BARRIERS AND DRIVERS FOR AN EFFICIENT INTEGRATION OF ECO-DESIGN OF COMPLEX SYSTEMS: A CASE STUDY IN THE FRENCH MILITARY INDUSTRY

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ABSTRACT

The defense industry tends to anticipate environmental issues through eco-design integration in the overall design process. This leads to focus on the impact of technological and design choices of complex systems while maximizing operational performance. Such development involves long and complex processes and is constrained in a project owner and industrial project manager context. In this context poorly described in the literature, the objective of this paper is to identify barriers and drivers to achieve an efficient application of eco-design. A comprehensive analysis of the interactions and the current design processes is performed in the context of the French defense industry. Through internal documentation and semi-structured interviews with the key actors, the generic design process of a project owner is analysed (including relationships with industrial project manager). The failure modes that currently limit the integration of eco-design in projects are also identified.

Keywords: Ecodesign, Complexity, Design process, Military industry, Socio-technical system

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1 INTRODUCTION

Eco-design implementation in complex system industries remains a major challenge. Its efficient and long-term integration requires a transversal investment from companies in the value chain. The design ecosystem is characterized by co-evolutionary dynamics between actors (Gaziulusoy and Brezet, 2015).
Environmental defence strategies are defined by the European Union and the North Atlantic Treaty Organization on climate and environmental issues (NATO, 2021; IRIS, 2021b; EEAS, 2021). On one hand, defence organizations seem ready to address climate change as a serious challenge (van Schaik et al., 2020). On the other hand, the improvement to reduce impacts of systems is huge. Disregarding the environment introduces risks and leads to troubles during the life cycle: obsolescence, additional cost, bad image (IRIS, 2021a), delayed acquisition (Michelin and Janin, 2018), impact on health of end-users, etc. Today's design must anticipate tomorrows: geopolitical, threats and conflicts (NATO, 2021), etc.
The environment is too little considered in the design process in the defence domain. In this paper, we are interested in the defence domain and eco-design integration in its processes. Eco-design is commonly an approach that aims to integrate environmental aspects into design process to reduce the negative environmental impacts of systems throughout their life cycle (ISO/TR 14062:2002). In the defence domain eco-design must also meet the customer desire while fitting the capacity approach (Michelin and Janin, 2018). This approach is composed of human and defence systems, organized, trained, and supported according to a doctrine, with a view to operational use. The common environmental impacts in the defence domain are the climate change and energy (Ministère des armées, 2022; Maisonneuve, 2022), the pollutant discharges, the evaluation of carbon footprint, etc.
We consider complex systems with different sizes and operating environment. They are composed of platforms (aircraft carrier, drone, etc.) and their equipments (optic, energy supply, etc.). Their specificities are high operational expectations, a long lifespan, multi-components systems, follows-up (regular evolutions/retrofitting, evolution of functions and increased performances (cf. incremental approach), etc. As complex system, their design and development commonly involve many stakeholders (e.g. different departments within the same company, outsourced suppliers) and it is complicated to shift employees' habits and current companies' practices (Saidani et al, 2016). The defence design process is also to be long and structured. Particularly, the final customers (i.e. armed forces) are end-users, well identified and aware of their needs / military effect to produce, in a cost-effective way.
This paper explores the transition from the traditional decision-making triptych (operational-technological-economic) to the integration of eco-design issues in a complex and multidimensional domain, such as defence sector. More precisely, this paper investigates the barriers and drivers to efficiently eco-design complex systems in the long-term, in the case of the French defence industry. We start with the literature review on socio-technical system, barriers and drivers of eco-design adoption during complex systems development, and the integration of environmental criteria in the military field. Then the method of investigation is explained through the research protocol and is enriched with the documents studied, the interviews and emblematic projects. Finally, the results are presented. They consist in positioning the socio-technical system of French defence design, realising a generic design process, identifying failure modes for a long-term eco-design integration, identifying the barriers and drivers and formulating recommendations.

