCA results are analysed. Sensitivity and uncertainty analyses are sometimes performed.

- *Improve:* the new technical solution is developed in detail. A comparative LCA identifies its environmental benefits (and the potential impact transfers). Economic and technical aspects are also considered.

- *Control:* the project responsibility is returned to the sponsors, who are able to include the new technical solutions in the commercial offer. The results of the whole DMAIC project are communicated and capitalised. The sponsors can also plan further works, or launch a new global approach by updating the previous one.

Once the specific approaches have been performed (after several months or years, depending on the considered system), a new iteration of the entire process may be launched. The global approach would then be implemented on the new and environmentally optimised system. This ensures a continuous improvement process, taking into account potential evolutions of the system's environmental performance.

The next section proposes an application of the first stage of the methodology (global approach) within a business unit of Alstom Grid.

3.4. Application of the Global Approach to Alstom Grid AC/DC Conversion Substations for the Aluminium Industry

The conversion substations are briefly described, then an application of the global approach is detailed, as well as perspectives for the specific approaches.

3.4.1. AC/DC Conversion Substations

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 is a particularly environmentally impacting and energy-consuming activity [11]. 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 (four in Figure 21) 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).

Figure 21. Example of an Alstom Grid AC/DC conversion substation (Aluar, Argentina)

In this context, Alstom Grid PEM wishes to minimise the environmental impacts of its products to answer to the environmental policy of the company and to be differentiated from competitors.

From the current substation's design, the objectives are to evaluate the environmental impacts throughout the product life cycle and to identify design parameters/impacting factors whose variation could minimise the environmental impact, while preserving the other design aspects. It will permit to identify and conduct environmental improvement projects. Finally, the results need to be reusable in the future

- The 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 really long, 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. We consider substations as a product family.

It is easy to understand that the complexity of the considered system makes the study delicate. The next section details how the global approach has been applied to an example of a substation.

3.4.2. The DMAIC Process Including LCA

3.4.2.1. Define

First the project charter was defined by following the template presented in Table 5. The main objective of the study is the identification of the main environmental impacts of a substation in order to identify projects to improve its environmental performance. Therefore, its purpose is to orient future eco-design activities at Alstom Grid PEM.

The study is focused on an Alstom Grid AC/DC conversion substation that has been designed and is currently under construction for the Hindalco Mahan aluminium smelter. The whole life cycle of the substation will be considered. The Hindalco Mahan aluminium smelter (under construction too) is located in central India (Bargawan, state of Madhya Pradesh). It is characterised by a captive coal power plant (900 MW) and is designed to produce 360,000 tons of primary aluminium per year with modern electrolysis pots.

Considering the constraints and characteristics of such a project, the following functional unit is considered: *"To ensure the conversion of 220 kV_{AC} high voltage energy to energy usable for aluminium electrolysis (360 kA_{DC}, 1650 V_{DC}) according to the Hindalco specifications for 30 years, without interruption"*. This functional unit is adapted to our needs, namely to feed internal eco-design works on substations. The substation lifetime is 30 years, which means that the reference flow is 1.

The substation is broken down into eight subsystems: regulating transformers, rectifier transformers, rectifiers, busbars, filters, control, civil engineering, and other equipment. Each of these subsystems is itself divided into sub-assemblies and hundreds of components.

Data granularity, that means the extent to which the system is broken down into small parts, is chosen to permit the identification of the main environmental impacts on the whole substation life cycle, without spending too much time in collecting the data. Limitations and weaknesses of the study are rigorously documented to facilitate the analysis and ensure the quality of future works. This means that a compromise has been found between the durations of the study and the quality of the results. By highlighting these constraints, the project charter has permitted to quickly define the data granularity and to make acceptable some simplifications as this LCA is performed for internal used only.

The system is modelled using SimaPro 7.2 software. Apart from the specific data that are issued from Alstom Grid, the LCI data come from Ecoinvent V2.1 database [45]. The LCIA results are calculated with the ReCiPe 2008 midpoint (H) V1.03 methodology [46]. Data inventory and data quality are managed thanks to a procedure based on [15].

Concerning the organisational aspects, the three first phases of the study were planned in five months. About one month was necessary to structure the project and define the scope and objectives (*Define*), four months to collect the data (*Measure*), and one month to collect and analyse the LCIA results (*Measure/Analyse*). Considering the size and the complexity of the system, this particularly satisfactory. The two last phases (*Improve* and *Control*) are not detailed.

3.4.2.2. Measure

Flow charts were built from a SIPOC analysis of each substation subsystem. SIPOC is a Six Sigma tool to identify the Suppliers, Inputs, Processes, Outputs and Customers of an industrial object. These analyses ensure the coverage of the life cycle of the substation. Different data sources were used:

- Internal Alstom Grid data,
- Data from suppliers, subcontractors or other units,
- Generic data (from LCA databases or literature).

Specific data was collected in a large predefined Excel sheet. It mainly concerns the following elements: masses, distribution, energy consumptions and end-of-life. Materials extraction and production, energy production and distribution, as well as other data, are generic.

The potential environmental impacts of the substations were calculated with the ReCiPe 2008 method [46]. About 35 simulations were conducted with different substation breakdowns (by life cycle phases, by subsystems). Moreover, three other electrical mixes were considered in addition to the coal mix effectively used at the Hindalco Mahan smelter as a way to easily manage the geographical dimension of the substation site: natural gas, hydro and nuclear.

3.4.2.3. Analyse

More details on the LCA results are given in [47]. We will only draw the main conclusions in this section.

Figure 22 gives an overview of the potential environmental impacts of the substation's whole life cycle, with a breakdown by life cycle phases. It appears that the use phase is responsible for more than 95 % of the total impacts, except for three impact categories: ozone depletion, ionising radiation, metal depletion. For these categories, the contribution of the materials phase is higher. This is mainly due to metal production (steel, copper, aluminium).

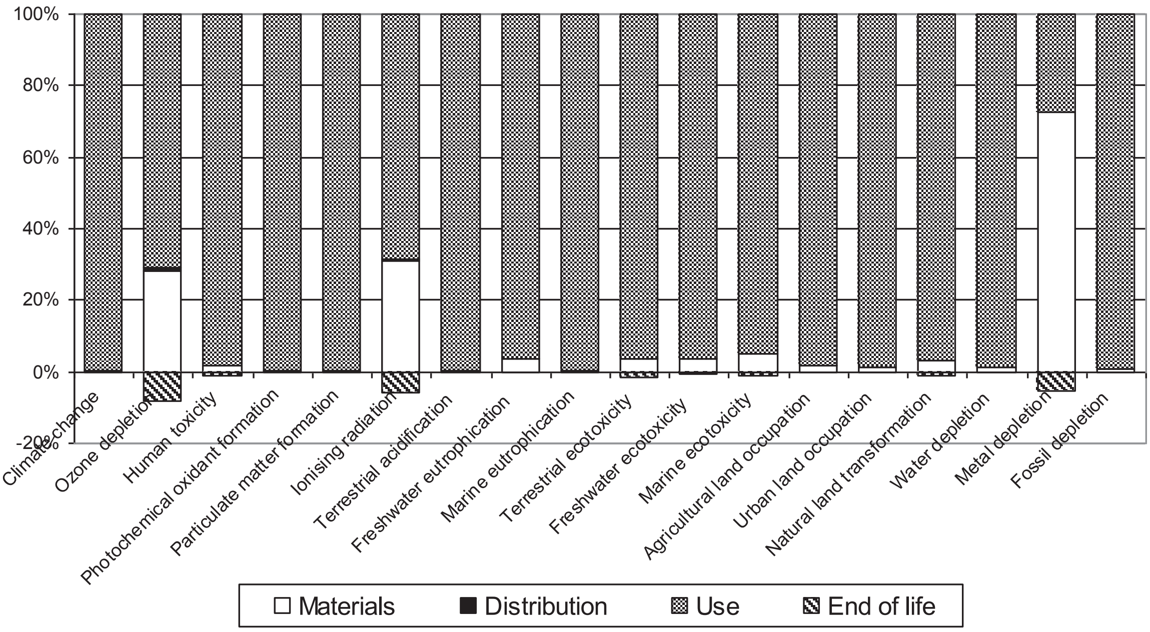

Figure 22. Breakdown by life cycle phases of the substation life cycle impacts

The domination of the use phase is clearly due to the production of electricity from coal, which is particularly impacting. Figure 22 also shows that the distribution phase is almost negligible. The end-of-life phase allows to reduce the impacts by a further 10% (see small bars below the horizontal axis) of the total impacts.

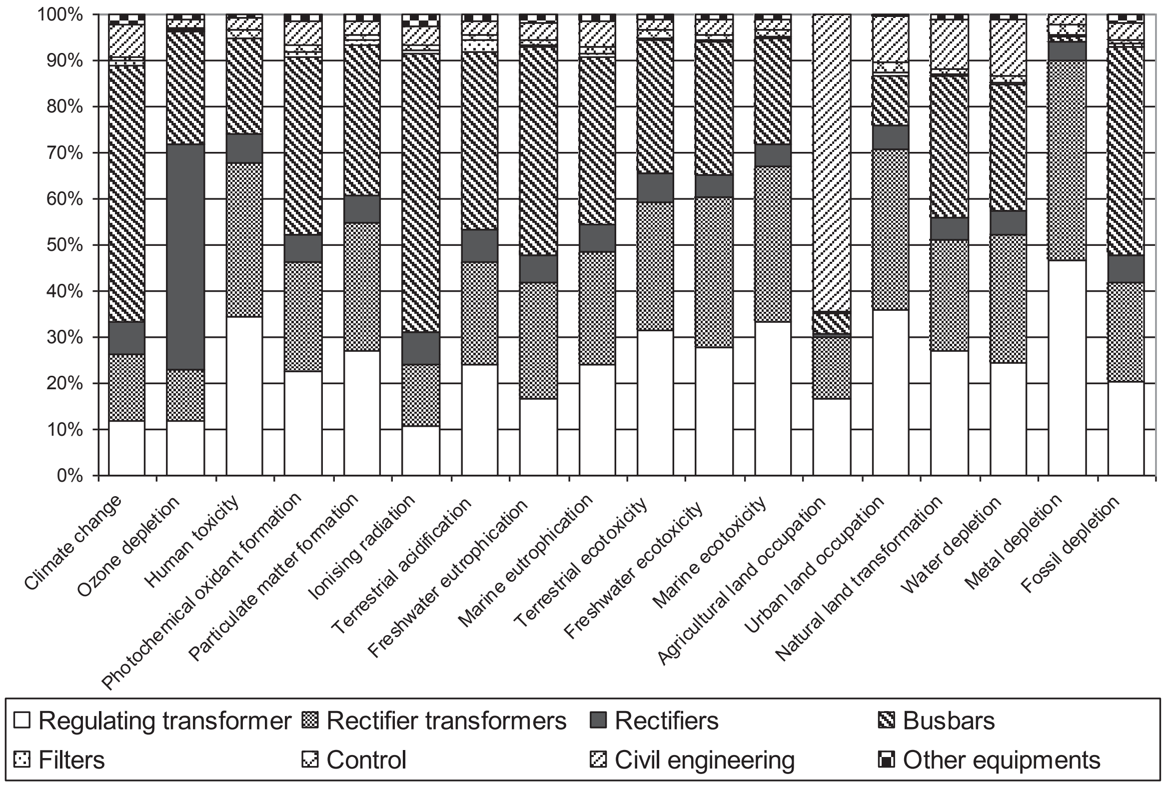

Figure 23. Breakdown by subsystems of the materials phase impacts

Figure 23 presents the breakdown by subsystem of the impacts associated with the materials phase. The busbars (550 tons of primary aluminium) and the regulating and rectifier transformers are the most impacting subsystems. However, three impact categories present singular results: ozone depletion, agricultural land occupation and metal depletion. These are explained by the use of some materials, like PTFE or concrete. The total impact generated by the transformers, rectifiers, busbars and civil engineering reaches more than 95 % of the total impacts of the materials phase. The other subsystems (filters, control and other equipment) have negligible impacts.

As the electricity used by these subsystems comes from the same source (a coal power plant), the contribution of the subsystems in the use phase is the same for every impact category and corresponds to their contribution to the electrical losses. Thus, the electrical losses of the rectifiers and transformers represent about 89 % of the total losses. The most impacting subsystem is the rectifier transformer, with 40 % of the impacts.

Finally, Figure 24 shows the comparison of the environmental impacts for the four electricity sources. 100 % represents the highest value among the four levels. If the hydro scenario is clearly the best alternative, it is more difficult to separate the three other scenarios. For example, the nuclear scenario is the worst one in ionising radiation and (only just) in metal depletion. The coal scenario reaches the highest values for the other categories. The comparison between the breakdown by life cycle phases for the hydro scenario and the coal scenario (the two "extreme" scenarios) gives the most interesting results. It appears that the contribution of the use phase has largely decreased in the hydro scenario. This means that the materials phase is now responsible for more than 50 % of the total life cycle impacts in most of the impact categories. This is an extremely important result, which shows that the eco-design activities or the configuration choice stemming from the analysis of these environmental profiles may be different from one substation to another. Actually, in the Hindalco Mahan case (electricity from coal), the lowering of the electrical losses is the best way to improve the overall environmental performance of the substation. Impact transfers from the use phase to the materials phase may be acceptable if the environmental benefits are significant. On the other hand, in a Canadian case (hydroelectricity), minimising weights and substituting materials can bring significant benefits.

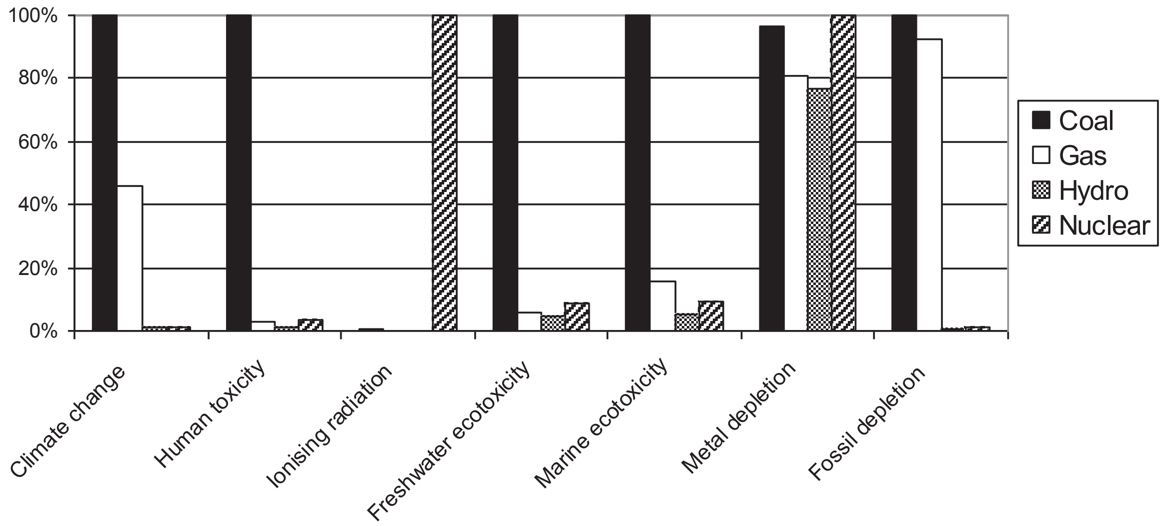

Figure 24. Comparison of four electricity sources scenarios for the whole substation life cycle. Only seven impact categories (in normalised results) are represented.

All these conclusions were documented in a full internal LCA report. They constitute a strong basis to feed the *Improve* phase.

3.4.2.4. Improve

The LCA results described in the previous part offered promising improvement methods to optimise the environmental performance of the substation, but it is clearly necessary to define them and to consider their technical and economic aspects. This knowledge is not owned by the eco-design experts, but by the substation designers. That is why the *Improve* phase was conducted via a working group and creativity sessions.

Using the eco-design strategy wheel (also known as the Brezet wheel [44]), the working group generated in two hours more than 100 improvement ideas, identified the 16 most powerful improvement projects, that means the best compromises between environmental performance improvement, technical feasibility and costs. 16 projects were selected and synthesised in predefined sheets (called “variant sheets”), and positioned thank to a dedicated assessment grid based on maturity scales and qualitative evaluations. Among these 16 projects, it was assumed that 50% would not have emerged without the creativity process deployed in the DMAIC framework.

3.4.2.5. Control

Once the *Improve* phase has been performed, the entire project has been be capitalised and precisely documented to be reusable in the future (for a new iteration of the global approach for example). Results have been communicated (internally and externally) and assigned a value. The responsibility of the project has now been given back to the sponsors (decision makers) who have chosen the improvement projects to perform in specific approaches. The general idea of this work is to build up a catalogue of eco-designed technological solutions. From a given context (country, electrical mix, customer specifications), it will be possible to define the best configuration of a substation from an environmental point of view.

3.5. Perspectives and Conclusions

In this paper, an adapted methodology has been presented to manage the eco-design of complex industrial systems. This methodology is based on a DMAIC approach and is integrated within the framework of ISO 14006 [5], ISO 14062 [6] and POEMS (Product-Oriented Environmental Management Systems [8]) as an operational layer. It is composed of two main stages (global approach/specific approaches), corresponding to the environmental assessment and improvement stages of a classical eco-design approach, and mainly answering to the PLAN and DO stages of a POEMS process. The global approach integrates Life Cycle Assessment to identify the potential environmental impacts of the full system. From a predefined project charter, the DMAIC process offers precise deliverables and milestones to make the process of eco-design for complex industrial systems more reliable. It permits in particular to plan in a short time and with limited resources an environmental assessment that is sufficient to feed an internal eco-innovation process, by identifying a compromise between data availability, boundary selection and constraints in the company. Once the environmental impacts have been determined, a working group is set up to identify environmental improvement projects thanks to eco-innovation tools. The last phase of DMAIC assures the capitalisation of the benefits and offers the decision makers the ability to plan the realisation of the most promising improvement projects. These projects are performed via specific approaches, which are also based on a DMAIC process. However, these specific approaches are more focused on environmental improvement and technological solutions development. A specific approach only considers a small part of the initial system life cycle and the association of the different specific approaches ensures a significant improvement in the environmental performance of the system. Iterations of the whole process will ensure continuous improvement in the course of time and will steer the classical organisation towards becoming an eco-designing organisation.

The global approach has been successfully applied on Alstom Grid AC/DC conversion substations for the aluminium industry. The *Define*, *Measure*, and *Analyse* phases have given excellent results to feed the creativity sessions of the working group in the *Improve* phase. The LCA of a substation has allowed the identification of the main contributors to life cycle impacts, such as subsystems, life cycle phases or materials. The technical knowledge of the Alstom Grid designers has then offered significant ways to improve the overall substation's environmental performance.

On this basis, the decision makers at Alstom Grid PEM will be able to plan the most promising of the 16 improvement projects as R&D projects. An environmental follow-up will also be provided to ensure the validity of the environmental benefits. The following process will be performed by complementing the classical R&D project:

- At the initiation review stage: definition of the environmental objectives and scope, identification of simplified environmental indicators and associated targets to easily monitor the project's progress. Examples of such indicators are aluminium mass, electrical losses, transformer oil volume… these can easily be manipulated by people who are not experts in eco-design. This review matches the *Define* stage of DMAIC.
- The other gate reviews (not detailed here for confidentiality reasons) assess the progress. They are set all along the *Measure*, *Analyse* and *Improve* stages of DMAIC.
- The last gate review coincides with the end of the *Control* stage of DMAIC. It marks the end of the project.

Following this process for different improvement projects will eventually generate a catalogue of eco-designed technical solutions available for future projects. After completing all the improvement projects (in maybe months or years, depending on the system), Alstom Grid PEM will be able to iterate the whole process by launching a new global approach.

Besides those organisational considerations on the eco-design of complex industrial systems, other more technical issues appear. This methodology actually offers the possibility of constituting a portfolio of eco-designed technological solutions, but it does not propose the best environmental configuration (best compromise between environmental impacts, costs, reliability according to the customer requirements) of a complex industrial system in a given context. For example, the best environmental configuration of a substation would not be the same if the electricity in the use phase is produced from coal or from hydropower. The main extension of this methodology now consists in developing simulation models based on design of experiments. From an implantation context, such a tool could identify the best parameters to design the substation. This concept is currently under way.

3.6. Acknowledgments

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Chapter 4. Paper #2: Exploitation scenarios in industrial system LCA

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Foreword

The first paper (Chapter 3) was chronologically written before the two other ones (Chapters 4 and 5). A first LCA is proposed concerning an Alstom Grid substation. This LCA is shown in the first paper as the application of the first steps of the methodology. But it was also a way to identify weak LCA methodological elements that are the base of the second paper (Chapter 4), i.e. a scenario-based LCA model.