2 LITERATURE REVIEW

This literature review explores the design process of complex systems and the long-term integration of eco-design while satisfying customer's needs. It is focused on the way the integration of environmental issues is beneficial or harmful to a multi-partner design project, seen as a socio-technical system.

2.1 Socio-technical description of complex system design environment

The concept of socio-technical system is used in the literature to explain how organisational outcomes are the collective result of individual changes (Hiatt and Creasey, 2003). The focus can be evaluative (caused by differing stakeholder needs and values), nested (resulting from two-way interactions between technical and organizational systems) and dynamic complexity (caused by difficulty in predicting system behaviour as well as subtle and unobvious cause-and-effect relationships) (Hollauer et al., 2015). Their paper "capture and analysis of various forms of complexity within the sociotechnical system comprising a PSS [Product-service systems] and their impact on the PSS". The conceptual framework proposed in the work of Gaziulusoy and Brezet (2015) is especially interesting because it studies design for

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innovation and system transitions with a wide focus on sustainability. They focus on the levels of design and innovation within firms and propose the matrix titled "Co-evolutionary dynamics within the socio-technical system." This matrix is used as a background for Figure 2, where it is directly customized for the case study presented in this paper. It shows some of the different elements of the socio-technical system that influence change on a co-evolutionary basis. The different types of socio-technical components (institutional, social/cultural, organizational and technological) are scaled (small, medium and large) representing the complexity. When it increases, managing change becomes harder and the pace of change gets slower. Also, small type of socio-technical system component is hierarchically dependent on larger scales of the same type (Gaziulusoy and Brezet, 2015). The circular arrow in the background frame indicates continuous and dynamic changes, and each element influences each other.

2.2 Internal drivers and barriers for eco-design adoption during the development of complex systems

It is interesting to learn from what has been documented in the civil sector about the drivers to integrating eco-design into the design of complex systems. For instance, Bey et al. (2013) mention that, according to their survey, the integration of environmental strategies in manufacturing companies is driven by customer demands and competitive edge. In the paper of Bossle et al. (2016), the internal factors are moreover related to efficiency (by cost reduction, equipment update, investment in R&D or certifications), environmental capacity and environmental concerns of managers (including environmental leadership), quality of human resources (including training and participation in sustainability programmes) and environmental strategy (including the culture of the firm). Liao et al. (2018) mention also that internal driving factors for enterprises' environmental innovations in China are: industrial competitive environment (market competition), the egoistic motivation (cost saving, resource acquisition and risk avoidance) and green development value.

There are also reasons to question the barriers that prevent technologies and systems from easily adapting to sustainable challenges. The significant challenges to sustainably design and construct are the first cost premium of the project, the long pay back periods from sustainable practices, the tendency to maintain current practices, and the limited knowledge and skills of subcontractors (Ahn et al., 2013). Additionally, based on a pre-defined survey of 15 questions, two clusters of barriers to integrate environmental strategies in manufacturing companies are identified: "Difficulties in finding information on environmental impact" (on environmental impact plus expert knowledge) and "No extra resources allocated to new environmental initiatives" (both time and human) (Bey et al., 2013).

2.3 Integration of environmental criteria in the military field

The integration of environment (climate change, energy, etc.) in the defence sector generally does not consider military systems and overseas operations, but only the infrastructures (Department of Defence, 2019; Ministère des armées, 2022). Design in the defence industry is driven by safety, functionality, ergonomics, costs, strength and technical parameters, before environmental problems (Mrozek, 2021). The author concludes that the main problem of the armed forces is the increased carbon footprint emissions. In that sense, Sarewitz et al. (2012) propose three interrelated golden rules to use and manage energy facilities: 1) Reduce energy usage and intensity 2) Increase renewable and on-site energy generation (distributed generation) 3) Improve energy security. According to Regaud (2021), the climate issue must be incorporated into the military strategy, doctrine, planning and programming documents, and links with other ministerial development departments must be developed. The integration of climate change tends to result in the adaptation of military infrastructure, equipment and training. Additionally, IRIS (2021a) studied the strategy of countries to face the climate change and they conclude that " The lack of tangibility of climate change, combined with the military culture, has resulted in an approach to climate and environmental issues through two specific prisms: emergency on the one hand, and technophilia on the other".

To sum up this state of the art, the concept of socio-technical system seems relevant to represent a complex environment. We therefore propose to use it to represent the ecosystem of military complex systems development. Moreover, if papers have been found on the study of barriers and drivers in various domains, few have been found in the defence domain. There is a real challenge to integrate eco-design in the defence domain.

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3 METHOD OF INVESTIGATION

The paper is the first step of the Action Research approach proposed by Yannou and Petiot (2011). It results in recommendations for long-term integration of eco-design into complex system projects. And it is in accordance with identified barriers and drivers and takes place in the French ministry projects.

3.1 Research protocol

The objective of the protocol (Figure 1) is to know where and how to act over the long-term to ensure integration of eco-design into complex system projects. We propose to bring out a better understanding of the place of eco-design within DGA (Armament General Directorate of the French government) and Thales company (defence industrialist). It is an opportunity to capitalize on the potential for sustainability of the military systems.

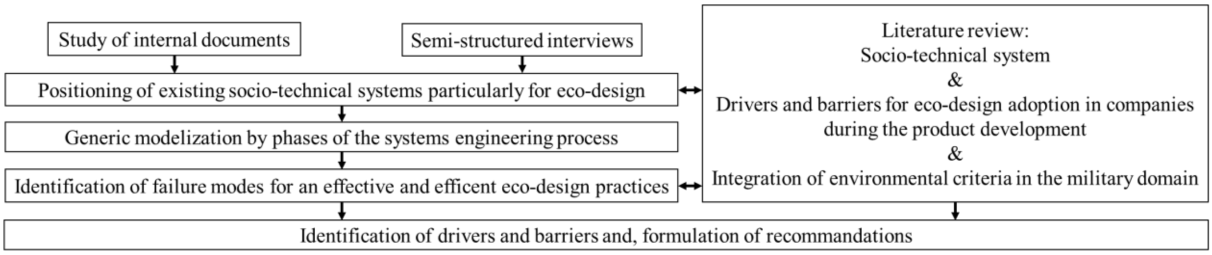

Figure 1. Research protocol for a long-term eco-design adoption in complex system projects

3.2 Study of internal documents and semi-structured interviews

The documents study began with the internal documents of both entities. The aim is to understand and describe organizations, design processes (especially eco-design), and the life cycle of military system. Additionally, the socio-technical system is described. The topics of the studied documents are:

- The conduct of armament operations: Ministerial Instruction on the conduct of armament operations i.e. IM1618 (Ministère des armées, 2019), master plans, functional/value analysis, etc.;
- The industrial interactions: outside the scope of program (showroom, feasibility studies, etc.) and inside (annual meeting, assessment of the environmental maturity of company's organization and operational performance of the eco-design approach (Michelin and Janin, 2018), etc.);
- Eco-design: guide, reference documents, environmental specifications, call for tender content, etc.

To apprehend the complexity of defence projects, four unstructured interviews were organized with persons in charge of the integration of eco-design within DGA and Thales. It appeared that having interviews with people directly involved in projects is a necessity (i.e. military - state engineers - industrial engineers). The interviewees were selected for their expertise on environmental dimensions or because of their involvement at least once in a design process integrating environmental concern. The interviewees' identification was done jointly with the four persons cited previously. We performed 22 interviews: 15 from DGA (Worker from "Environmental risk management", worker from "Materials, components and energy", Workers from Capability Coherence, Defence system architect, Functional/Value analysis project manager, etc.) and 7 from Thales (Product policy director, HSE corporate product, HSE (Health, Safety, Environment) product designer, Product manager, etc.).

Semi-structured format of interviews is retained because the expected answers are qualitative. It allows to give a framework to the discussion while not forgetting the data we wanted to obtain. It also allows to leave the interviewee free to bring up elements that were not anticipated. The interviews were recorded to ensure the validity of the information collected and to be fully focused on the exchanges.