In a new and fictive implementation of the general methodology, the scenario-based LCA model would directly be applied instead of the classical LCA application proposed in the first paper, as it is proved to be more efficient and adapted to R&D strategic orientation than a classical LCA.

Finally, the general methodology proposed in the first paper includes a step of generation and selection of eco-innovative R&D projects. No application of this process was proposed in it, as the paper was written before this application. The detailed process and its application are thus proposed in the third paper (Chapter 5).

To synthetize, the first paper (Chapter 3) proposes a methodology in two steps: environmental evaluation and environmental improvement. The environmental improvement is applied in the first paper through a classical LCA study, but a more accurate and adapted model based on exploitation scenarios is then developed and applied in the second paper (Chapter 4). The environmental improvement step is detailed and applied in the third paper (Chapter 5).

Abstract: *Purpose:* This paper considers the variabilities that exist in the exploitation of a complex industrial system. Our scenario-based LCA model ensures the reliability of results in situations where the system life cycle is very uncertain, where there is substantial lack of data and/or where time and resources available are limited. It is also an effective tool to generate exploitation recommendations for clients.

Method: Existing quantitative uncertainty methods in LCA require a huge amount of accurate data. These data are rarely available in simplified and upstream LCA for complex industrial systems. A scenario-based approach is the best compromise between acceptable quality of results and resources required. However, such methods have not yet been proposed to improve the environmental knowledge of the system in the case of exploitation scenarios. The method proposed here considers a limited number of scenarios (3 or 4) that are defined using the Stanford Research Institute (SRI) matrix. Using results from past projects, relevant parts of the system are listed, and expert knowledge and parameters are associated with these parts and quantified. A classical LCA process then provides the results for the different scenarios.

Results and discussion: The method was applied to an Alstom Grid AC/DC conversion substation for the primary aluminium industry. A previous study had limited scope, as the life cycle was poorly understood. Relevant parts were thus clearly identified: spare parts program, transport failures, preventive and corrective maintenance, updates and revampings, lifetime modulation and end-of-life. Four scenarios were considered: best case, worst case, baseline (expected future) and a highly different alternative. Results show the pertinence of considering several exploitation scenarios when the life cycle is not predictable, as the environmental impacts may vary widely from one case to another. A sensitivity analysis also shows that some relevant parts such as *updates and revampings* will need to be carefully considered in futures studies.

Conclusions: The consideration of three exploitation scenarios (best case, baseline and worst case) appears to be extremely pertinent when considering simplified LCA of industrial systems with high uncertainties and limited time and resources. This model is also very useful to generate good practice and recommendations towards customers, thus initiating a dialog centred on eco-design and continuous improvement.

Keywords: Life Cycle Assessment, Life Cycle Inventory, complex industrial system, scenario-based LCA, exploitation scenario.

4.1. Introduction

In recent decades, Life Cycle Assessment (LCA) has become an essential tool for performing eco-design in companies. Indeed this normalised methodology (ISO 14040:2006, ISO 14044:2006) is said to be the most effective quantitative environmental assessment tool (Millet et al. 2007) as it delivers the most accurate results (Dewulf 2003). The identification of the most environmentally impacting elements of a products system life cycle generates eco-innovation insights to develop new products (Finnveden and Ekvall 1998). However, the results of such a process clearly require a large amount of high quality data (Reap et al. 2008a, 2008b), and LCA is thus undeniably a time- and resource-consuming activity (Hur et al. 2005; Weckenmann and Schwan 2001). Even if eco-design is generally expected and supported by the top management of companies, it is often awkward to obtain complete data and the necessary allocation of human resources for satisfactory analysis. Consequently, life cycle scenarios of complex industrial systems are not sufficiently thought through or modelled, being at best an aggregate of factors. This also results in decorrelated life scenarios (along lifetime) and, ultimately, to non-representative environmental impact profiles of real life.

4.1.1. Specificities of complex industrial systems in LCA

This opposition between the quality of LCA results and available resources is amplified in companies supplying complex technical and organizational industrial systems such as factories. Here, complexity induces major issues in terms of modelling, prediction or configuration. In the systems engineering domain, Blanchard and Fabricky (2011) characterise engineered systems as systems that achieve operational objectives; that operate over a complete life cycle; that are composed of a combination of resources (humans, materials, equipment, money, etc.); that are composed of subsystems and components that interact with each other; and that are influenced by external factors from larger systems and in interaction with the natural world. Adding an environmental dimension, we define a complex industrial system in the sense of eco-design as:

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

But LCA is more convenient for relatively simple products than for complex systems (Millet et al. 2007). The application of LCA for such systems highlights particular needs not only in terms of time and resources, but also in terms of technical aspects such as goal and scope definition or data inventory. Thus, organizing the eco-design of complex industrial systems requires the conventional LCA process to be adapted. For instance, lean principles can be applied, as shown in (Cluzel et al. 2012). For this adapted eco-design approach to complex industrial systems, a first LCA is performed for a reference system and its corresponding environment. But difficulties quickly appear because there is currently no clear method to analyse impacts at different levels of complexity. This is why before being able to communicate LCA results (through product environmental profiles for example) that would lead to long term work, the first strategic step consists in identifying the potential environmental impacts, at a high level and in the most reliable way. Consequently, the primary need is to use the first system assessment to build a list of eco-innovative improvement projects that can feed the R&D program of the coming years.

Considering LCA for these types of system, the major issue concerns the availability and the quality of the system life cycle data (Cluzel et al. 2012). Indeed in many complex system industries, the use phase and the end-of-life phase only depend on the clients, and data are awkward to obtain where no client relationship management system exists. The Alstom Grid substations, for example (see Section 4.4), are characterised by their long life (more than 30 or 40 years) or their uniqueness (each substation is customized to comply with a tender). Companies now consider that the realization of one specific LCA for each system design would require too much time and resources. However, the environmental impacts of a factory such as an electrical substation may differ markedly from one geographical site to another due, for example, to the electrical mix or the client management in terms of maintenance or updates. We include these issues in the more global notion of "industrial system exploitation".

4.1.2. Considering exploitation scenarios

It is thus necessary to define a compromise between the simplification of the LCA model, the scientific validity of the results and the commercial use in answering specific tenders. Actually an over-simplified model would probably limit both the effectiveness of the results for a given system and the ability to meet clients' requirements. On the contrary, a very accurate model applied to complex industrial systems would not be easily appropriable by a company as it would need too much time and resources. Great accuracy is not necessary at an upstream level, where the objectives consist in defining first improvement directions (Leroy and Froelich 2010).

The ideal model would combine LCA, giving a high level global view of the product family, with the ability to customize studies for each specific project, thus taking into account uncertainties and system life cycle variables. The notion of scenario really fits this need to represent complex life cycles and to take into account the numerous associated factors in a simplified LCA approach. That is why it is preferred in this study to more mathematical uncertainty models (see for example (Huijbregts 1998)) that we consider too complex and poorly applicable (Ross et al. 2002). Indeed these methods offer accurate uncertainty data, and thus better decision support, but they require additional efforts (Ciroth 2003). Concerning Monte Carlo methods in particular, Huijbregts et al. describe the specification of uncertainty distributions as *"a very difficult and time-consuming exercise […] for the enormous amount of parameters involved in the inventory analysis"* (Huijbregts et al. 2001).

Two main objectives are targeted in the scenario-based model. The first one is to give more credence to the LCA results of complex industrial systems in order to generate appropriate eco-innovative R&D projects. The second one is to initiate productive discussions with clients, thus generating exploitation recommendations.

Section 4.2 considers scenario development techniques and their application into the LCA field. This literature review allows us to choose an adapted technique and propose a methodology to consider exploitation scenarios in LCA. This methodology is detailed in section 4.3 and applied in section 4.4 to an Alstom Grid AC/DC conversion substation for the aluminium industry. Finally, some concluding remarks and perspectives are proposed in section 4.5.

4.2. Scenario development and use in LCA

4.2.1. Scenario definition and categorization

The notion of scenario in model-based approaches has received numerous definitions in the literature. Pesonen et al. (2000) give an overview of some of these definitions, including three basic elements: definition of alternative future circumstances, path from the present to the future, and inclusion of uncertainty about the future.

In the same paper, which synthesizes the works of a SETAC working group on scenario development in LCA, the following definition is chosen: *"A description of a possible future situation relevant for specific LCA applications, based on specific assumptions about the future, and (when relevant) also including the presentation of the development from the present to the future."* We adopt this definition in this paper.

Different scenario types may be considered in prospective studies. A categorization of scenarios is proposed by Börjeson et al. (2006). This categorization distinguishes 3 main scenario categories, divided into 6 types:

- *Predictive scenarios* answer the question *What will happen?* Predictive scenario types are *forecast* (the likely scenario occurs) and *what-if* (conditioned to some specific events).

- *Explorative scenarios* answer the question *What can happen?* Explorative scenario types are *external* (considering external (exogenous) factors) and *strategic* (conditioned to some actions completed in a certain way).

- *Normative scenarios* answer the question *How can a specific target be reached?* Normative scenario types are *preserving* (adjustments to current situation) and *transforming* (the prevailing structure blocks necessary changes).

Earlier studies consider different scenario types, or rather different designations that could describe the same types. For example, Fukushima and Hirao (2002) consider *forecasting* and *backcasting* scenarios, while Pesonen et al. (2000) take *what-if* and *cornerstone* scenarios into account by considering time and complexity. *What-if* scenarios concern simple objects and short term studies, while *cornerstone* scenarios are more suited for complex objects and long term approaches.

A CALCAS report (Zamagni et al. 2008) states that these scenario types are included in Börjeson's scenario categorization. Concerning the two different scenarios considered by Pesonen et al. (2000) and Weidema et al. (2004), it estimates that *what-if* scenarios belong logically to the predictive scenarios of Börjeson's categorization, while the *cornerstone* scenarios belong to Börjeson's explorative scenarios (Zamagni et al. 2008).

4.2.2. Scenario development techniques

Börjeson et al. distinguish three main steps to generate a set of scenarios (Börjeson et al. 2006):

- Generate ideas and knowledge about some parts of the future;
- Integrate them into scenarios;
- Check the consistency of the scenarios.

Particular methods are used to perform these different steps. Scenario development techniques (covering the second step) enable the construction and use of a set of scenarios. Bishop et al. (2007) give an overview of numerous techniques, classified into eight categories:

1. Judgment: based on the judgment of individuals describing the future.
2. Baseline/expected: produces only one scenario, which could be the base for alternative scenarios (generated with other techniques).
3. Elaboration of fixed scenarios: based on simple tools to generate a predefined number of scenarios.
4. Event sequences: based on probability trees.
5. Backcasting: based on a desirable future and the identification of the way to reach it.
6. Dimensions of uncertainty: based on the identification of specific sources of uncertainty.
7. Cross-impact analysis: based on probability matrices and the calculation of conditional probabilities.
8. Modelling: based on simulations and the variation of the inputs or the structure of the model.

Another interesting method is Formative Scenario Analysis (FSA), detailed by Tietje (2005). The method consists in identifying a small and reliable set of consistent scenarios with mathematical tools such as consistency analysis. It is a powerful method but it clearly needs accurate quantified data.

However these techniques concern scenario development in general. The next subsection particularly focuses on scenarios in Life Cycle Assessment.

4.2.3. Scenarios in LCA

Annex 2 of the CALCAS report D7 (Zamagni et al. 2008), concerning current research needs and limitations in LCA, gives a precise literature review of the use of scenarios in Life Cycle Assessment.

The definition of the set of scenarios is performed in the goal and scope stage (ISO 14040:2006), while the modelling of scenarios is performed in the LCI and LCIA phases. The results are discussed in the interpretation phase (Zamagni et al. 2008). But scenarios have received little attention in LCA, and two of the main questions raised by (Zamagni et al. 2008) are the following: How should scenarios be defined and categorized? And how should scenarios be developed?

Höjer et al. (2008) consider the use of scenarios for environmental system analysis, including Life Cycle Assessment. The paper focuses on products with a long expected life. In this case external scenarios (in the sense of Börjeson et al. (2006)) are recommended to assess *"different options for the foreground system under the influence of different external scenarios"*.

The working group "Scenario development in LCA" launched by SETAC-Europe (Pesonen et al. 2000; Weidema et al. 2004) focused on two main goals that are to find solutions for problems concerning prospective LCA, and to define a procedure to model uncertain parts of a product system, or parts with different possible alternatives.

They propose a five-step approach (Weidema et al. 2004) that corresponds closely to Börjeson's approach:

- Identification of the relevant parts of the product systems,
- Identification of the precision required,
- Choice of an appropriate method,
- Scenario development,
- Consistency check.

Concerning step 3, Weidema et al. highlight the use of extreme scenarios (e.g. a worst case scenario like the Bhopal disaster) (Weidema et al. 2004). They also identify 6 groups of future research methods:

1. Extrapolating methods: the future is an extension of the past,
2. Exploratory methods focus on structuring possible futures,
3. Dynamic modelling takes mechanisms of past events and causal connections among system elements into account,
4. Cornerstone scenario methods : future is essentially unpredictable and several scenarios are helpful,
5. Participatory methods use experts to identify one consensual scenario,
6. Normative methods identify the scenario leading to one predefined goal.

The number of scenarios to consider is an issue highlighted by Pesonen et al. (2000). A limited number of scenarios (less than four) is recommended, for example one base scenario and two others. Actually if more than four scenarios are proposed, *"it becomes unmanageable for most decision makers"* (Wack 1985).

Some other research using scenario-based LCA has also been undertaken. For instance, Spielmann et al. apply Formative Scenario Analysis to prospective LCA of transport systems (Spielmann et al. 2004). They focus on strategic scenarios and the evolution of technologies.

4.3. Methodology

This section will put forward a methodology that meets the requirements expressed in section 4.1.2.

4.3.1. Global positioning

The use of scenarios in LCA seems particularly well-adapted to model the exploitation of complex industrial systems. But the objectives of the existing studies we mentioned in section 4.2.3 do not meet our own objectives. Actually these studies are mainly positioned at a more strategic level (Lloyd and Ries 2007):

- To compare product alternatives when the future is unpredictable or may follow different trajectories (e.g. with future electrical mixes). This perspective is equivalent to the *what-if* scenarios.
- To make the best choices in the development of (for example) public policies by minimizing the environmental impacts. This perspective is equivalent to the *normative* scenarios.

These two perspectives already focus on environmental impact optimisation, whereas in our case the objective is to make the LCA results more reliable because the operational exploitation (in particular the use phase and the end-of-life phase) of the current products is not known precisely enough and may vary from one industrial client to another. These needs concern explorative external scenarios in Börjeson's categorization (Börjeson et al. 2006).

This distinction is extremely important as it means that in the present case some data are simply missing, while the other data are uncertain, and no probability distribution is clearly known. Adding to this issue the need for a flexible and easily customizable scenario-based procedure, we propose the following methodological process adapted from (Weidema et al. 2004):

1. Identification of the relevant parts of the product systems: performed through surveys on past projects and meetings with experts in the company or clients.
2. Identification of the level of precision required for results: the results must identify improvement projects at a high level, but as these results will not be communicated externally, a high degree of precision is not necessary.
3. Choice of an appropriate method
4. Scenario development
5. Consistency check

Steps 3, 4 and 5 imply the selection of one particular scenario development technique. Among the 8 categories proposed by Bishop et al., only a few seem adapted to our needs. Judgment techniques are considered too opaque and insufficiently formalized. Baseline techniques only include one scenario, which is clearly in contradiction with our needs. Event sequences, dimensions of uncertainty, cross-impact analysis and systems modelling techniques are mainly based on accurate quantified data (probabilities of occurrence for example) that are not available in our case. They are judged too complex and time-consuming to be easily applied to a simplified LCA model. Backcasting techniques concern technology-related prospective analysis and they are thus not pertinent in our case. Finally, elaboration of fixed scenario techniques seem adapted to our needs, as they are easily applicable, they do not require accurate quantified data and they are fully compatible with exploitation scenarios. Two such techniques are proposed by Bishop et al. (2007): Incasting and SRI. The first of these, incasting, creates a set of scenarios using group creativity. It is more oriented towards strategic and surprising scenarios. It does not fully fulfil our needs.

The SRI matrix is a simple tool developed at the Stanford Research Institute in the late 1970s. It is particularly adapted to exploitation scenarios based on past projects and fragmented information from clients. That is why this technique is used in this study. It generally considers four scenarios (expected future, worst case, best case, and a highly different alternative, i.e. a scenario including surprising or unusual events) (Bishop et al. 2007). An illustration of this low number of scenarios is given in Figure 25 and must allow environmental impacts to be framed in time. The highly different alternative is used in the current study to check the robustness of the model.

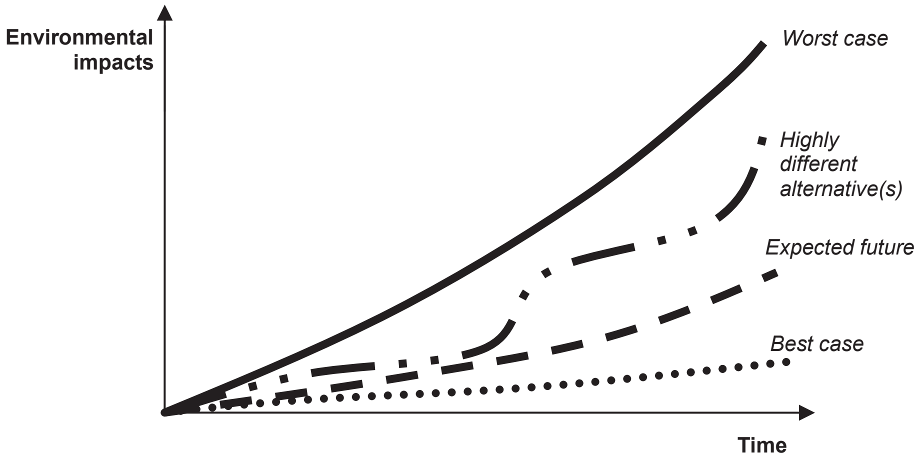

Figure 25. Example of potential environmental impacts generated along four scenarios: best case, expected future, highly different alternative and worst case

Scenarios are listed in columns, while dimensions of the world (i.e. parameters linked to the "relevant parts of the product systems") are recorded in rows (see Table 6). Cells are simply filled out by the users for each scenario and each parameter.

The consistency check is performed manually: the maximum number of scenarios (four, including the best and worst cases) means that it is easy to check if a sufficient range of possible life cycles is being covered. The two next sections give more details about this process.

4.3.2. Identification of the parameters

By studying the life cycle of some Alstom Grid substations (see section 4.4), different relevant parts of the system that were not taken into account in the primary LCA have been identified. This process is not new in nature, as it is used in scenario-based approaches or in parameterized LCA (Ostad-Ahmad-Ghorabi and Collado-Ruiz, 2011). However even if these relevant parts are issued from expert knowledge and past project in the company, we consider that they may be reused for numerous applications on complex industrial systems.

The relevant parts of the system may concern all the life cycle phases:

- Spare part programs that may be planned at the design stage,
- Transport failures may occur en route to the implantation site, leading to the loss of

equipments,

- Preventive maintenance operations,

- Corrective maintenance operations,

- Updates and revampings (changing or adding of subsystems),

- Lifetime extension or shortening, depending on the economic situation, the client choices, or political decisions

- An end-of-life scenario that is often dependent on the implantation country. Transfer options may be included, i.e. the transfer of one healthy subsystem – ordered to stop – to another site to be reused for some years.

For each study, parameters are associated with these relevant parts by company experts. These parameters are the so-called “dimensions of the world”, i.e. the rows of the SRI matrix. Some examples of parameters are listed in Figure 27.

4.3.3. Scenario development

The filling out of the SRI matrix allows formalizing the different life cycle scenarios.

Table 6 proposes for example an overview of three scenarios. The best case scenario describes the events that would minimize environmental impact generated throughout system exploitation. The client preserves the equipment and favours a long-term vision. But this does not mean that all the parameters are optimized. For example, there is more preventive maintenance in this scenario than in the worst case, because preventive maintenance minimizes corrective maintenance, which is generally more impacting. The worst case scenario describes the events that maximize the environmental impacts of the exploitation of the system, trying to stay in a realistic perspective. The client favours profitability at all costs and has a short-term vision. The baseline scenario describes what could happen in a “normal” or expected life cycle. It is an intermediary scenario between the worst and the best case. The client follows the supplier recommendations but is not particularly proactive to preserve equipment. Other scenarios may be added to these three base scenarios, but they need to be tailor-made for each study.

Values are then associated to each parameter and for each scenario according to company or client knowledge, expert estimations or hypothesis (depending on the uncertainty of these data).

Table 6. Simplified SRI matrix with three examples of possible scenarios

Relevant parts	Best case scenario	Baseline scenario	Worst case scenario
Spare parts program	Contractual quantities	Contractual quantities	Intensified quantities (more than the contractual quantities)
Transport failures	No failure	No failure	Some failures
Preventive maintenance	Intensified (the client is very reactive and exceeds the supplier recommendations)	Normal (the client follows the supplier recommendations)	Neglected (the client does not follow the supplier recommendations)
Corrective maintenance	Minimal (the preventive maintenance policy limits the corrective maintenance needs)	Average	Intensified (the neglected preventive maintenance leads to more frequent failures)
Updates/revampings	No update (the equipment is in good condition and does not need to be changed. It fits clients' needs).	Average (some equipment becomes obsolete and needs to be changed).	Intensified (some equipment is obsolete and in poor condition. New equipment is needed to improve service quality).
Lifetime modulation	Extension of initial lifetime (as the equipment is healthy)	No extension or shortening (the initial lifetime corresponds to the reality.)	Shortening of initial lifetime (some equipment is in poor condition, or the economic situation is unstable).
End-of-life	Optimized (with high recycling rates) + transfer of some subsystems to be used on another site	Medium (medium recycling rates) + no transfer	Minimalist (low recycling rates) + no transfer

4.3.4. Results valuation

The LCIA results then provide a set of data than can be used in two perspectives.

The first perspective is internal to the company. It concerns the identification of a portfolio of eco-innovative R&D projects. The use of this model ensures that more reliable decisions are made by focusing on environmental issues that are valid with a large number of clients, or in other words for a generic industrial system. This is in particular a powerful tool to guarantee the capability of the system to meet environmental objectives while these impacts largely depend on exogenous parameters for the system supplier.

The second perspective is intended for the clients. For the Alstom Grid example it turns out that the substation designers have only few degrees of freedom. Indeed the clients' specifications are very detailed on technical aspects, which limit the ability to radically innovate, as only long-term proven technologies are used. Continuous dialog with the clients is thus necessary to introduce new technologies and make them acceptable, despite the fact that the client would benefit from adopting a more proactive eco-design attitude towards its suppliers. The proposed scenario-based LCA supplies an interesting tool to support this dialog. Indeed the LCIA results may reveal exploitation issues and enable the introduction of good practice, greener technologies and services (concerning maintenance and end-of-life for example), or improved strategies (reuse of components for example).

The next section proposes to apply this model to an Alstom Grid conventional substation. We will see below that a poor preventive maintenance program may multiply the environmental impacts by a factor of two.

4.4. Application to an Alstom Grid AC/DC conversion substation

4.4.1. General purpose

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 is a particularly environmentally impacting and energy-consuming activity (Schmidt and Thrane 2009; Liu and Müller 2012). An electrolysis substation represents thousands of tons of power electronics components and transformers, costing tens of millions of Euros.

A substation is made up of several groups (four or five in numerous cases) that are composed of a regulating transformer, a rectifier transformer and a rectifier. The groups are connected on the 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 (greater than 1 GW). Some details of the flows associated with a substation life cycle are shown in Figure 26 to give an overview of the substation complexity.

The substations are considered to be complex industrial systems for a number of reasons. First, the number of subsystems and components is considerable. For example a substation may include five rectifiers each containing 168 rectifier diodes (i.e. 840 diodes), all of which are large and massive semi-conductors consisting of several types of material. Some subsystems could themselves be considered as complex industrial systems (like transformers or rectifiers). Secondly, the lifetime of a substation is long, up to 35 or 40 years. Many uncertainties exist for the use and end-of-life phases. No end-of-life scenario is clearly defined beforehand. In addition, the substation is only a part of the aluminium plant. Their processes are closely connected and interdependent. Finally, no standard design exists: the substation is tailor-made for each industrial client, even though the general design is often the same. It is for these reasons that we consider substations as a product family.

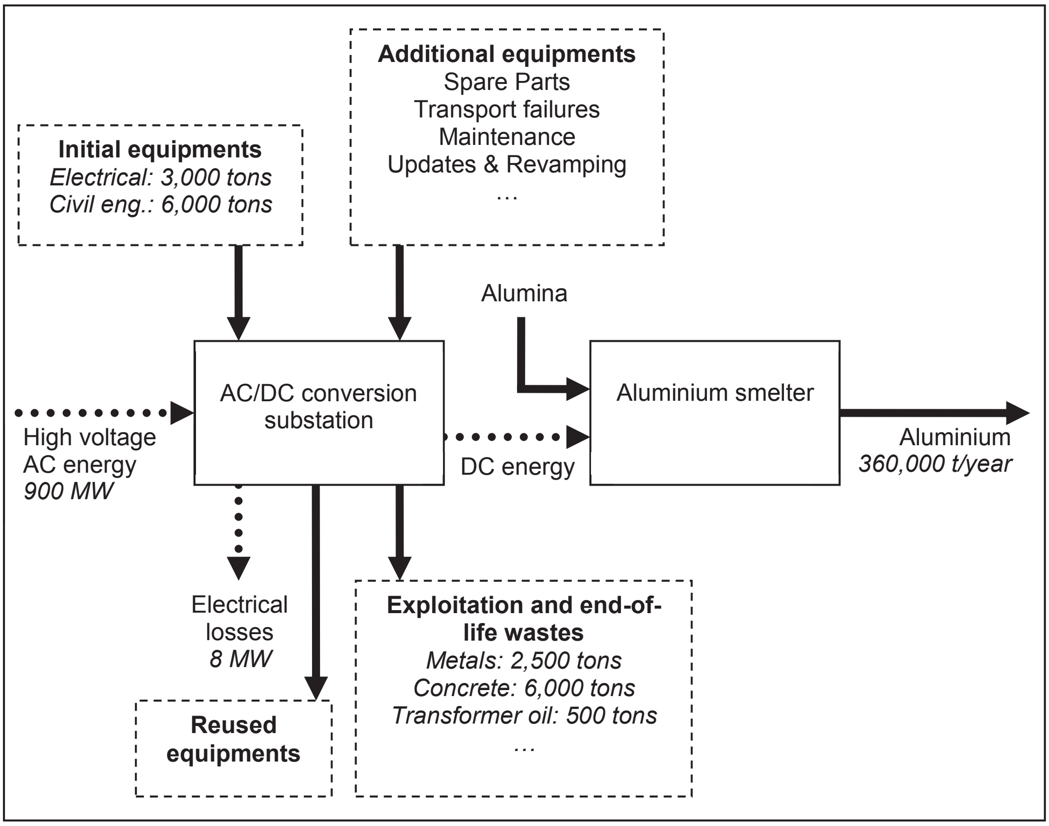

Figure 26. Overview of the flows associated with a substation life cycle. Figures are voluntary rounded off for confidentiality reasons.

In this context, a first LCA was performed on a substation to identify the potential environmental impacts throughout its life cycle, and then to generate improvements (Cluzel et al. 2012).

However the life cycle modelled in this first study was considered as “frozen” as it was not adaptable to a specific case - the use phase, for instance, only considered electrical losses (maintenance, updates and lifetime modulation were not taken into account). Thus the model described in this paper has been applied to the initial study of a conventional substation, in order to make the results more reliable and adaptable to specific projects by taking into account several exploitation scenarios.

4.4.2. Goal and scope

The main objective of the present study is to assess in a reliable way the potential environmental impacts of an AC/DC conversion substation life cycle thanks to different exploitation scenarios. These scenarios enable the customization of the LCA modelling for a specific study. The results also show if the use of scenario is pertinent, and possible benefits for future studies in the company. The selection of adapted scenarios must allow eco-innovative R&D projects to be better lead, and is a valuable tool to provide founded recommendations to clients for the future use and maintenance of their system.

Four main life cycle phases are considered, but the application of the model described in this paper has allowed new relevant parts to be added compared to the initial LCA (see (Cluzel et al. 2012)), detailed in Figure 27. The relevant parts are linked to the pre-existing life cycle phases. Some examples of parameters used in the study are associated with each relevant part. The dotted arrows highlight some consequential links between several relevant parts. A large part of the corrective maintenance is for instance determined by the client policy for preventive maintenance.

The study focuses on an Alstom Grid AC/DC conversion substation that has been designed and is currently under construction for the Hindalco Mahan aluminium smelter (India), associated with a captive coal power plant. The following functional unit is chosen: "To provide without interruption the conversion of high voltage energy to energy usable for aluminium electrolysis (360 kA_{DC}, 1650 V_{DC}) according to the Hindalco project specifications, considering the whole system life cycle normalized on one year." This normalized duration (one year) has been chosen to compare alternatives with different life times.

Previous results showed that the electrical mix has a strong influence on the one hand on the global substation impacts (as it is an energy system), and on the other hand on the relative contribution of the life cycle phase to global impacts. That is why two electrical mixes are considered in this study: electricity from coal (real Hindalco case) and hydroelectricity (from the regional grid, extrapolated from other smelters).

The system is modelled using SimaPro 7.3 software. Beside the specific data from Alstom Grid, the LCI data come from Ecoinvent V2.1 database (in particular concerning electricity production). The LCIA results are calculated with the ReCiPe 2008 midpoint (H) V1.03 method.

Finally, a last case was considered to control the results of the study. It is called the "initial case", as it corresponds to the "frozen" LCA modelling performed before this study. This case behaves as if no exploitation options have been taken into account (no new relevant parts such as maintenance or lifetime modulation have been added).

The values allocated to each scenario have been identified thanks to past Alstom Grid projects and expert knowledge.

A questionnaire included in an Excel file was used to configure the SRI matrix. This file automatically calculates the value of the parameters that are manually written in Simapro.

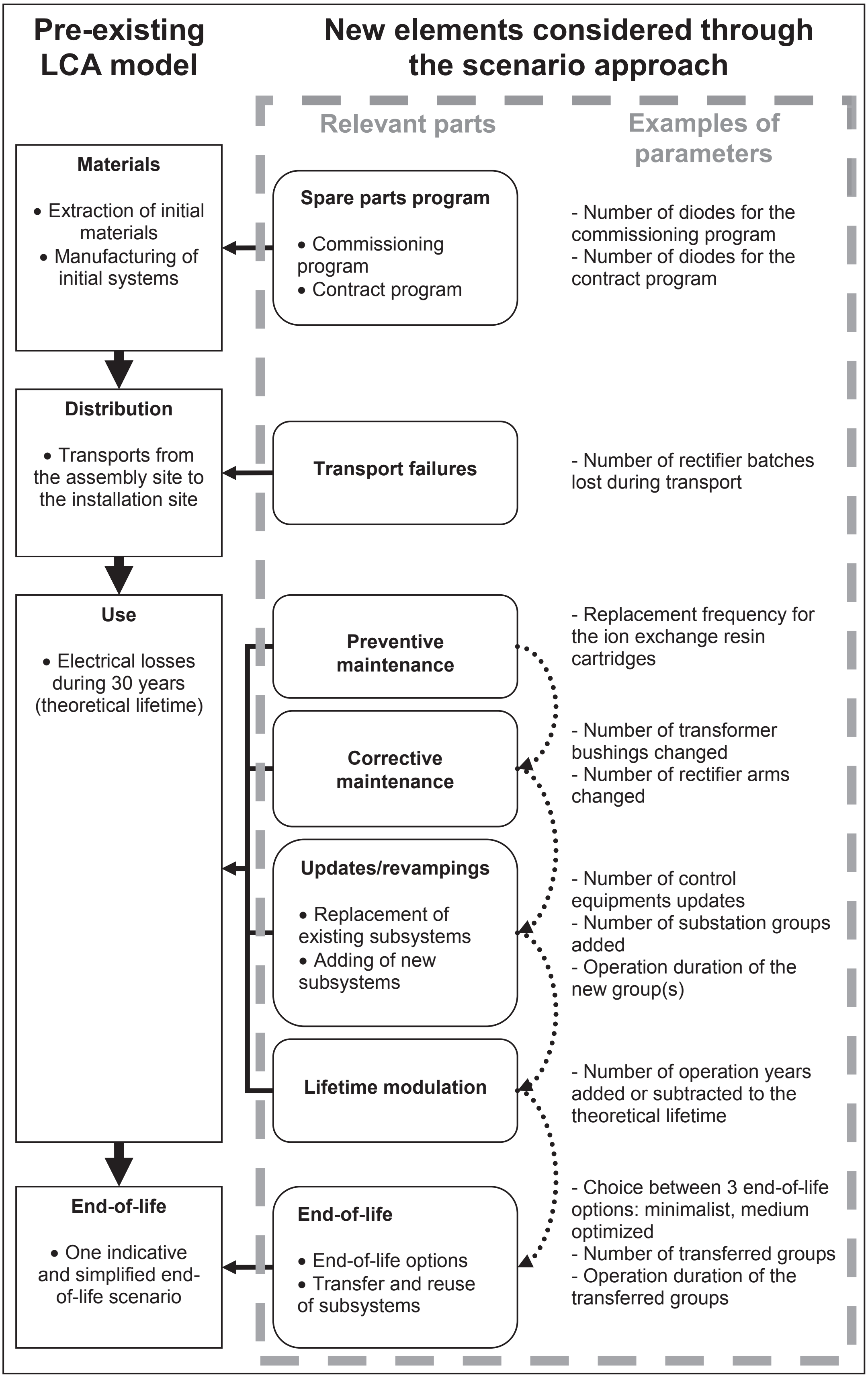

Figure 27. Description of the initial LCA model and the new elements considered through the scenario approach

4.4.3. General results

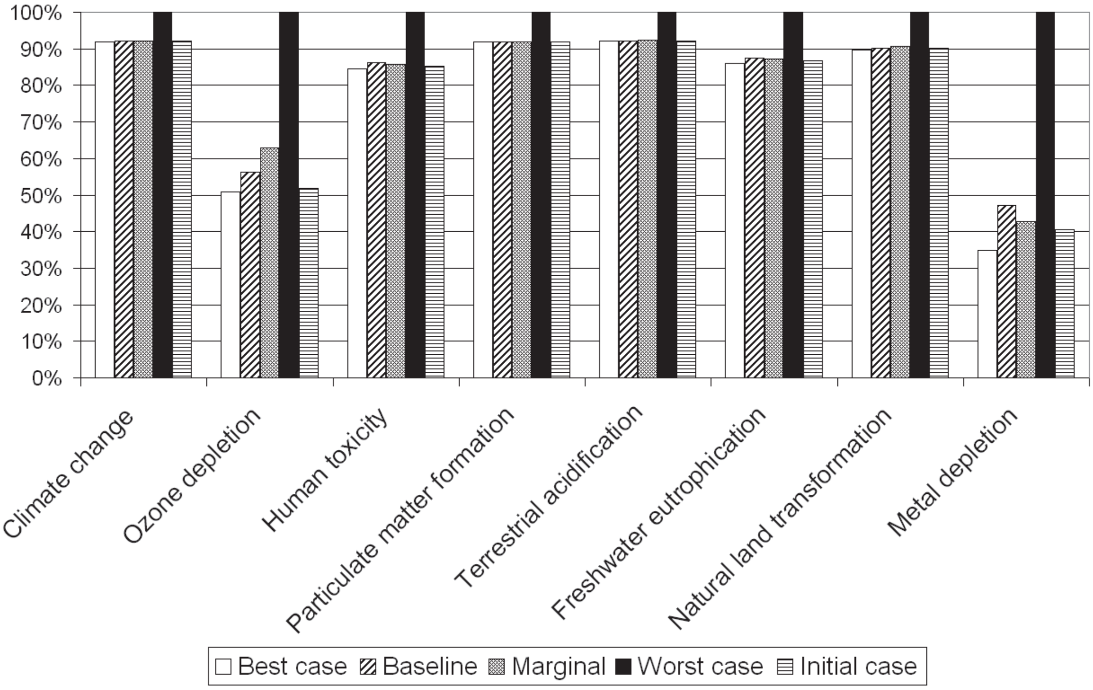

Figure 28. Comparison of the potential environmental impacts of the four scenarios with a coal mix

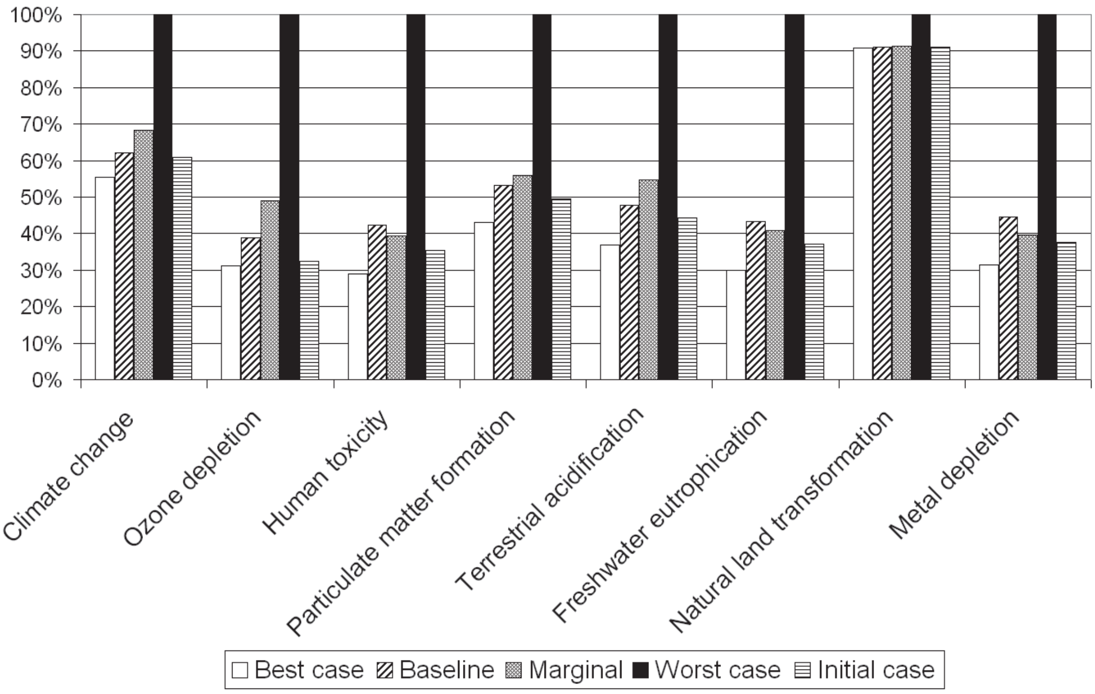

Figure 29. Comparison of the potential environmental impacts of the four scenarios with a hydro mix

The LCIA results are presented in Figure 28 and Figure 29. The initial results are measured in Simapro without the eventual transfer cases (best case and marginal scenarios). Indeed we considered that the Simapro reuse function is not adapted in our case as it considers that a reused product has the same efficiency as a new product, and all the impacts generated by this subsystem are allocated to the second life cycle (reuse loop). In the best case scenarios for example, 3 groups of the substation are reused for only 2 years, which does not justify this rule. We have preferred to manually allocate the materials phase impacts using a *pro rata* rule, according to the effective number of years of use in the two life cycles. The end-of-life impacts or benefits are allocated to the second life cycle.

Only conclusions resulting from the use of scenarios are proposed in this paper. Other conclusions are presented in more detail in (Cluzel et al. 2012). In order to make the results easy to understand, the LCIA results have been restricted to eight mid-point impact categories that were considered relevant and showing different aspects of the system.

Figure 28 and Figure 29 compare the potential environmental impacts of the four scenarios in, respectively, a coal and a hydro mix. The worst case scenario is chosen as a reference (100% on all impact categories).

In all cases the worst case scenario is logically the one which has the impact on all the impact categories, whereas the best case is always the least impacting. The initial case scenario is always more impacting than the best case, but always less impacting than the baseline scenario. This is also in accordance with what was expected.

However, the gap between the best case and the worst case scenarios, and the relative positioning of the baseline and the marginal scenarios, clearly depends on the electrical mix.

For the coal mix, the gap between the best case and the worst case scenarios is always inferior to 20%, and the best case, baseline, marginal and initial case scenarios are quite similar, except for two impact categories where the materials phase dominates: *ozone depletion* and *metal depletion*. In these categories the best case, baseline and marginal scenarios are not close, and the worst case scenario is much more impacting.

For the hydro mix there is a real distinction between all the scenarios, but the best case, the baseline and the marginal scenarios remain within a small range that never exceeds 20% of the worst case scenario impacts. On the other hand, the gap between this group of scenarios and the worst case scenario is always superior to 32%, except for the impact category *natural land transformation*. The gap between the baseline and the marginal scenario never exceeds 10%, but neither of the two scenarios is better in all the categories.