The interviews allowed to know the reasoning and the tools leading to technological/design choices, specially according to environmental criteria. They were also useful to identify the eco-design definitions for each of the two entities. Hereafters are the areas of interest, which were the basis for questions that we asked and were personalized according to the interviewee's area of expertise:

- The interviewees' contribution to the design phase(s) in which they are involved;
- The resources they use (tools, methods, reference document, etc.) on environment or not;
- Their interfaces with stakeholders (internal or external to their domain silo);
- The analyses leading to technological/design choices: risk analysis, functional/value analysis, etc.

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3.3 Emblematic projects of environmental integration

A set of military systems development projects were selected, with the previous four eco-design experts from DGA and Thales. They are considered as the five most emblematic projects of environment integration shared by these two partners. We don't talk about eco-design integration because there is no questioning throughout the whole design process.

However, they provide good insights on the environmental impulses in defence projects. The impulses were through specifications and depended on the experts' maturity on the subject at the time of the project. They are on reduction of packaging, higher biodegradability, increase of recyclability of systems, reduction of hazardous substances, better waste management and reduction of carbon footprint.

The five projects have few differences: The stakeholders involved (at least DGA and Thales); the environments of use (air, land, surface water, etc.); the phases of integration of environmental expectations within the project; the person promoting the integration of the environmental dimension in the project; the environmental improvements retained.

4 RESULTS

4.1 Co-evolutionary dynamics within military socio-technical system

The design process of military systems is assimilated in this article to a socio-technical system. It is intended to integrate eco-design. To act on the long-term, it requires the identification of the influences of the socio-technical system elements and the analysis of their co-evolution. The matrix proposed by Gaziulusoy and Brezet (2015) is thus appropriate. It proposes a visual representation that systematically identifies co-evolutionary dynamics between elementary systems.

Following the literature review and interviews, we identify the co-evolutionary dynamics involved in the integration of eco-design over a long time (from 10-15 years in average to 30 years). We frame the elementary systems of the Figure 2 and we identify the ones (in-)directly impacting the integration of eco-design in military system design. They can be direct (solid lines) or indirect (dotted lines). The following article is based on the ones in solid lines.