Finally this analysis shows that the results of the first LCA performed on this substation (initial case scenario) do not reveal all the potential environmental impacts generated all along the substation life cycle, because some relevant parts have not been taken into account. Moreover the large uncertainty existing on these data shows a large range of possible impacts, in particular with a hydro mix, showing a great influence of material aspects. Even if the difference between all the scenarios is not really significant in a coal mix for most of the categories, the results on *ozone depletion* and *metal depletion*, as well as the results with a hydro mix justify in the future the use of several life cycle scenarios to make the decisions based on LCA results more reliable. These results could be refined thanks to an uncertainty analysis. It would consist in measuring uncertainty ranges for the four scenarios in order to determine if the results are significant. However this is not the aim of this paper, whose objective is to introduce the methodology and to propose a first implementation on a real and simplified case study.

As the marginal scenario reveals itself close to the baseline scenario, we propose to consider in the next study at Alstom Grid three exploitation scenarios: best case, worst case and baseline. But within these scenarios the contribution of each relevant part may differ significantly. These contributions are studied in the next section through a sensitivity analysis.

4.4.4. Sensitivity analysis

The baseline scenario has been chosen as a reference and the sensitivity of the parameters linked to the relevant parts is assessed for the best case and the worst case scenarios. For the relevant parts *Spare parts program* and *Transport failures*, the values of the parameters are the same for the baseline and the best case scenarios (see Table 6), so the sensitivity of the parameters linked with the worst case scenario only are considered. The results appear on Tornado diagrams presented in Figure 30 for a coal mix and in Figure 31 for a hydro mix. The 8 previous impact categories (see Figure 28 and Figure 29) are considered. The relevant parts are presented in order of importance on the majority of the impact categories (this order is not true for some categories, but it is used on all graphs to simplify comparison):

1. Updates/revampings
2. Lifetime modulation
3. End-of-life
4. Transport failures
5. Corrective maintenance
6. Spare parts program
7. Preventive maintenance

With a coal mix, two cases may be distinguished. For all the impact categories except *ozone depletion* and *metal depletion*, the only significant results are obtained with the relevant part *Updates/revampings*. Indeed the use phase, and consequently the electrical losses, clearly dominates the environmental impacts, and the only relevant part acting on these losses is *Updates/revampings* (only in the worst case scenario through the addition of a new group). For the two other impact categories, material aspects dominate, so the impacts are much more modulated by the best case or the worst case scenario. These last results involving material aspects concern all the impact categories with a hydro mix, except *natural land transformation*.

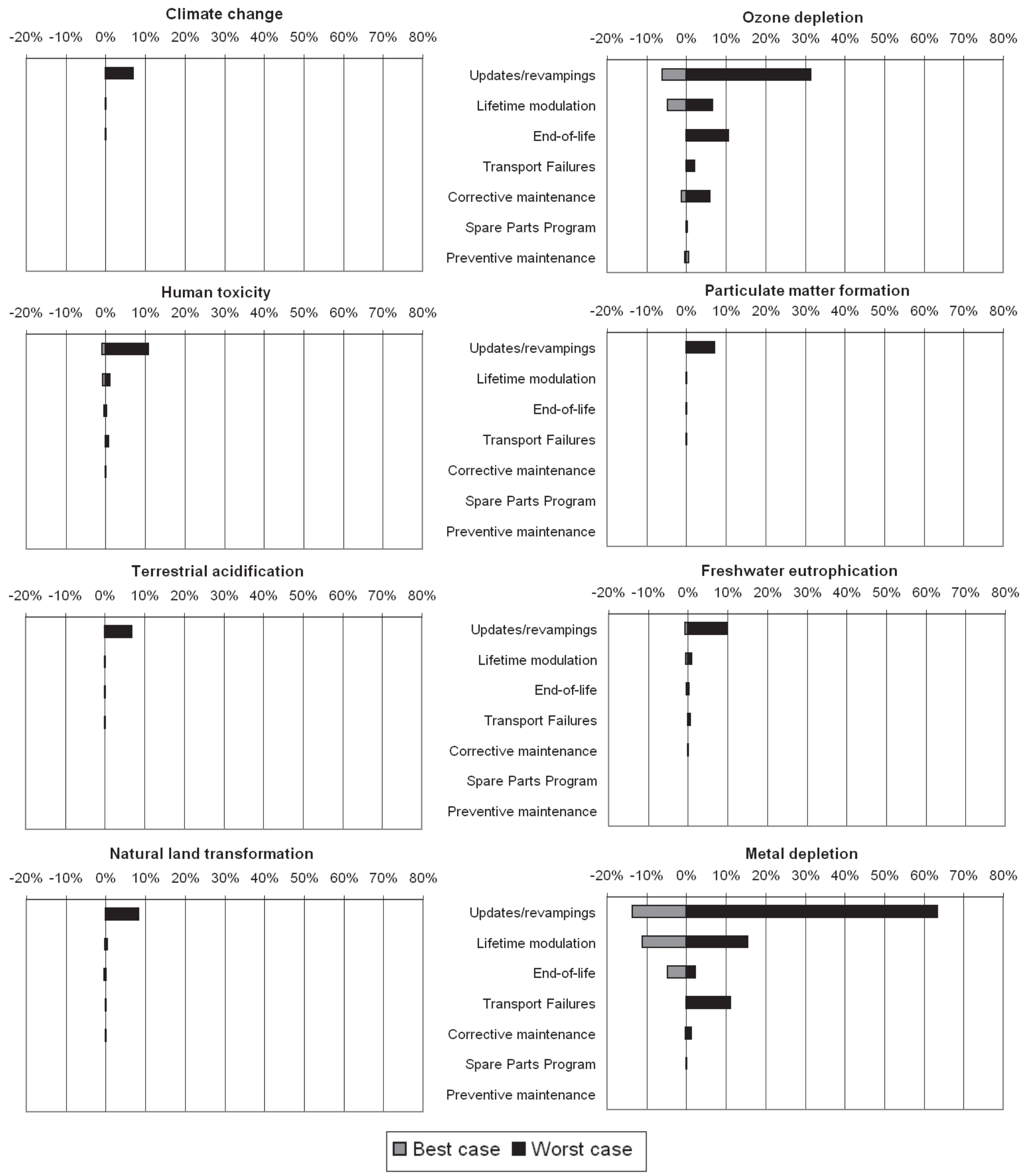

Figure 30. Sensitivity analysis of the relevant parts associated with the best case and worst case scenarios, compared to the baseline scenario taken as a reference and for a coal mix.

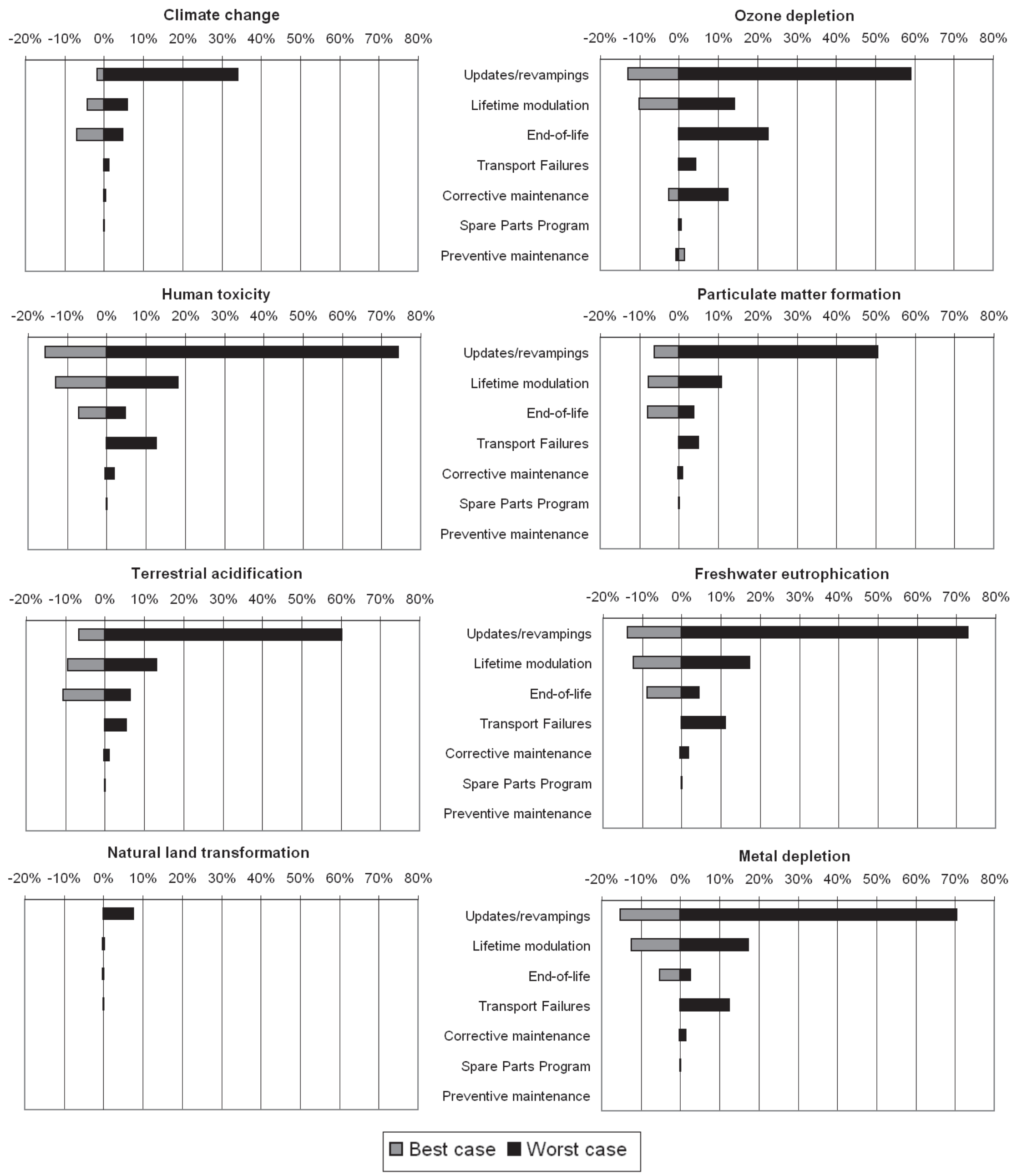

Figure 31. Sensitivity analysis of the relevant parts associated with the best case and worst case scenarios, compared to the baseline scenario taken as a reference and for a hydro mix.

The analysis of these results allows us to draw some conclusions:

- The contribution of the relevant parts *Preventive maintenance* and *Spare parts program* is always negligible, so it may not be useful to consider them in future scenarios.
- The major contributor in all cases is the relevant part *Updates/revampings* (the gap between the best case and the worst case scenarios goes from 7 to 90% of the baseline scenario impacts).

- The relevant parts *Lifetime modulation*, *End-of-life* and *Transport failures* are also major contributors when material aspects are involved.

- The relevant part *Corrective maintenance* is only significant on *ozone depletion* because of the use of PTFE in a critical rectifier component.

However this sensitivity analysis does not take into account the correlations between some relevant parts (for example those highlighted in Figure 27). A model based on the design of experiments theory would be useful but more complex to develop and apply. With this limitation, the current sensitivity analysis allows the scenarios to be refined by focusing on the most significant relevant parts. In this way *Spare parts program* and *Preventive maintenance* are not essential, whereas *Updates/revampings* is indispensable. If more time and resources are allocated to the study, attention needs to be focused on these aspects. This would then become particularly interesting for internal use.

Concerning the external use of these results, the study of the most significant relevant parts such as *Updates/revampings* or *Lifetime modulation* may help identify recommendations and good practice for the clients. This particular point is illustrated in the following section.

4.4.5. Proactive and interactive client-oriented use of the model

Once the model is well implemented in the company, a more proactive and interactive use oriented towards clients may be considered. This process leads to recommendations and good practices to improve the environmental performance of the substation.

In this case the exploitation scenarios of the model are known by the aluminium producer and formalized thanks to a proactive dialog with him. The process is divided into three phases:

1. The client exploits the substation in a certain way. A scenario of exploitation is built and implemented in the LCA model.

2. A dialog with the aluminium producer identifies the existing degrees of freedom for this scenario. One or several alternative exploitation scenarios are built and implemented.

3. The environmental benefits are measured according to the initial scenario on each impact category. Recommendations are generated by analysing the significant benefits.

A simple example is proposed to illustrate this process. The aluminium smelter is supplied by hydroelectricity. A dialog with the aluminium producer enables the identification of the initial exploitation scenario that is equivalent to the baseline scenario already used in the previous sections. One particular degree of freedom has been identified concerning the preventive maintenance. Indeed the producer admits that this maintenance may be intensified, and it has been estimated that it would lead to less corrective maintenance, and that the global life time of the substation could be lengthened by two years. All these elements have been quantified and implemented in the LCA model. As previously shown, the environmental impacts generated by reinforcing preventive maintenance are negligible compared to the potential impacts to be generated by a corrective maintenance.

Table 7. Difference of the annual environmental impacts between the initial scenario and the alternative scenario

Impact categories	Unit	Difference	Benefits
Climate change	kg CO2 eq	4.26E+04	3.36%
Ozone depletion	kg CFC-11 eq	1.36E-02	11.76%
Human toxicity	kg 1,4-DB eq	2.07E+05	17.82%
Particulate matter formation	kg PM10 eq	2.37E+02	8.62%
Terrestrial acidification	kg SO2 eq	3.51E+02	9.39%
Freshwater eutrophication	kg P eq	1.22E+02	16.17%
Natural land transformation	m2	9.38E+00	0.13%
Metal depletion	kg Fe eq	2.16E+05	18.07%

The comparison between the two scenarios leads to the environmental benefits presented in Table 7. For the metal depletion impact category for example, the annual potential impacts are decreased by 18.07 %, representing about 216 tons of Fe eq. These quantified results are a powerful driver for the clients to improve their practices.

Used iteratively, they would permit the deployment of a continuous improvement approach centred on eco-design between the supplier and the client. The aim would be to evolve towards more sustainable exploitation scenarios, i.e. scenarios reaching the best compromise between environmental performance and economic requirements. Such a process may be fed by the internal eco-design projects and it may be reiterated in a regular way (every five years for example).

4.5. Conclusions

To quickly and accurately assess the environmental performance of complex industrial systems, we have proposed in this paper an LCA model including different exploitation scenarios. The main objective of this approach consists in assessing the potential impacts of generic industrial systems in a more reliable way compared to classical streamlined and upstream LCA, while preserving time and resources. A second interesting perspective concerns the generation of exploitation recommendations to industrial clients in order to optimize the life cycle of the system from an environmental point of view.

The exploitation scenarios consider exogenous parameters, i.e. parameters that are not controlled by the supplier of the system. This model is based on a set of external explorative scenarios and the SRI matrix, a simple and intuitive tool. Four scenarios are considered: best case, worst case, baseline (expected future) and a highly different alternative. After identifying relevant parts of the system to be included in the scenarios, values are associated with each parameter and each scenario. The scenarios are implemented in the LCA software and a classical LCA process is performed.

A case study has been proposed concerning an Alstom Grid AC/DC conversion substation used to convert and supply power to aluminium electrolysis plants. We have shown that the consideration of different exploitation scenarios brings accurate and reliable knowledge about the potential environmental impacts generated throughout the life cycle of industrial systems.

However this scenario-based LCA model needs to be manipulated by an LCA expert, or at least by a person familiar with LCA. Future research may consider a more automated and interactive approach through, for example, the generation of a software layer linked with the LCA software and easily manipulable by a non-expert.

4.6. Acknowledgements

We would like to thank Frankie Rico-Sanz for his contributions to the applicative steps of this work. We also gratefully thank Joël Devautour and François Puchar from Alstom Grid to their full support in this research.

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Chapter 5. Paper #3: Eco-ideation and eco-selection of R&D projects portfolio in complex systems industries

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Foreword

The first paper (Chapter 3) was chronologically written before the two other ones (Chapters 4 and 5). A first LCA is proposed concerning an Alstom Grid substation. This LCA is shown in the first paper as the application of the first steps of the methodology. But it was also a way to identify weak LCA methodological elements that are the base of the second paper (Chapter 4), i.e. a scenario-based LCA model.

In a new and fictive implementation of the general methodology, the scenario-based LCA model would directly be applied instead of the classical LCA application proposed in the first paper, as it is proved to be more efficient and adapted to R&D strategic orientation than a classical LCA.

Finally, the general methodology proposed in the first paper includes a step of generation and selection of eco-innovative R&D projects. No application of this process was proposed in it, as the paper was written before this application. The detailed process and its application are thus proposed in the third paper (Chapter 5).

To synthetize, the first paper (Chapter 3) proposes a methodology in two steps: environmental evaluation and environmental improvement. The environmental improvement is applied in the first paper through a classical LCA study, but a more accurate and adapted model based on exploitation scenarios is then developed and applied in the second paper (Chapter 4). The environmental improvement step is detailed and applied in the third paper (Chapter 5).

Abstract: Eco-innovation methodologies and tools are applied in companies to an increasingly greater extent. None of them are however particularly adapted for complex systems industries, where the eco-design requirements are highly specific. These systems are characterised in particular by their large size and masses, and their relatively long and uncertain life cycle. We propose, in this paper, an adapted eco-innovation process based on the eco-design strategy wheel. We put together 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 analysed and assessed using an appropriate multi-criteria grid. Three formalized filters allow for an informed selection of the most promising projects that will then make up a balanced R&D projects portfolio. The whole process has been applied at Alstom Grid on large electrical stations used in the primary aluminium industry. Within a limited time frame and resources over 100 ideas were generated and analysed. The first filter allowed for a pre-selection of 16 ideas for further study, while the second filter led to a final portfolio involving 12 projects. The third filter validated the portfolio in terms of global coherence. The quantity, variety, novelty and quality of the projects were satisfactory. The process then benefitted from further improvement with the contribution of external eco-design experts.

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

5.1. Introduction

Environmental concerns take on greater importance as the awareness of the impact human activities have on the environment increases. It results in companies manifesting a need to respond to new environmental requirements and regulations. From this perspective, eco-design allows us to consider, manage and improve the environmental performance of products, processes and services.

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

Innovation is increasingly perceived as a solution for European industries to survive the emergence of developing markets (Association des Centraliens - Think Tank Innovation, 2011). Within this vein, eco-innovation would appear to be an apt solution to the ecological and possibly even the financial global crisis. However eco-innovation on complex industrial systems is a challenging task. R&D projects in complex systems industries are often driven by technological and 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 projects are necessary, but the complexity of the products makes the initiation of an eco-innovation approach tricky. Furthermore only few are trained in eco-design or Life Cycle Assessment (LCA). This is why a simple and effective eco-innovation method is necessary, with little preliminary environmental knowledge required. This would make the collaboration between multidisciplinary experts possible.

Thus we propose in this paper one such intuitive eco-innovation process. From a classical ideas-generation phase, based on the eco-design strategy wheel, (Brezet and Van Hemel,

1997) it allows for identification of a powerful portfolio of eco-innovative R&D projects through three successive filters using limited resources. A first set of eco-innovative projects is identified and then analysed by the working group using an original hybrid R&D project portfolio selection model. This model is based on a simple scoring model and a mapping approach taking five dimensions into consideration, including potential environmental benefits. From this multi-criteria assessment a final set of projects is selected and its global coherence is tested in order to ensure a homogenous rising of eco-design competences in the company. The whole eco-innovation process is then deployed at Alstom Grid on complex electrical substations.

Section 5.2 presents a literature study about eco-innovation and R&D projects evaluation and selection for complex industrial systems. It permits to introduce the adapted eco-innovation process in Section 5.3. Section 5.4 deals with the application of this process at Alstom Grid. Section 5.5 goes further to test the robustness of the model and discuss the validity of the results. Concluding remarks and perspectives are presented in section 5.6.

5.2. Background literature on eco-innovation of complex industrial systems

5.2.1. 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. If we consider the systems engineering domain, Blanchard and Fabricky (Blanchard and Fabrycky, 2011) characterise engineered systems as systems that achieve operational objectives; that operate over a complete life cycle, that are composed of a combination of resources (humans, materials, equipment, money…), that are composed of subsystems and components that interact with each other, that are influenced by external factors from larger systems and in interaction with the natural world. Adding an environmental dimension, we define a complex industrial system in the eco-design vein as:

- A large-scale system in terms of subsystems and components, mass and resource usage,
- A system whose life cycle is hardly predictable at the design level in the long-term, in particular its lifetime, upgrades, maintenance and end-of-life,
- A system whose subsystems may have different life cycles and different obsolescence times,
- A system in close interaction with its environment (super system, geographic site…),

- A system supervised by human decisions and management.

A particular example of such systems is an energy system like the Alstom Grid conversion substations described in Section 5.4. Concerning eco-innovation, the main problem of such systems is that the customers' specifications or the regulations and standards largely limit the ability to radically innovate, as only long-term proven technologies are used. Thus the challenge associated with an eco-innovation approach is whether to identify a set of reliable incremental eco-innovative projects, and/or to be able to make possible radical eco-innovations acceptable to the customers.

To deploy an adapted and effective eco-innovation approach, a literature review is first performed on eco-innovation and R&D projects portfolio evaluation and selection. This facilitates the identification of the limits associated with the current practices and to select the most powerful methods and tools for complex industrial systems.

5.2.2. Eco-innovation

5.2.2.1. Definition

Eco-innovation has been associated with numerous definitions in recent years. Carrillo-Hermosilla *et al.* list for examples 16 definitions (Carrillo-Hermosilla et al., 2010). Taking these definitions into account, the authors propose 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, this also includes radical and incremental innovations. This distinction allows for a depiction of an eco-innovation categorization shown on Figure 32.

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

Considering the hierarchical nature of complex industrial systems, as well as the fact that radical changes are often hardly acceptable for customers in complex systems industries, we consider the eco-innovation framework defined by Carrillo-Hermosilla as 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). This is why we have chosen to work within Carrillo-Hermosilla *et al.*'s definition throughout the paper.

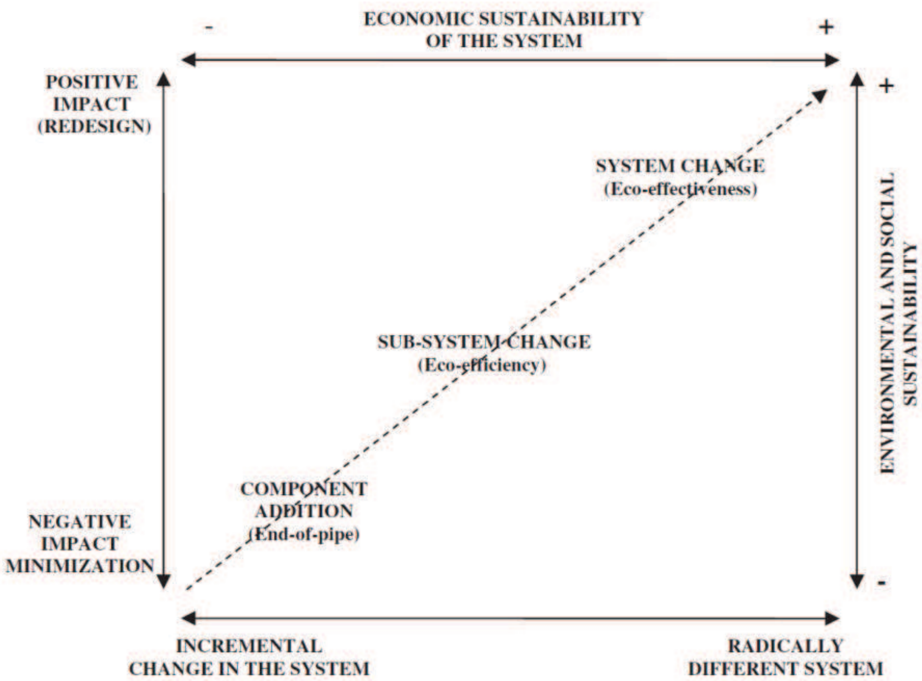

Figure 32. Categorization of eco-innovations according to the radical or incremental nature of produced technological change and the level of impacts to the system (from (Carrillo-Hermosilla et al., 2010))

5.2.2.2. Eco-ideation

An eco-innovation approach indicates two major activities: the identification of eco-innovative ideas (or eco-ideation), 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 5.2.3 is devoted to the evaluation and selection of R&D projects, as we will see that it exceeds the field of eco-innovation.

Bocken shows that eco-ideation has not been widely explored and proposes to separately study ideation and eco-design (Bocken et al., 2011). However, different tools have been designed to support an eco-innovation process. The most widely known are explained in details in the following paragraph.

Regarding the eco-ideation process in itself, a distinction can be made between collective and individual eco-ideation processes. According to Bocken *et al.* (Bocken et al., 2011), *"group ideation is generally less effective than individual creativity"*. But few individual tools exist and their usage remains complicated.

Apart from these few examples of individual eco-ideation process, experts groups are largely used through creativity sessions (Bocken et al., 2011). Researches performed in the last decade have identified some best practices to perform an effective creativity session in eco-innovation. Collado-Ruiz advises to diffuse only 'soft' environmental information to the group because 'hard' environmental information may restrict creativity (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010). Pujari shows that the multidisciplinarity in the working group is an eco-innovation success factor (Pujari, 2006).

Finally, eco-ideation processes in companies are often performed as classical creativity sessions supported by an eco-innovation tool. These tools are studied in the next paragraph.

5.2.2.3. Eco-innovation tools

Different eco-innovation tools are well known or regularly used in the literature, like the eco-design strategy wheel (Brezet and Van Hemel, 1997), also known as the LiDS wheel, Eco-compass (Fussler and James, 1997), Product Ideas Tree (Jones et al., 2001) or TRIZ-based tools.

The eco-design strategy wheel is a simple tool that proposes eco-design guidelines divided in 8 axes on a graphic wheel. 7 axes cover the whole life cycle of the product, whereas the last one aims at identifying new concepts. According to Tyl, its appropriation is really easy. It does not imply 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 hardly allow to go further than product-level considerations (Tyl, 2011). The wheel is shown in Figure 33 with the axes labels.

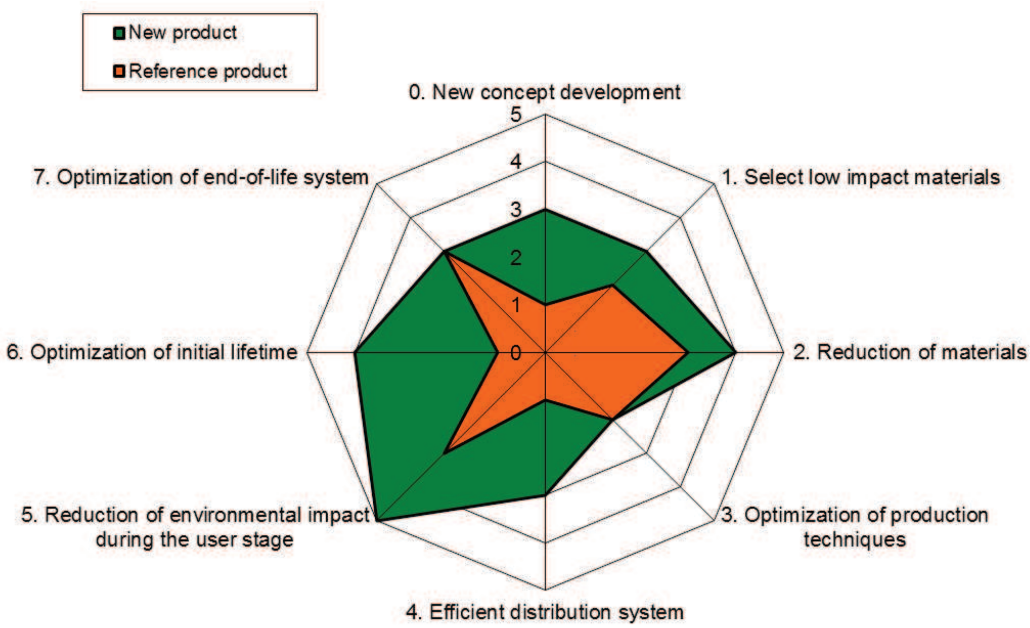

Figure 33. Illustration of the eco-design strategy wheel proposed in (Brezet and Van Hemel, 1997)

Eco-compass is another simple and graphical tool. It is composed of 5 axes that are less linear than the axes of the eco-design strategy wheel, because they mix life-cycle-oriented and impact-oriented considerations. But as the eco-design strategy wheel, it is often considered as an eco-design tool, limited to a product-level approach (Tyl, 2011).

Product Ideas Tree (PIT) aims to structure eco-innovation creativity sessions using mind-mapping techniques. It is thus more oriented on idea structure than ideation. The use of such a structure 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 (Mann and Jones, 2002; Kobayashi, 2006; Yang and Chen, 2011). TRIZ is known as a highly effective ideation tool, but it is also perceived as a complex approach. Tyl also states that the TRIZ innovative principles do not adequately fit the eco-innovation principles and need to be reworked (Tyl, 2011). He proposes a TRIZ-based tool, EcoASIT, which offer good performance in the eco-ideation phase. However in this paper we focus more on the project selection phase and that is why we propose later to adopt a very simple and appropriable tool.

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.

5.2.3. Evaluation and selection of R&D projects

5.2.3.1. Overview of the methods

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 projects portfolio.

This issue is related to the field of R&D projects evaluation and selection and R&D portfolio management. It has been under study for several decades and a significant panel of methods and tools have been produced. Mikkola precises 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"* (Mikkola, 2001).

Cooper proposes a classification of portfolio management techniques (Cooper et al., 1999).

The authors mainly distinguish financial models, strategic approaches, scoring models and checklists, analytical hierarchy approaches, behavioural approaches and mapping approaches (or bubble diagrams). Cooper also states 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 *et al.* (Bitman and Sharif, 2008) or Lawson *et al.* (Lawson et al., 2006) who have compared several approaches, is that the methods only based on financial aspects do not yield the best results. The relevance of a hybrid approach is also emphasized by Cooper *et al.* (Cooper et al., 1999).

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

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

Among all the methods, scoring models and mapping approaches are well-known and popular, mainly because they are easy to use and give acceptable results. They are also in line with the previous success criteria. We focus in the two next sections on these models.

5.2.3.2. Scoring models

The 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 forces of a scoring model is its ability to be easily implemented in companies. In fact and contrarily to mathematical or financial models, the use of qualitative scales allows a large 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.*, information concerning markets, customer needs, competitors and regulatory and environmental concerns need to be taken into account (Coldrick et al., 2005). In addition to ‘classical’ financial factors, Apperson *et al.* also consider four general areas: external forces (including environmental impacts), marketing, company dynamics, and technical capabilities (Apperson et al., 2005).

However among these different categories, environmental aspects are sometimes mentioned, but never analysed in depth.

5.2.3.3. Mapping approaches

Historically the BCG (Boston Consulting Group) and the McKinsey matrices are the most familiar mapping approaches (Mikkola, 2001). The BCG Matrix considers relative market share and industry growth rates as the two dimensions of success in a four-cell matrix. The McKinsey Matrix is built on a nine-cell matrix that takes into account competitive position of a company and industry attractiveness.

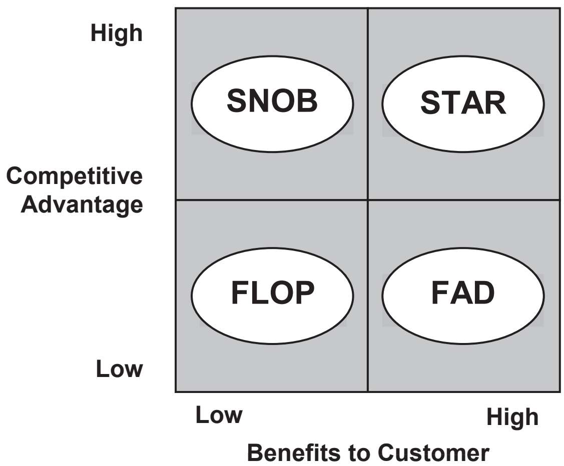

Figure 34. The R&D Project Portfolio Matrix (Mikkola, 2001)

Highlighting the particular needs for R&D projects selection, Mikkola puts forth the R&D Project Portfolio Matrix (Mikkola, 2001). Two dimensions are considered: competitive advantage and benefits to customer. The positioning of the candidate R&D projects (see Figure 34) permits to define four quadrants:

- FLOP projects are unlikely to generate positive returns for the company, and they should be removed from the portfolio.
- SNOB projects often characterise first generation innovations, as they combine a high competitive advantage with a low demand or high production costs.
- FAD projects often characterise imitation or mass production of existing products, as they meet customer’s needs with a low competitive advantage.

- STAR projects are the best on the two dimensions, and characterise successful breakthrough innovations.

Mikkola draws attention to the fact that a balanced R&D project portfolio should naturally include STARs, but also SNOBs and FADs, and in some cases FLOPs *"to achieve the growth and profit objectives associated with its corporate strategy without exposing the company to undue risk"* (Mikkola, 2001).

Nevertheless this matrix seems more adapted to B to C products, as the two axes may be associated with perceived quality (for competitive advantage) and real quality (for benefits to the customer). In complex systems industries, the number of customers is relatively limited, and the customers are able to assess global costs and quality. If these two dimensions do not seem adapted to our needs, we notice that this representation type involving two (or more) dimensions may be powerful.

Moreover the addition of a third dimension on these 2D matrices is considered by Cooper under the term *"bubble diagrams"* (Cooper et al., 1999).

As for scoring models, eco-innovation aspects, or more generally environmental concerns have not really been considered in the past. One single example is proposed by Millet to select areas of environmental improvement at the early stage of the design process (Millet et al., 2009). Three dimensions are considered: technico-economic feasibility, functional attractiveness (customers' values), and environmental impacts through an Environmental Improvement Rate (EIR).

5.2.4. Requirements for an adapted eco-innovation process

Considering the constraints associated to complex industrial systems, as well as the literature review in the field of eco-innovation and R&D projects evaluation and selection, an adapted and effective eco-innovation process should:

- Consider the different system levels (components, subsystems, system…), as incremental innovations that are constantly made at a component or subsystem level, where radical innovations are more likely to appear at a system level (new unexpected architecture),
- Be very simple, as multidisciplinary knowledge is mandatory to consider all the aspects of such a large scale system, i.e. the process mainly involves non-environmental experts,
- Be performed in a short time frame with limited resources, to be easily accepted by the management and the involved experts, as the introduction of eco-design is often perceived as a new constraint (Jacqueson et al., 2003),

- Be very efficient, to reach the best possible ratio between used resources and results,
- Build a strong basis for future eco-design works, 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 proofs in terms of feasibility and interest for the customers, 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), we propose to base the approach on an already existing eco-ideation tool. However it does not seem possible to give to the working group in-depth training, whether it concerns eco-design or creativity tools. For this reason we do not consider TRIZ-based tools in this paper. The ideal tool to assist creativity should give predefined stimuli based on checklists or guidelines. Eco-compass and the eco-design strategy wheel propose such stimuli. We estimate that the guidelines proposed by the eco-design strategy wheel are more detailed, so we will consider this tool in the next section. This choice is in line with the requirements summarized by O'Hare to increase the industrial adoption of design tools, as for instance *"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. any process to evaluate and select the most promising ideas. The R&D projects associated with complex industrial systems may be long term studies and they would probably be too numerous according to the available resources. It is thus essential to build an adapted portfolio of R&D projects through a multi-criteria assessment of each project, even if it is mainly based on qualitative evaluations. The participation of a multidisciplinary working group appears to be the best way to obtain a complete knowledge of the system.

Consequently we propose in the next section an adapted eco-innovation process for complex industrial systems, based on a multidisciplinary working group, supported by the eco-design strategy wheel and using a hybrid scoring/mapping model for R&D projects evaluation and selection.

5.3. Proposition of an adapted eco-innovation methodology for complex industrial systems

5.3.1. 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). It is built on the following hypothesis:

- Eco-innovation is deployed in a company providing complex industrial systems (as defined in section 5.2.1), 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 permitted identification of highly impacting elements (materials, components, subsystems, life cycle phases…) of the complete system life cycle.

Moreover, as expressed in numerous works of 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.

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…). 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 is the animator.

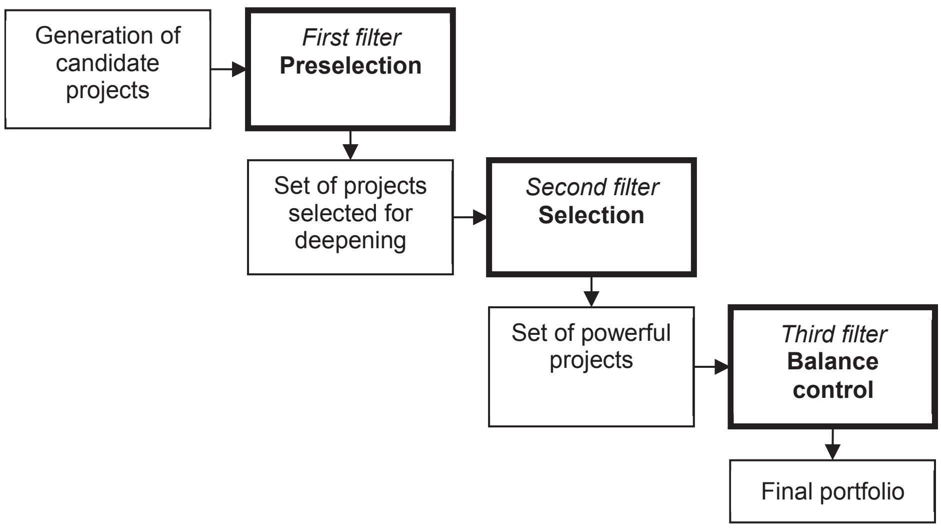

Figure 35. Overview of the global process including the three filters

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 works, as the members of the working group will be able to act as eco-design 'ambassadors' in their respective departments.

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 on Figure 35, and it is detailed in the next paragraphs.

5.3.2. Eco-innovative projects generation and preselection

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

The first session is called the 'introduction session'. As the members of the working group are predominantly unfamiliar with environmental concerns and eco-design principles, it aims at introducing the main eco-design concepts, the previous environmental assessments as well as the eco-innovation approach (including the eco-design strategy wheel). As stated by Collado-Ruiz (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010), the diffusion of 'soft' environmental information is favoured. Collado-Ruiz has 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).

The second session is called the 'creativity session' and may be performed as a half-day meeting. A short introduction is first necessary to remind 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 voluntary omitted). Each of the 8 axes of the eco-design strategy wheel is separately considered 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') using Post-it® notes,
- Following this, will be 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 ideas groups (composed of closed or complementary ideas) which are from now called eco-innovative projects.

This convergent phase is illustrated in Figure 36. It represents the first filter that permits to preselect the most promising projects and to build a powerful R&D projects portfolio. Each project is discussed. If at least a working group member is opposed to the 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 deepened according to the available resources) they are analysed one more time to consensually reject the less 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 deepened. The rejected projects are capitalized for future use.

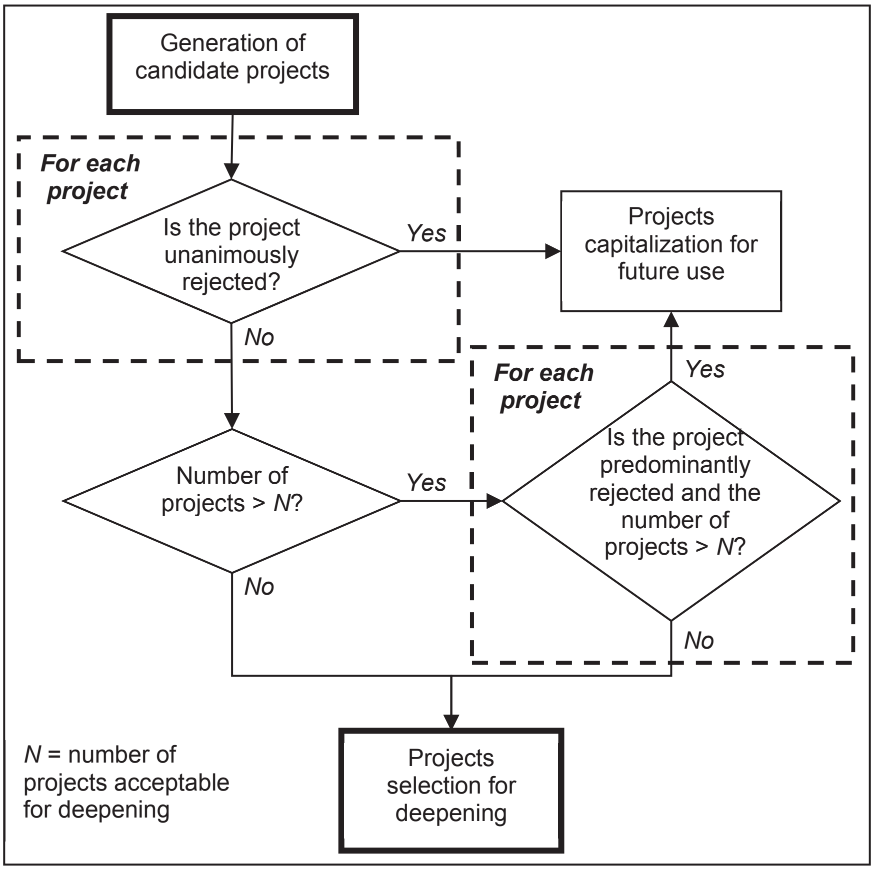

Figure 36. First filter: preselection of projects

The chosen eco-innovative projects are then synthesised on standardised sheets (see Figure 37) that include:

- a description of the project,
- the objectives of the project,

- the potential environmental benefits,
- the technical feasibility,
- the 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 standardised sheets are then deepened over a few weeks by sharing them out between the working group members according to their own competencies. The standardised sheets are then updated with the new information.