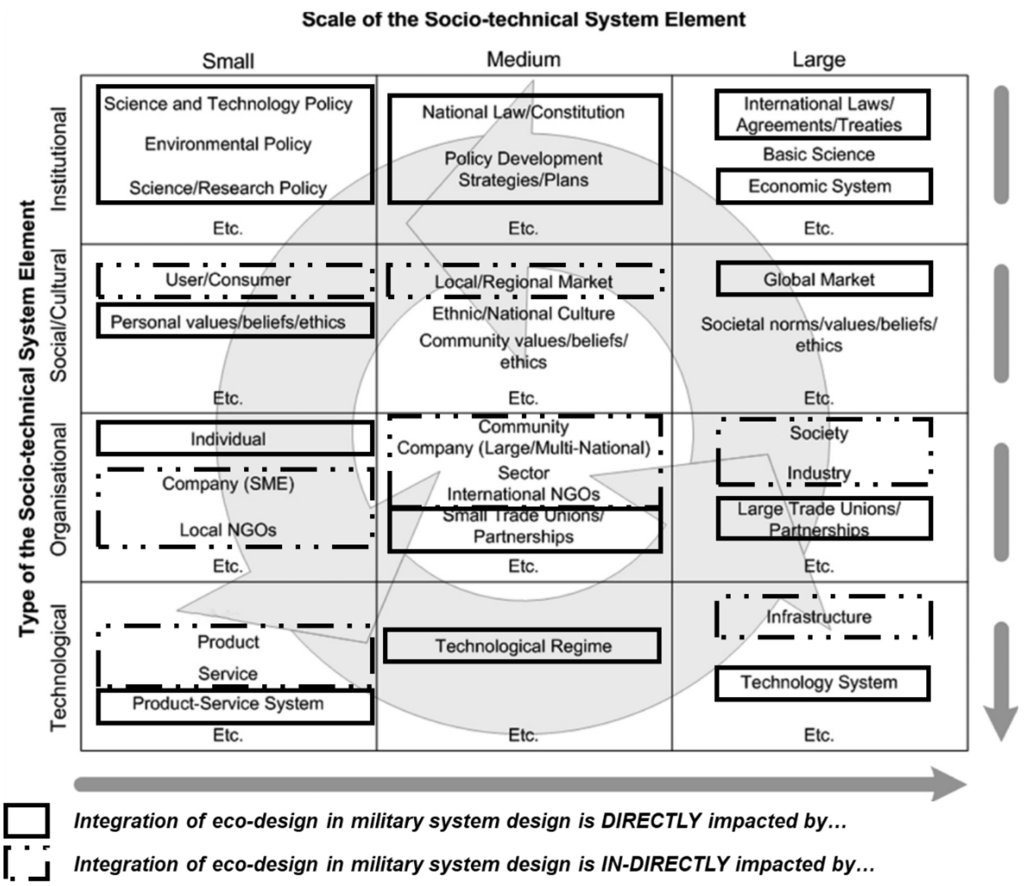

Figure 2. Co-evolutionary dynamics within defence socio-technical system. Adapted from Gaziulusoy and Brezet (2015)

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The interdependencies of elementary systems must be considered spatially and temporality (Gaziulusoy and Brezet, 2015).
Based on the diagnosis done on the French defence socio-technical system, we systematically identified the elementary elements involved. It is a key to have an enriched design process that include the appropriate stakeholders, responsibilities, etc. in a context of multi-partners projects. The generic design process of DGA's is described in the next section.

4.2 Generic systems engineering process

A systemic design model provides an effective basis to build a complex design process. We have modelled the DGA's generic design process (for any military systems and industrial project manager, cf Figure 3). We used a systemic investigation approach based on internal DGA documents describing the design process (especially IM1618) and semi-structured interviews. The resulting systemic design model presents stakeholders and their roles, interactions between DGA and Industrial project manager, and tools related to (eco-)design activities. The model has been validated by eco-design managers from DGA. They were identified to understand the eco-system of the defence industry and to build the design process. However, in the article, we will work with a simplified model (Figure 3) focusing only on the interactions. The others are not useful for the following study and will be studied in next papers.
The model of French (1985) is used as an inspiration to simply represent the defence design process. It is based on a classical decomposition into four stages: analysis of the problem; conceptual design; embodiment of schemes, and detailing. In defence design processes, statements of problem must incorporate capacity considerations. The capacity approach is composed of human and defence systems, organized, trained, and supported according to a doctrine, with a view to operational use. The DGA's generic design process (top of Figure 3) presents how an initial expression of the military forces' need is studied through a capacity approach (optional) and then into one or more armament operations (depending on the magnitude of the expected need).
Based on semi-structured interviews, the stakeholders essential for the integration of eco-design are those primordial during the upstream design phase (phases of orientations and technological/capacitated choices,), i.e. architects and project managers.
The interactions between DGA and Industrial project manager (middle of Figure 3) are indicated by numbers from #1 to #5: (1) Contribution to feasibility studies and acquisition strategy; (2) Contribution to selection of studies (done or to do); (3) Consultation/negotiation; (4) Industrial development, production cycle, industrial test, experimentation plan and proof of concept; (5) Support/maintenance in operational condition (specimens can be delivered for early use/return of experience).
The five projects (bottom of Figure 3) are the emblematic defence projects selected in section 3.3. The starting point of the grey bubble is the one of the environmental improvement of project and the dimension of bubble represents the current state of progress of the project.