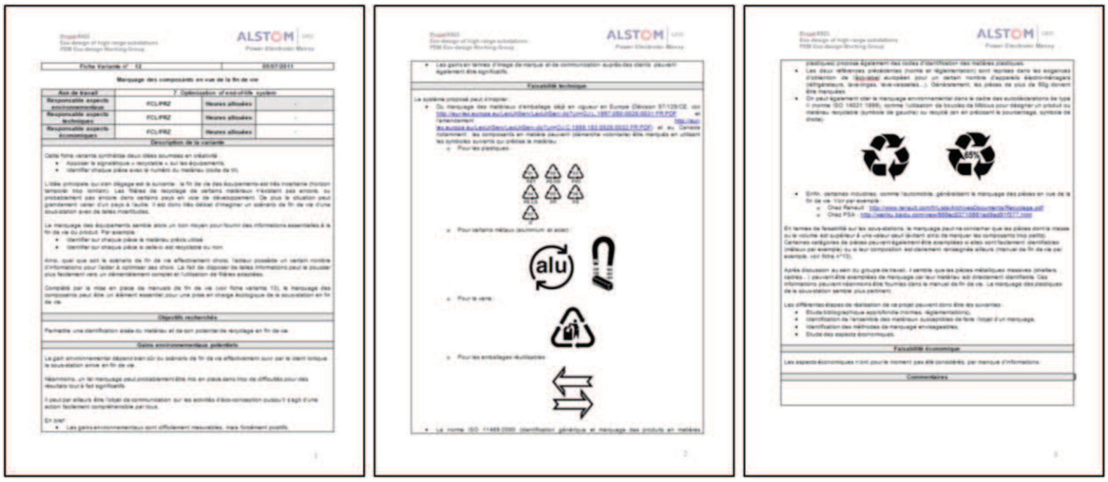

Figure 37. Example of a standardised sheet for a project on the marking of the components for the end-of-life.

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 have been identified. But they are generally too numerous to be all considered as R&D projects, due to a lack of resources. Moreover and even if some qualitative elements have been synthesised in the standardised 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.

5.3.3. Projects selection based on a multi-criteria assessment

Thanks to Section 5.2.4, we have shown that scoring and mapping models are well adapted to our requirements, i.e. the upstream and multi-criteria selection of R&D projects in a very simple and effective process, with little quantitative data and a special focus on environmental aspects.

We propose in this paragraph 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 are issued 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 8). 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.

Table 8. 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.

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 considered project are minimal.
4	The benefits brought by the considered project are significant.
5	The benefits brought by the considered project are very important.

- **Feasibility:** this dimension explores both the technical and the economic feasibility with the use of 4 indicators issued from 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 issued from (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). It permits to obtain a final customers' value on 20 points, calculated as the sum of the four scores.

- **Time horizon:** this fourth dimension gives information concerning the term 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'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 we assume that each project is clearly linked to one level without ambiguity.

- **Project nature:** this last dimension allows identifying the nature of projects: methodological, organisational, and/or technological, as a project may have several natures. This dimension is not included in the assessment grid as we assume 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 four first 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, we give more value 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 Figure 38.

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 its 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 (3):

$$NSexp_{i,j} = \frac{Sexp_{i,j} \times 50}{\sum_i Sexp_{i,j}} \quad (3)$$

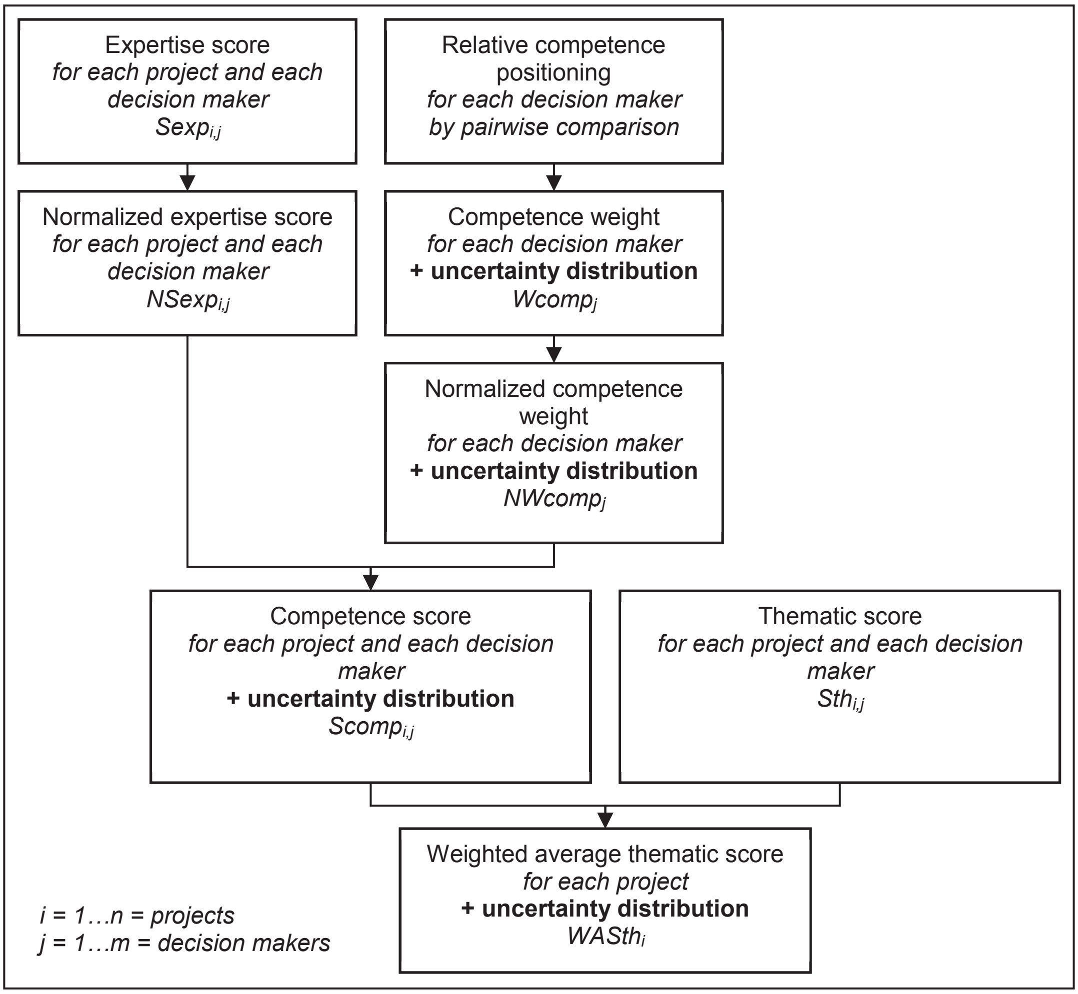

Figure 38. Calculation of the thematic (environment, feasibility, customers' value) scores in the multi-criteria assessments

Next, it is also asked to the decision makers to compare themselves relatively to the other members in terms of global competence on the working group work. This assessment is performed through the use of a pairwise comparison approach. The process of pairwise comparisons (PC) starts with the filling of a PC matrix (see Figure 39a). 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 competences pairwise comparisons, not necessarily all of them; it is tolerated that the PC matrix be scarce. These comparisons are qualitative assessments in a 7 levels scale (much less, less, slightly less, equal, slightly more, more, much more) noted (<<<, <<, <, =, >, >>, >>>) (see (Limayem and Yannou, 2002)). By 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 (4)):

$$c_{ij} \approx \frac{w_i}{w_j} = \frac{-1}{1 - \frac{1}{c^*_{ij}}} \tag{4}$$

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 $\min_k\left(c^*_{ijk}\right)$ and $\max_k\left(c^*_{ijk}\right)$ and with a modal value $\overline{c^*_{ijk}}$. Then, we use the MCPC method (Monte Carlo Pairwise Comparison) as in (Limayem and Yannou, 2002) to result in a competence weight distribution $Wcomp_j$ (see Figure 39b).

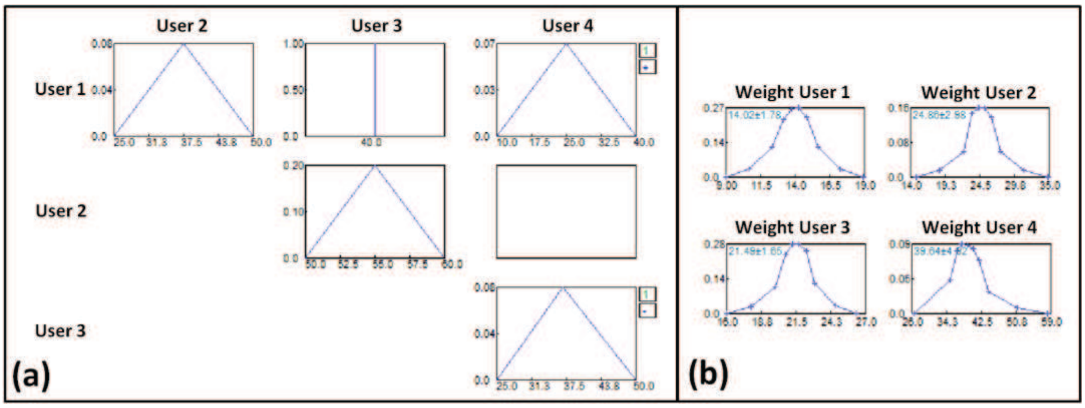

Figure 39. Example of a pairwise comparison matrix (a) and the corresponding competence weights distributions (b)

A Monte Carlo simulation is further performed with 10000 runs to measure the uncertainty range on the thematic scores. Each Monte Carlo run is renormalized in order for the sum of the weights stays 100. We obtain the $NWcomp_j$ in formula (5):

$$NWcomp_j = \frac{Wcomp_j \times 100}{\sum_j Wcomp_j} \tag{5}$$

Finally a competence score $Scomp_{i,j}$ is calculated in formula (6) for each project and each decision maker, for the 10000 Monte Carlo runs:

$$Scomp_{i,j} = NSexp_{i,j} \times NWcomp_j \quad (6)$$

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 (7):

$$WASth_i = \frac{\sum_j Scomp_{i,j} \times Sth_{i,j}}{\sum_j Scomp_{i,j}} \quad (7)$$

Among the 10000 Monte Carlo runs, the minimum and maximum $WASth_i$ are identified, as well as the score issued 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 45). So if two distributions overlap each other, there is a case of undecidability.

The assessment grid involving the four first dimensions is filled by the working group members. Once the assessments have been performed, Figure 40 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 per dimension according to 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.

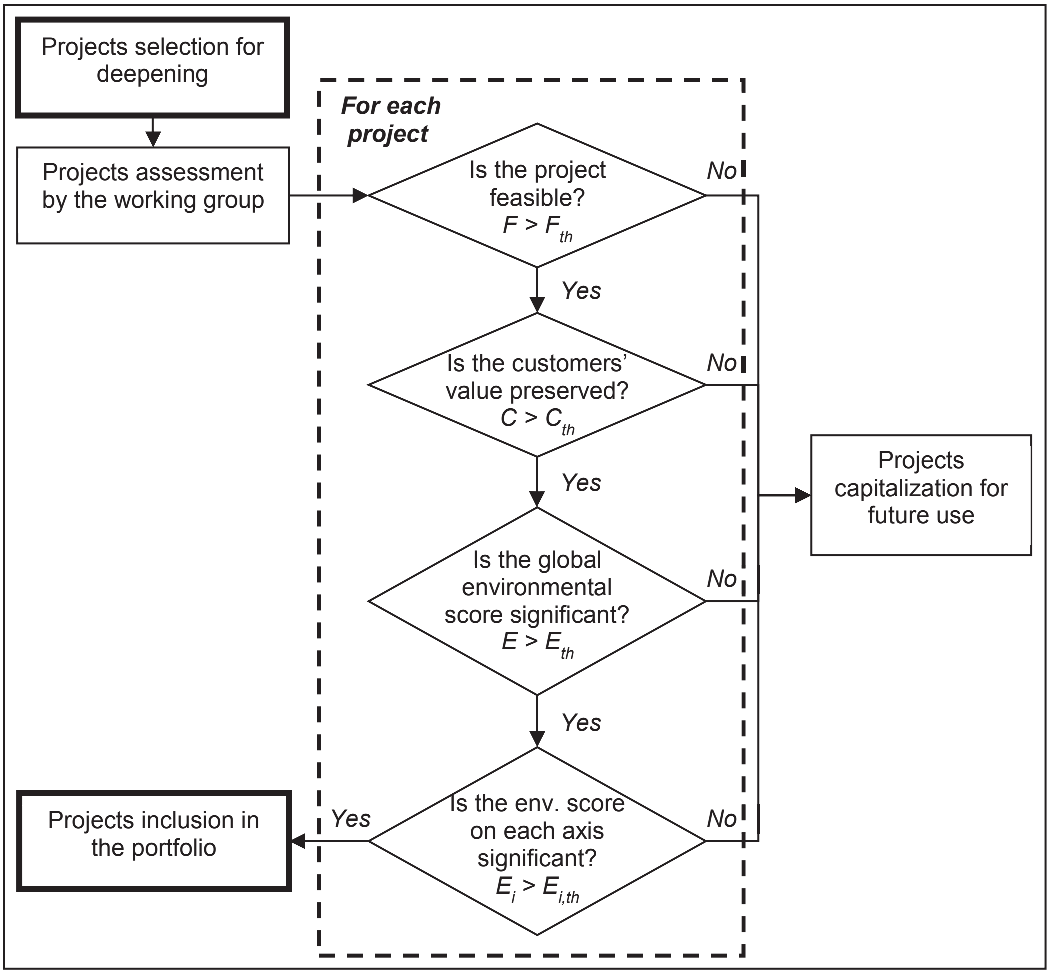

Figure 40. Second filter: selection of projects

5.3.4. Portfolio balance control

The individual selection of R&D projects permits to build a portfolio. However it does not ensure that the combination of these projects is optimal. We have indeed 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, we propose a third and final filter based on a qualitative assessment of the overall portfolio. This filter is described in Figure 41. The last three dimensions expressed in Section 5.3.3 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: organisational, 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. We assume 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 we do not propose any general rule.

If the portfolio is considered not to be well 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.

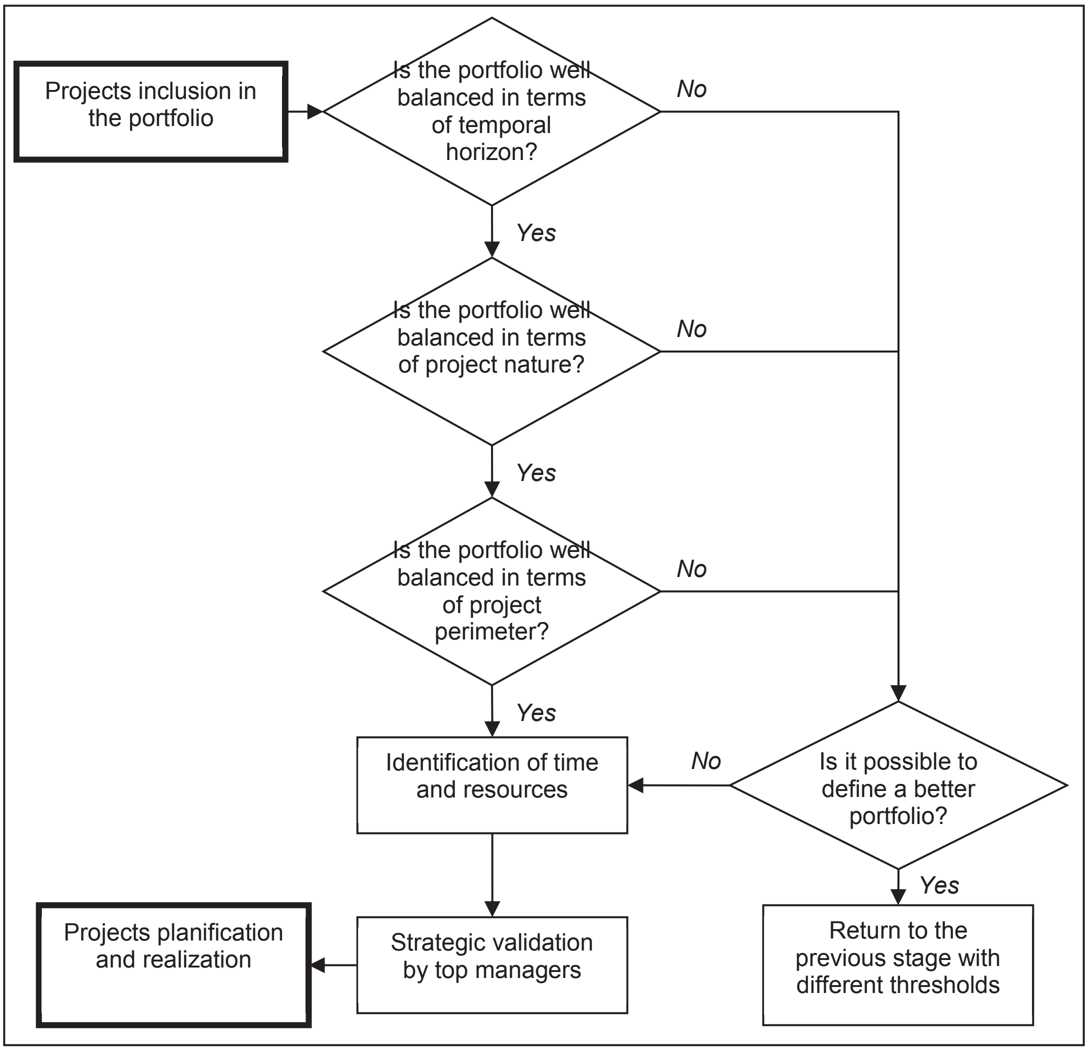

Figure 41. Third filter: balance of the projects portfolio

The final steps of the approach then consists 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 company top 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 to the decision-makers the right information to ensure the best choices at an upstream level.

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:

1. Bubbles diagrams (inspired by the R&D Project Portfolio Matrix (Mikkola, 2001)) are useful to consider at the same time the three most important dimensions (environmental benefits, feasibility, clients' value). This classical mapping vision ensures a good overview of the projects performance but uncertainty is not represented.

2. Another useful visualization of the results may be realized thanks to semantic profiles inspired by the Semantic Differential Method (Osgood et al., 1957). This representation is for example a good way to quickly identify Pareto optima, but the information related to the uncertainty distributions is ignored.

3. Monodimensional diagrams including the uncertainty ranges are also useful to easily visualize the positioning of the projects and its eventual overlaps.

4. Finally, partial ordering graphs allow easily identifying if a project is outranked by another on the three dimensions (considering the uncertainty ranges). This is an alternative to the previous monodimensional diagrams, easier to read but the quantitative information is lost.

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

In the current approach, we propose to show to the decision makers these different visualization possibilities, 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 projects sheets, we consider that the decision makers have the right amount of data to make the right decisions.

5.3.5. Projects realization

Once the projects 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.

5.3.6. Validation criteria

The validation of such a process is not easy, because it involves subjective and qualitative elements. In numerous papers from the literature, the performance of an ideation process is assessed by the *quantity* of generated ideas. In other sources, *quality* is also assessed, but this notion is highly subjective.

We consider in this paper the four criteria proposed by Shah (Shah et al., 2003), who adds *variety* and *novelty* to *quantity* and *quality*. *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. We propose to validate our eco-innovation approach by associating the following indicators with those 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 already exist before the eco-innovation approach in the mind of one or several persons in the company, in an underlying way? 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, organisational, methodological projects…).

- ***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 considered.

- ***Quality*** is assessed thanks to the three dimensions: potential environmental benefits, feasibility and customers' value.

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

5.4. A case study: application at Alstom Grid

5.4.1. AC/DC conversion substations for the aluminium industry

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 is a particularly environmentally impacting 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 42.

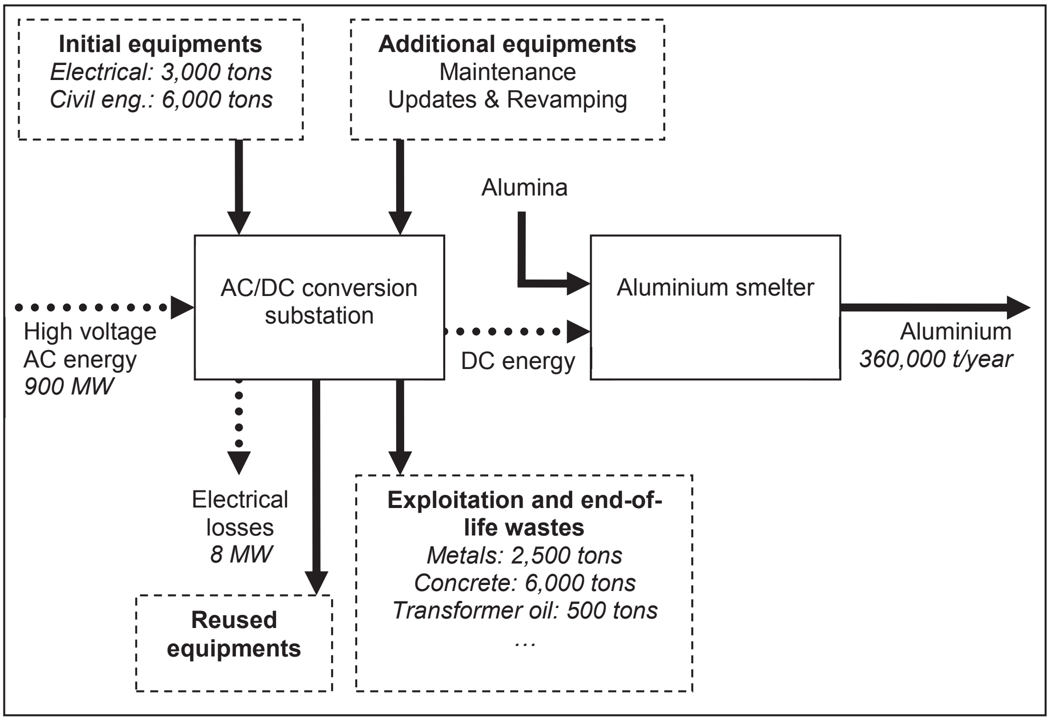

Figure 42. Overview of the flows associated with a substation life cycle. Figures are voluntary rounded off for confidentiality reasons.

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 really long, 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. We consider substations as a product family.

In this context, Alstom Grid PEM wishes to minimise the environmental impacts of its products to answer to Alstom's environmental policy and to be differentiated from competitors. A first global Life Cycle Assessment has been performed on an entire substation (Cluzel et al., 2011). This LCA is the basis for the eco-innovation process described in the next parts.

5.4.2. Eco-innovation process deployment

The eco-innovation approach was deployed at Alstom Grid following the time line described in Figure 43. 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.

The animation was managed by one junior eco-design expert assisted by one eco-design trainee, who were not proposing ideas during the creativity session. So the eco-innovation process involved in total 9 persons.

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 in order to 'digest' 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

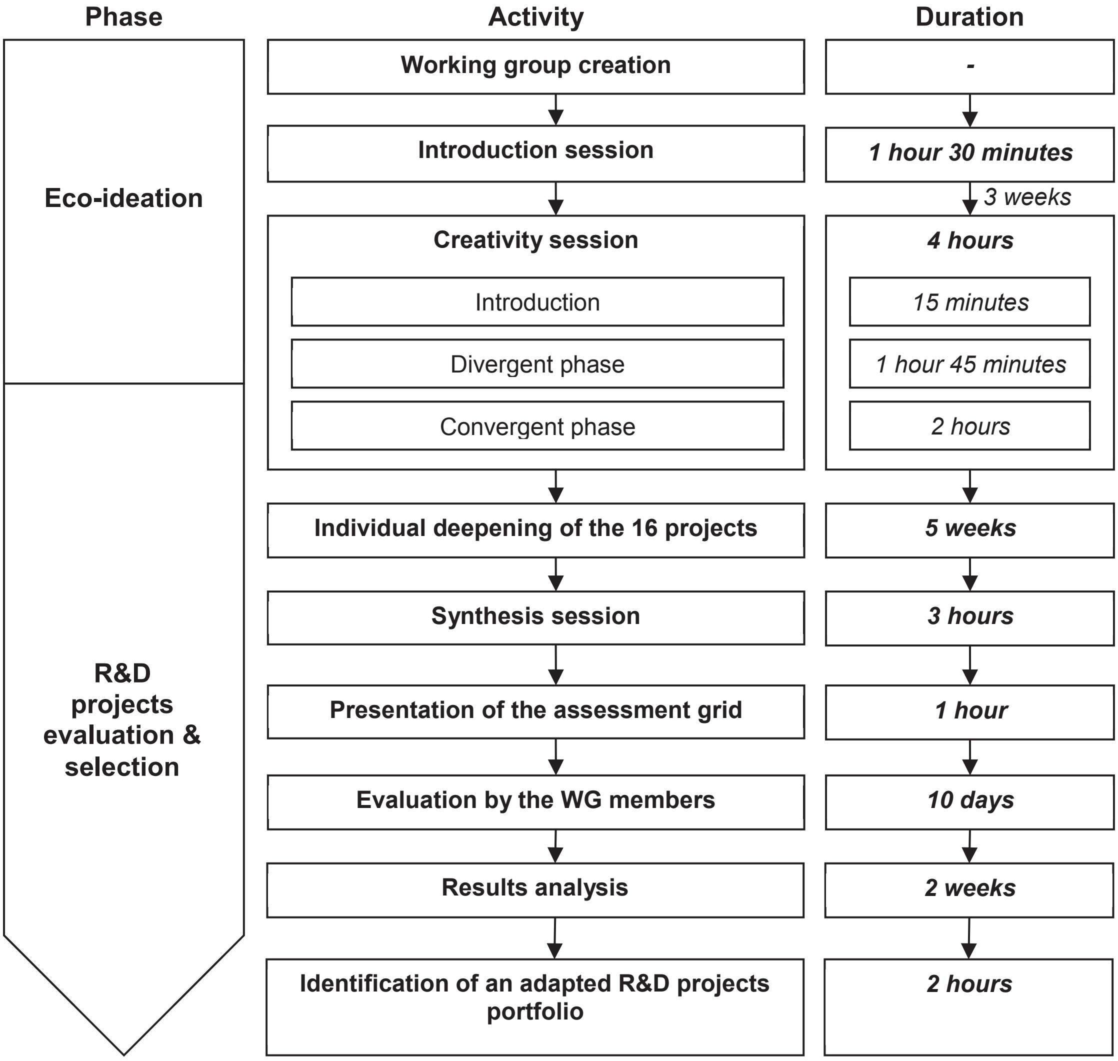

Figure 43. Time line of the eco-innovation process at Alstom Grid PEM

Then during the divergent phase each axis of the eco-design strategy wheel was considered during a 15 minutes session. Two axis 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 do not have competencies in these fields and the production is made by subcontractors.

16 eco-innovative projects were then selected at the conclusion of the convergent phase, where each idea was reconsidered according to Figure 36. These projects were deepened during five weeks and synthetized in predefined sheets during the synthesis session.

The final step of the approaches consisted in assessing and selecting the most promising projects in order to build an adapted eco-innovative R&D projects portfolio. This process in described in greater detail in Section 5.4.4. Some of the 16 preselected projects are first introduced to illustrate the results.

5.4.3. Detail of some projects

In the 16 projects issued from the creativity sessions, different project types were obtained in terms of project nature, perimeter and time horizon for example. In order to illustrate this diversity, some projects are briefly detailed below. Confidentiality reasons limit the ability to provide more information.

5.4.3.1. Optimization of transformers

The transformers used in electrolysis substations are massive electrical devices, of over 200 tons, composed mainly of metals such as copper, steel and aluminium as well as transformer oil. They are designed and produced by another Alstom Grid unit. It has been noticed that no particular eco-design actions were performed on these particular transformers. However from the LCA results they are the elements who are mainly responsible for the environmental impacts of the substation life cycle, due to their mass, the materials used or the electrical losses in use.

That is why this project aims at structuring eco-design in the transformer unit by introducing a dedicated organization with adapted methodologies. The collaboration between PEM and the transformer unit is also a key-success factor of this project. Some technological innovation ways have also been identified but they could be considered after the deployment of the organizational and methodological aspects.

This project has received the following scores:

- Environmental benefits: 11.75/20, meaning that interesting results may be obtained at the substation level, even if the transformers only are considered in this project.
- Feasibility: 12.50/20, which shows a high feasibility rate even if organisational and methodological changes are needed.
- Customer values: 11.63/20, which is a relatively satisfactory score, as the transformers are a key element of a substation, and they are thus particularly visible for the clients.

5.4.3.2. End-of-life leaflets

End-of-life issues are an important element of the potential environmental impacts of a substation. But little information is available at Alstom Grid, mainly because it depends on the clients, and with a deadline far in the future and it may vary significantly from one country to another. On the other hand the amount and the nature of the substation materials justify taking these issues into account.

As no information is easily available, the most adapted course of action would appear to be prevention. The delivery of end-of-life leaflets to the customer seems to be an economic and credible way to inform him/her about the materials used in the system, the way to dismantle it or the existing and expected end-of-life options (recycling, reuse, remanufacturing…) of the components. Associated with a marking of the components according to their materials, it has been identified as a sound and economical way to improve the end-of-life stage before performing more in-depth actions in collaboration with the clients.

This project has received the following scores:

- Environmental benefits: 10.07/20. As this is a preventive action and because of the high uncertainties concerning the end-of-life of substations, the environmental benefits are necessarily limited, but the cost/benefit ratio is particularly interesting.
- Feasibility: 14.75/20, which shows that this project is highly feasible with limited time and resources.
- Customer values: 11.21/20, which is a relatively satisfactory score for such a "small" action.

5.4.3.3. Heat losses recovery

An AC/DC conversion substation may be seen as an energy transfer function between the electrical network and the energy generation unit from one side, and the aluminium smelter on the other side. But its efficiency is not 100% as heat losses are continuously generated on each subsystem during the conversion process.

This project aims at identifying the amount of these losses that could be recovered and used to heat buildings or water, or to generate electricity. It particularly focuses on technological aspects and one first result consists in assessing the technical and economic feasibility of such a project.

This project has received the following scores:

- Environmental benefits: 9.31/20; the environmental benefits are uncertain or really limited.
- Feasibility: 9.20/20. This project seems hard to deploy with limited time and resources and the technical feasibility has not been clearly proven.
- Customer values: 9.34/20. The potential benefits for the customers are really limited compared to the losses that could be recovered from the electrolysis pots of the

aluminium smelter.

The three projects briefly described in the previous paragraphs illustrate the diversity of the selected projects and their relative innovation potential. But the available resources in the company may not be in line with these 16 projects, and some of them may not appear as really feasible after a short deepening. That is why we propose in the next paragraph an example of a restricted and adapted portfolio of eco-innovative R&D projects.

5.4.4. Choice of an optimized eco-innovative R&D projects portfolio

At this stage 16 projects were selected, as shown on Figure 44. 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 within some dimensions after the deepening. 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 5.3.4 were drawn to support the decision making.

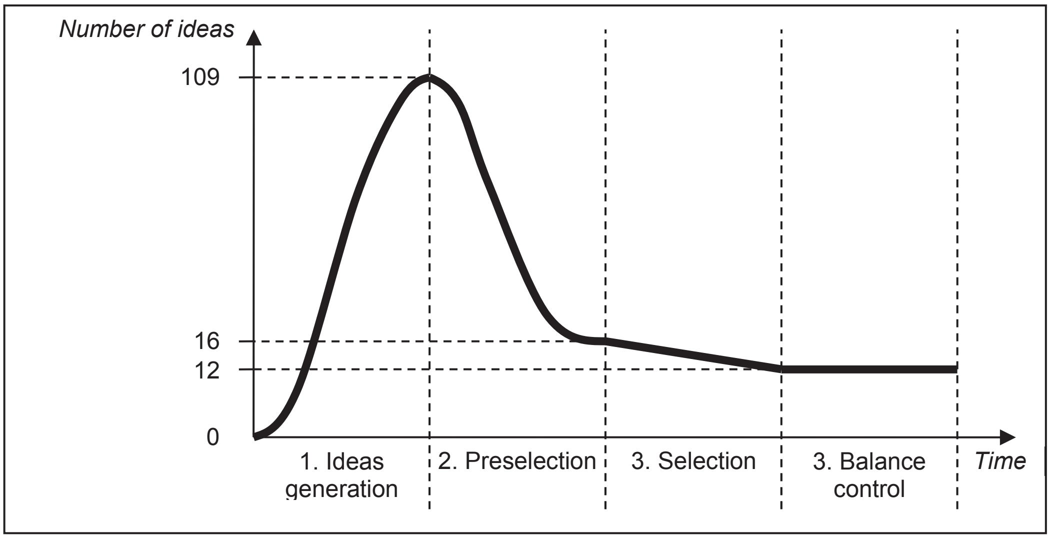

Figure 44. Evolution of the ideas number according to the process stages

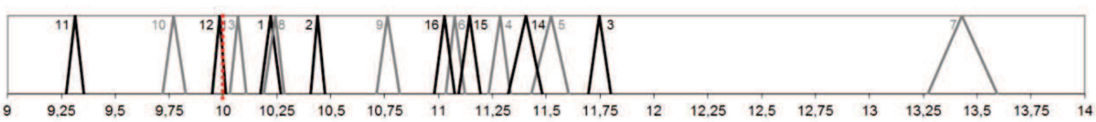

Figure 45. Positioning of the 16 projects and their uncertainty grade according to their global environmental score. The threshold value was fixed at 10 according to the strategy of the company and the global distribution of the projects.

By running with consensual threshold values the second filter described in Section 5.3, a short process permitted to select twelve projects that were considered as the best compromises between environmental performance, feasibility and customer values. Figure 45 and Figure 46 show some graphical results from the same results, that are useful to assist the decision makers is the company.

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.

Next section gives some elements to validate the eco-innovation process according to the four criteria defined by (Shah et al., 2003).

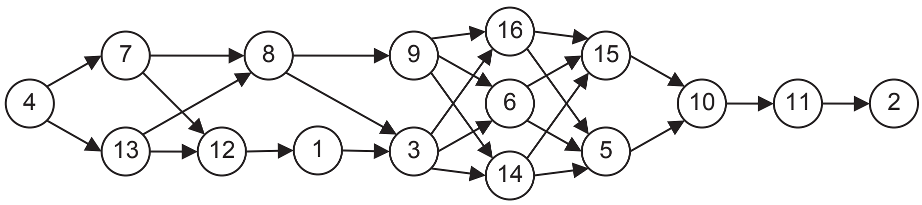

Figure 46. Outranking diagram of the 16 projects according to their feasibility grade. Project 2 dominates all the other ones, while it is not possible to determine if Project 16 is better than Project 6 or Project 14.

5.4.5. Methodology validation

5.4.5.1. Quantity

109 ideas were generated during the creativity sessions. Each axis of the eco-design strategy wheel provided between 10 and 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 really 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 the company requirements and it was also judged as satisfactory.

5.4.5.2. Variety

The variety of the final portfolio is ensured through the portfolio balance control step (third filter, see Figure 41).

Table 9 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 step. But the realization of these projects may allow the emergence of components environmental issues that may be considered in the future.

These results are considered as really 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.

Table 9. 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

5.4.5.3. Novelty

For 7 of the 16 projects, a majority of the working group members 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 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 pre-existing ideas that would not have emerged otherwise. The approach is thus satisfactory on the novelty potential too.

5.4.5.4. 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 shows that the average score is 10.8 (out of 20), but with a low standard deviation (0.98). It means that the 16 projects propose environmental improvements on some axes of the eco-design strategy wheel, but no generalized environmental improvements. This clearly characterises 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 if we consider that only incremental eco-innovations have been identified, it could be explained by the fact that the projects would only bring little benefits for the client's value.

5.5. Discussion

The definition and the use of the third formalized filters thus appear as a pertinent answer to ensure good performances of the process according to the four criteria proposed by Shah (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 would have been selected instead of 16, the amount of work to deepen these projects would have been too substantial for the capacity of the working group. This 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 the organisation. On the contrary if only 8 projects would have been selected whereas about 15 projects were wanted by the company, the problem would have again been different. Indeed it means that no consensus has been identified in the working, 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 5.2.4.

We have also performed a second assessment of the environmental performance of the projects (corresponding to the second filter) 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 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 permit to clearly distinguish the project, the distribution of the 16 preselected projects is with the external experts 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. We consider that 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, we obtain, with the same rules, a portfolio of 9 projects. These 9 projects are included in the first portfolio of 12 projects defined in Section 5.4.4 from the working group results. For the 3 other projects, great 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 5.4.5.4), we have proposed to the company to combine the evaluations of the working group with the evaluations of the external experts, leading to a final portfolio 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.

5.6. Conclusions & perspectives

Starting from the statement that eco-innovation methods are not adapted to complex industrial and technological systems, we have proposed an adapted eco-innovation process based on a simple tool. 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 1997].

- A multi-criteria assessment phase performed by the working group, considering environmental, but also technical and economic feasibility, client's value, project perimeter and time horizon.

This process has been applied at Alstom Grid on large electrical substations. The results are very satisfactory as we have shown that this method permits to obtain a high number of ideas with limited time and resources. From these ideas a balanced eco-innovative R&D projects portfolio is 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 does not seem sufficient to assess the projects, as the constraints associated with complex industrial systems favour incremental eco-innovations.

That is why further works have been done to include the contribution of external eco-design experts in order to obtain more accurate results on the environmental aspects. A final portfolio of 9 projects has been proposed to the company management, and the first projects will probably be implemented in the coming months.

Two perspectives may be considered for future works:

- The focus of this paper was more on the overall eco-innovation process and the way to assess and select the best ideas, than on the ideation phase itself. The eco-design strategy wheel offers acceptable performance but it is not particularly adapted for radical innovations. That is why it could be useful to apply the proposed eco-innovation process with other eco-ideation tools, like Eco-ASIT (Tyl, 2011).

- It could also be interesting to go further in the robustness analysis by applying the approach in different companies and on different complex industrial system, for example in the aeronautic, automotive or energy generation industry.

5.7. Acknowledgement

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Chapter 6. General discussion

Each of the three research axes presented in this dissertation is discussed in the dedicated paper. However no discussion is proposed to ensure the coherence of the whole methodology. This is the aim of this last chapter.

6.1. Robustness of the whole methodology

One essential question when deploying a new methodology is the evaluation of its robustness face to changes in the applicative context. The question of the methodology application to other companies and systems is treated in the next section. In this section we only consider changes that may occur within one specific application.

The main element that may change during the deployment of the methodology is the people. Changes may indeed occur in the company management or within the experts collaborating to the eco-innovation process. In the first case it may mean that the new management is not fully aware of environmental concerns and that it will not support the approach. The project charter, written and approved by all the involved persons (including the current management) during the *Define* phase of the DMAIC process, guarantees the initial commitments of the participants during all the projects. This formalized document is a strong element to ensure the project cohesion and we believe that it is a good way to overcome management changes in the company.

Concerning the changes that may occur within the experts collaborating to the eco-innovation process, potential problems concern the possible variability of the results in the two phases:

- In the eco-ideation phase, the emergence of ideas may differ according to the group line-up. That is why it needs to be very carefully chosen. The represented specialities and the number of members are key aspects of this choice. We consider that with 6 to 10 working group members with well-balanced competences, this variability is limited.

- In the projects assessment phase, the evaluations performed by the working group members may be extremely different if members are changed. This point has already been discussed in the dedicated paper, and we consider that with a sufficient number of assessors (13 persons in the case study), the average results are stable enough to generate a reliable portfolio of eco-innovative R&D projects.

6.2. Results generalization

One weakness of the Action Research protocol raised by O'Hare (O'Hare, 2010) concerns the generalizability of the methodology to other contexts than the application context proposed to validate the study.

The applications performed all along the three reproduced papers have been made only in one company – Alstom Grid PEM – and on one complex industrial system – AC/DC conversion substations –. One may argue that these applications are too limited to prove the generalizability of the work. But some elements may allow contradicting this assertion:

- The existing organization at Alstom Grid PEM has no particular specificities. Other Alstom Grid units, as well as numerous companies providing complex industrial systems in different sectors (automotive, aeronautics, energy…) are built on the same model with a R&D department providing technologies to the engineering department. So we are convinced that our methodologies and tools are still valid in these companies.

- The AC/DC conversion substations are of course a specific system. However the analysis of this system shows that it is "only" an assembly of subsystems and components and that its life cycle follows the classical phases of numerous large industrial systems. For these reasons we believe that our work is also still valid with other complex industrial systems.

Of course the application of the work to other companies and systems would make the results very different. For example, the relevant elements that need to be listed to build the scenario-based LCA are issued from Alstom Grid substations, and even if we consider them as easily applicable on numerous systems, they may not be valid on some particular systems. The uniqueness of such systems requires having a highly customizable methodology. In that way the implementation of the methodology is specific to the studied system (the scenarios may hardly be reused on other systems), while the theoretical methodology is generalizable to other systems. Out of this consideration we consider our methodologies and tools as highly generalizable. However it would be of course useful to test the proposed methodologies and tools on other systems and in other companies, in terms of performance and efficiency.

6.3. Adaptation to other contexts

More generally, the two previous points show that the proposed methods and tools have been designed with the ability to be easily adapted and generalized to another context in mind. More accurate indications concerning these adaptations may be useful for future uses.

The general methodology, based on a DMAIC process, is in our mind easily deployable in any industrial context, as a classical DMAIC process. This is one particular reason that has motivated this methodological choice.

Concerning the two other research axes, that focuses on particular aspects of the eco-design process, it is clearly different. We have proposed methodologies and tools that are adapted to complex industrial systems, but the requirements and the resources of the company may differ from the ones observed at Alstom Grid. Even if the saving of time and resources has been a constant concern when developing these methodologies, we are aware that in some cases it can be very different.

LCA is for example an expert tool and its use is very costly in terms of time and resources to collect high quality data. In the first chapter of this dissertation, we have quickly mentioned that numerous environmental evaluation tools exist, and that LCA is only one of them. In some industrial contexts, LCA may not be adapted to the organization, and the proposed DMAIC process is clearly able to integrate other evaluation tools than LCA, like for example qualitative environmental assessment tools. The transition with the environmental improvement phase (associated in this dissertation with the eco-innovation process) stays the same, as the identification of the environmental impacts of the system life cycle may not require to be issued from a LCA study.

In the same perspective, we consider that the DMAIC process may be performed without necessarily performing the proposed eco-innovation approach for the *Improve* and *Control* stages. Actually other improvement methodologies may be more adapted for several reasons. For example all the R&D organizations are not based on portfolio management.

Finally, the adaptation of the general methodologies to another context is for us easily possible with only minor changes in the DMAIC stages contents, the objective of each stage staying the same.

Conclusions and perspectives

Summary

Face to the growing environmental issues and in the current context of global crisis, it appears more and more essential to fundamentally revise the actual mass-consumer model. To quickly converge toward the *Third Industrial Revolution* proposed by Rifkin (Rifkin, 2010), technology management is a key lever. In this perspective companies need to integrate environmental concerns in their design processes in order to put on the markets more sustainable products.

Eco-design answers to this challenge through multiple methods and tools. However mainly mass-consumer products have been considered so far, and the question of the adaptation of eco-design methods and tools to the heavy industry sector now appears. That is why we propose in this PhD dissertation to develop adapted methods and tools to implement eco-design for complex industrial systems.

Positioning our research in the Action Research paradigm, three research questions are identified from the Alstom Grid industrial context and the study of the eco-design field. These questions are then associated after literature reviews to three research axes.

The first axis concerns the development of a global methodology to implement eco-design for complex industrial systems. Based on a DMAIC process issued from the Lean 6 Sigma field, this methodology permits structuring and managing the eco-design process from pre-defined deliverables and milestones. The methodology covers both the two basic stages of an eco-design approach, namely the environmental evaluation stage and the environmental improvement stage. The two other axes are focused on them.

The second research axis concerns the environmental evaluation of complex industrial systems. Assuming that a classical LCA approach reaches some important limitations face to those systems, we propose a LCA approach based on the modelling of exploitation scenarios. This model allows identifying relevant parts of the system that are rarely considered in LCA (like maintenance, upgrades or life time modulation). Then possible exploitation scenarios of the system are drawn to answer with limited resources to the lack of visibility on the system life cycle (lack of data, uncertain data…). The environmental impacts associated to these scenarios are finally analysed and they permit both to optimize design choices and to stimulate collaborations with clients.

The third research axis aims at identifying a portfolio of eco-innovative R&D projects for complex industrial systems. From the previous LCA results and the expertise of the company designers, a multidisciplinary working group generates eco-innovative ideas during a creativity session supported by the eco-design strategy wheel (Brezet and Van Hemel, 1997).

The ideas are then sorted out and assessed thanks to three structured filters and an evaluation grid that takes into account the environmental performance of the projects as well as other aspects such feasibility and customers' values. The analysis of the results allows quickly identifying a set of powerful R&D projects.

The three research axes have been applied at Alstom Grid on AC/DC conversion substations used in the primary aluminium industry. The results show a satisfactory implementation of eco-design in the company. The approach has got a good welcome. The LCA results have given a better knowledge of the substations and they have supplied accurate inputs to the eco-innovation process. A final portfolio of 9 projects has been proposed to the top management to be realized in the next months.

Contributions and limits

From this research, the main contributions of our work are:

- A generic and general methodology to implement eco-design in complex systems industries with limited time and resources. Pre-defined deliverables have been supplied to structure and support the process.

- A scenario-based LCA model that permits having a better knowledge of the environmental impacts generated during a system life cycle. This model is built on a qualitative approach to obtain a good compromise between results quality and available time and resources and it may be easily deployed on different systems.

- A generic eco-innovation process based on a recognized tool, the eco-design strategy wheel, and involving a multidisciplinary working group. An original eco-selection protocol based on three structured filters and a multi-criteria assessment grid to identify an optimized projects portfolio is the main contribution of this process.

- The application and the validation of the theoretical contributions to a real and industrial case study in a large and international company. We have also highlighted the good robustness and generalization potential of our contributions.

Of course, some limits need to be mentioned:

- As this work has been performed in a 3-years PhD thesis (legal duration in France), we have not been able to implement the whole methodology proposed in the first research axis. Indeed the eco-innovative R&D projects, that have been identified and proposed to the company, have not been realized (each of these projects may last several years) and a complete iteration of the process has not been performed. For these reasons only the first part of the general methodology is validated.

- The applications have been realized only on one system and in one company. Even if we have highlighted the generalization potential of our work, it has not been proven that this work is easily applicable in another context.

- The scenario-based LCA model is designed to be easily applied on another system. However the time necessary to adapt the model may be long and limit the implementation of the model.

- The eco-innovation model uses the eco-design strategy wheel, whose radical innovation potential is often described as limited. Consequently only incremental eco-innovations have been selected in the final portfolio, and the link between the eco-innovation process and the tools used for the eco-innovation phase would need to be deepened.

Perspectives

This research work is a satisfactory stage to develop eco-design for complex industrial systems. However, this is only a first contribution to this particular context and a lot of work probably needs to deploy this approach in numerous companies. So several major perspectives may be sketched in order to improve its performances and its usability.

The main perspective would consist in deploying the whole methodology to other companies and other complex industrial systems. The first application concern the energy sector, the next ones could concern the aeronautic or the automotive sector for example.

The second main perspective to our mind would be to test the performances of the methodology on a long-term application. This application would include the stages that have already been validated at Alstom Grid, but also the realization of the eco-innovative projects and the reiteration of the whole process on several cycles. This long-term application could also be an ideal field to develop an extension of this approach, focused on the identification of the optimal environmental configuration of a complex industrial system in a given context (electrical mix, geographical situation, exploitation management…), taking into account the improvements brought by the eco-innovative projects.

Last, but not least, we are convinced that adoption of new processes and tools by companies clearly depends on their usability. And that is why we consider that the deployment of our methodology would be easier in a more automated version. The scenario-based LCA model could be integrated in a software module with a direct communication with LCA software. The eco-innovation process could also been improved by automating the evaluation process and the data processing in a dedicated computer tool.

Personal publications

Journal papers

- Cluzel F., Yannou B., Millet D., Leroy Y., “Eco-ideation and eco-selection of R&D projects portfolio in complex systems industries”, submitted to *Technovation*.

- Cluzel F., Yannou B., Millet D., Leroy Y., “Exploitation scenarios in industrial system LCA”, submitted to *the International Journal of Life Cycle Assessment*.

- Cluzel F., Yannou B., Leroy Y., Millet D., 2012, “Proposition for an Adapted Management Process to Evolve from an Unsupervised Life Cycle Assessment of Complex Industrial Systems Towards an Eco-Designing Organisation”, *Concurrent Engineering: Research and Applications*, 20 (2), pp 111-126.

Conference papers

- Cluzel F., Yannou B., Millet D., Leroy Y., "Identification and selection of eco-innovative R&D projects in complex systems industries", Proc. *International Design Conference - Design 2012*, Dubrovnik, Croatia, May 21-24, 2012.

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Other publications (in French)

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Appendices

1. Overview of the multi-criteria assessment grid for eco-innovative R&D projects

Figure 47 and Figure 48 show an overview of the multi-criteria assessment grid (in French) for eco-innovative R&D projects. This grid is used in the second research axis to assess the pre-selected project, in order to constitute the final R&D projects portfolio. A short notice introduces the grid to the user. Then the following points are evaluated for each project:

- Expertise level of the user on the considered project,
- Potential environmental benefits, thanks to the positioning of the project on the eco-design strategy wheel axes,
- Feasibility, through four qualitative indicators,
- Customers' values, through four qualitative indicators,
- Temporal horizon,
- Evaluation of the eco-innovation process (to validate the theoretical approach),
- Eventual comments.

Projet d'amélioration n°xx

L'évaluation s'effectue selon différentes catégories d'indicateurs :

- La catégorie *"Niveau d'expertise"* permet d'estimer votre connaissance du sujet traité. Cet indicateur sera utilisé pour pondérer votre évaluation lors de l'analyse des données.
- La catégorie *"Potentiel de gain environnemental"* permet de mesurer les gains environnementaux obtenus en réalisant le projet. Il s'agit d'une note sur 20.
- La catégorie *"Faisabilité"* permet d'évaluer la faisabilité technique et économique du projet. Il s'agit d'une note sur 20 obtenues en sommant quatre notes sur 5.
- La catégorie *"Valeurs des clients"* permet d'évaluer les gains attendus pour les clients (aluminier). Il s'agit d'une note sur 20 obtenues en sommant quatre notes sur
- La catégorie *"Horizon temporel"* permet d'évaluer à quelle échéance les bénéfices du projet seront perceptibles. Il s'agit d'un indicateur qualitatif.
- La catégorie *"Apport de la démarche d'éco-innovation"* permet d'identifier si le projet aurait pu émerger sans la démarche. Cet indicateur sert à valider l'approche d'un point de vue scientifique.
- La catégorie *"Commentaires"* permet de rentrer des commentaires si jamais vous le souhaitez.

Seules les cellules de cette couleur nécessitent d'être remplies (sauf la case *"Commentaires"* à la fin de l'onglet, qui est facultative) :

Pour les catégories "Horizon temporel" et "Apport de la démarche d'éco-innovation", une liste déroulante de choix vous est proposée.

Niveau d'expertise

Quel est votre niveau d'expertise sur le sujet considéré dans ce projet d'amélioration ?	
1	Je ne suis pas du tout expert du le sujet traité. J'estime mon évaluation peu pertinente.
2	Je ne suis pas vraiment expert sur le sujet traité mais j'estime que mon évaluation est assez pertinente.
3	Je suis partiellement expert sur le sujet traité. J'estime que mon évaluation est pertinente.
4	Je suis expert sur le sujet traité. J'estime que mon évaluation est très pertinente.

Note: /4

Potentiel de gain environnemental

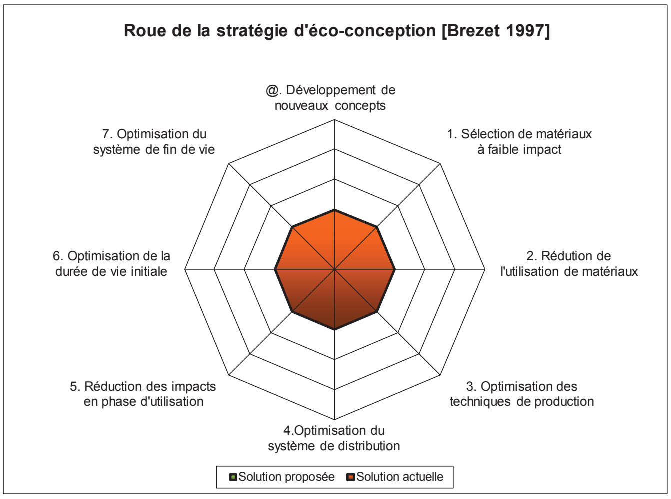
La solution actuelle est positionnée à 2 sur chaque axe de la roue de Brezet ci-dessous. Le détail des axes vous a été fourni avec le document de présentation des projets d'amélioration.

La solution apportée par le projet d'amélioration considéré doit être positionnée sur chaque axe par rapport à la solution existante, en suivant l'échelle ci-dessous :

0	Le projet dégrade fortement le score environnemental de la solution actuelle sur l'axe considéré
1	Le projet dégrade significativement le score environnemental de la solution actuelle sur l'axe considéré
2	Le projet n'apporte aucun gain sur l'axe considéré par rapport à la solution actuelle
3	Les gains apportés par le projet sur l'axe considéré sont minimes
4	Les gains apportés par le projet sur l'axe considéré sont significatifs
5	Les gains apportés par le projet sur l'axe considéré sont très importants

	Axe	Solution actuelle	Solution proposée
@	**Développement de nouveaux concepts**	2	
1	**Sélection de matériaux à faibles impacts**	2	
2	**Réduction de l'utilisation de matériaux**	2	
3	**Optimisation des techniques de production**	2	
4	**Optimisation du système de distribution**	2	
5	**Réduction des impacts en phase d'utilisation**	2	
6	**Optimisation de la durée de vie initiale**	2	
7	**Optimisation du système de fin de vie**	2	
	Total	**16**	**0**

/40



Au vu des gains environnementaux potentiels sur la roue de Brezet, la moyenne est calculée et ramenée sur 20. L'échelle ci-dessous est appliquée. Attention, cette échelle reste valable si les notes sont assez homogènes. Si ce n'est pas le cas, une analyse plus fine doit être effectuée et la note peut être changée à la main.

De 0 à 5	Le projet dégrade la performance environnementale de la solution actuelle.
De 6 à 10	Le projet n'améliore pas sensiblement, voire dégrade légèrement la performance environnementale de la solution actuelle. Des tranferts d'impacts importants peuvent apparaître.
De 11 à 15	Le projet améliore le bilan environnemental de la solution actuelle, mais l'amélioration n'est pas forcément perceptibles sur l'ensemble des axes.
De 16 à 20	Le projet améliore sensiblement, voire significativement le bilan environnemental de la solution actuelle sur l'ensemble des axes.

Note totale: **0** /20

Figure 47. Overview of the multi-criteria assessment grid (Part 1/2)

Faisabilité

Facilité de mise en œuvre	
0	La mise en œuvre demande trop de ressources et/ou de temps (non réalisable en l'état actuel)
1	La mise en œuvre demande énormément de ressources et/ou de temps (difficilement réalisable en l'état actuel)
2	La mise en œuvre est longue et demande beaucoup de ressources
3	La mise en œuvre est rapide mais demande beaucoup de ressources, ou la mise en œuvre est longue mais demande peu de ressources
4	La mise en œuvre est rapide et demande assez peu de ressources
5	La mise en œuvre est extrêmement rapide et demande peu de ressources

Note /5

Retour sur investissement financier	
0	Le projet demande énormément de ressources financières pour un gain minime sur les affaires
1	Le projet demande énormément de ressources financières pour un gain très incertain sur les affaires
2	Le projet demande peu de ressources financières pour un gain minime sur les affaires
3	Le projet demande peu de ressources financières pour un gain très incertain sur les affaires
4	Le projet demande beaucoup de ressources financières pour un gain très significatif sur les affaires
5	Le projet demande très peu de ressources financière pour un gain très significatif sur les affaires

Note /5

Faisabilité technique en termes de connaissances	
0	Les connaissances nécessaires ne sont pas disponibles (personne ne sait faire)
1	Les connaissances nécessaires ne sont peut-être pas disponibles
2	Les connaissances nécessaires sont disponibles en dehors d'Alstom Grid (personne ne sait faire chez Alstom Grid)
3	Les connaissances nécessaires sont disponibles chez Alstom Grid
4	Les connaissances nécessaires sont disponibles chez PEM mais non mobilisables immédiatement
5	Les connaissances nécessaires sont immédiatement disponibles et mobilisables chez PEM

Note /5

Degré de maîtrise en interne	
0	L'ensemble du projet doit être délégué à un sous-traitant ou un fournisseur
1	L'ensemble du projet doit être délégué à une autre unité d'Alstom Grid
2	Une majeure partie du projet doit être déléguée à un sous-traitant, un fournisseur ou une autre unité d'Alstom Grid
3	Le projet peut être réparti de manière à peu près égale entre PEM et un sous-traitant, un fournisseur ou une autre unité d'Alstom Grid
4	Une partie mineure du projet doit être déléguée à un sous-traitant, un fournisseur ou une autre unité d'Alstom Grid
5	L'ensemble du projet est maîtrisable en interne

Note /5

La note totale est calculée en sommant les notes des 4 indicateurs. La note totale de faisabilité est donc sur 20. L'échelle ci-dessous est appliquée. Attention, cette échelle reste valable si les notes sont assez homogènes. Si ce n'est pas le cas, une analyse plus fine doit être effectuée et la note peut être changée à la main.

De 0 à 5	Le projet est considéré comme très peu faisable en l'état actuel. Les risques sont très élevés.
De 6 à 10	Le projet est considéré comme difficilement faisable en l'état actuel. Les risques sont élevés.
De 11 à 15	Le projet est faisable. Les risques sont acceptables.
De 16 à 20	Le projet est extrêmement faisable. Les risques sont très faibles.

Note totale: 0 /20

Valeurs des clients

Amélioration de l'image de marque des clients	
0	Le projet dégrade fortement l'image de marque des clients
1	Le projet dégrade sensiblement l'image de marque des clients
2	Le projet n'apporte aucune amélioration de l'image de marque des clients
3	Le projet apporte une amélioration minime de l'image de marque des clients
4	Le projet apporte une amélioration sensible de l'image de marque des clients
5	Le projet apporte une amélioration significative de l'image de marque des clients

Note /5

Réduction des coûts pour les clients	
0	Le projet augmente fortement les coûts des clients.
1	Le projet augmente sensiblement les coûts des clients.
2	Le projet de modifie pas les coûts des clients.
3	Le projet diminue légèrement les coûts des clients.
4	Le projet diminue sensiblement les coûts des clients.
5	Le projet diminue significativement les coûts des clients.

Note /5

Diminution des risques pour les clients	
0	Le projet augmente fortement les risques pour les clients.
1	Le projet augmente sensiblement les risques pour les clients.
2	Le projet de modifie pas les risques pour les clients.
3	Le projet diminue légèrement les risques pour les clients.
4	Le projet diminue sensiblement les risques pour les clients.
5	Le projet diminue significativement les risques pour les clients.

Note /5

Amélioration de la qualité de service pour les clients	
0	Le projet dégrade fortement la qualité de service pour les clients.
1	Le projet dégrade sensiblement la qualité de service pour les clients.
2	Le projet de modifie pas la qualité de service pour les clients.
3	Le projet améliore légèrement la qualité de service pour les clients.
4	Le projet améliore sensiblement la qualité de service pour les clients.
5	Le projet améliore significativement la qualité de service pour les clients.

Note /5

La note totale est calculée en sommant les notes des 4 indicateurs. La note totale de valeurs des clients est donc sur 20. L'échelle ci-dessous est appliquée. Attention, cette échelle reste valable si les notes sont assez homogènes. Si ce n'est pas le cas, une analyse plus fine doit être effectuée et la note peut être changée à la main.

De 0 à 5	Le projet dégrade les valeurs des clients.
De 6 à 10	Le projet n'améliore pas sensiblement, voire dégrade légèrement les valeurs des clients. Certains critères peuvent apporter des aspect négatifs notables.
De 11 à 15	Le projet améliore les valeurs des clients, mais l'amélioration n'est pas forcément perceptibles sur l'ensemble des critères.
De 16 à 20	Le projet améliore sensiblement, voire significativement les valeurs des clients sur l'ensemble des critères.

Note totale: 0 /20

Horizon temporel

Horizon temporel	
Court terme	Les résultats du projet seront perceptibles très rapidement (mois de 6 mois après le lancement des études)
Moyen terme	Les résultats du projet seront perceptibles à moyen terme (entre 6 mois et 2 ans après le lancement des études)
Long terme	Les résultats du projet seront perceptibles à long terme (plus de 2 ans après le lancement des études)
Prospectif	Les résultats du projet seront peut-être perceptibles à très long terme (plus de 5 ans après le lancement des études)

Note

Apport de la démarche d'éco-innovation

Pensez-vous que ce projet d'amélioration était déjà présent avant le lancement de la démarche d'éco-innovation dans l'esprit d'une ou plusieurs personnes chez PEM/PTR, de façon non formalisée et/ou sous-jacente ?

Réponse

Pensez-vous que ce projet d'amélioration aurait pu émerger, être formalisé et sérieusement considéré par la hiérarchie sans les travaux du groupe de travail et le processus d'éco-innovation ?

Réponse

Commentaires

Avez des commentaires sur l'évaluation de ce projet d'amélioration ?

Figure 48. Overview of the multi-criteria assessment grid (Part 2/2)