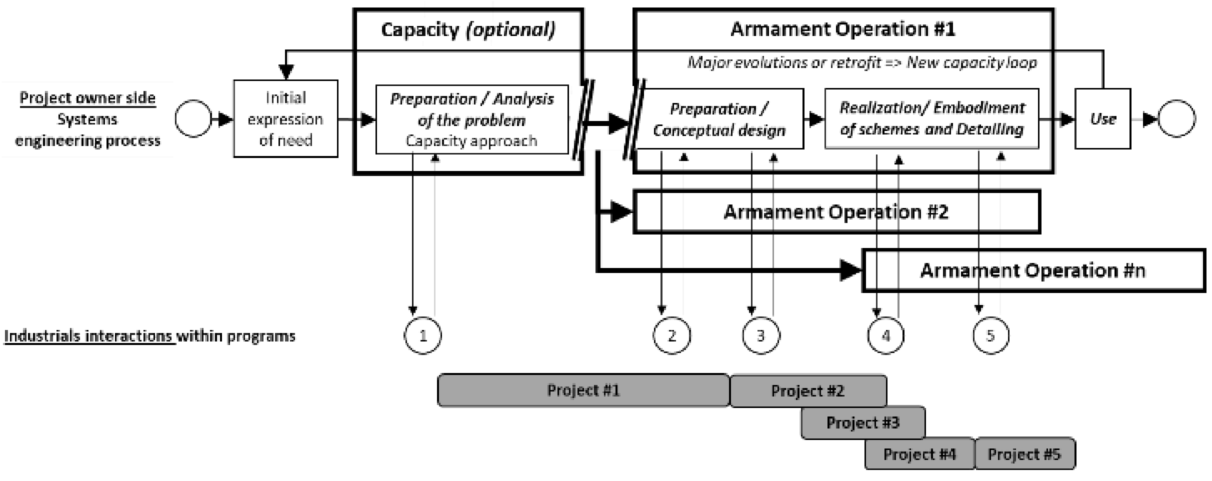

Figure 3. Generic model by phases of the systems engineering process centred on the project owner documented with industrial interactions. Position of five "environmental cases"

This study has considered the design process to structure the project into key phases, to which are associated design activities and interactions with industrials. They make it easier to support and identify the failure modes for eco-design integration in the projects, presented in the next section.

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4.3 Identification of failure modes for eco-design integration

The objective of this study is to identify the failure modes of the long-term integration of eco-design at the levels of project owner (DGA) and industrial project manager (Thales). They are presented for the applicative case of defence projects (assimilated to a socio-technical system in section 4.1) and are analysed with the well-known "non-performance analysis". The failure modes are the result of crossing the interviews and the previous socio-technical systems elements with seven themes inspired by the Ishikawa diagram (alphabetically ordered from #1 to #7). They are structured in Table 1. Each of the themes is associated to classes of failure mode(s) and are fragmented into elementary ones, that do not appear in Table 1 for lack of space. The failure modes are then associated to their causes of occurrence.

Table 1. Failure modes and main causes of non-integration of eco-design in defence projects

Themes	Classes of failure modes	Causes
#1 - External environment	Not all actors in the project life cycle are sufficiently qualified or intended to take the environment into account in their daily tasks	Lack of motivation of actors/companies Lack of resources: human, temporal, tools Possibility to ask for defence exemption and activatable regulatory approval
	Industrial project managers are not sufficiently precursory in eco-design	Lack of impulse and budget at high hierarchical level to get human resources
#2 - Financial mean	Environmental costs are not integrated	Environment is not in line with company's business model
#3 - Maintenance	Low communication and recurrence of updating of eco-design documents	Lack of motivation and resources for diffusion of news about eco-design
#4 - Management – project approach	Eco-design framework is not known or is poorly understood	Lack of diffusion of good practices, succeed projects and environmental integration failure
	No dialogue between the architects and designers and, the purchasing department	Daily work structured in silo
#5 - Material	Number of standard components alternatives for a given environmental and technical expectation is very low	Low purchasing volume High security/specification expectations
	Information on environmental impact of purchasing and technological choices is lacking	Difficult to obtain information from suppliers No data bank for questions of competitiveness or non-disclosure of sensitive data
	Difficult access to environmental archives limiting knowledge capitalization	Restricted access to data No system to capitalize the knowledge Very few methods and tools self-supporting
#6 - Method	Narrow scope of eco-design tools: Impossibility to simulate effects, usage, functional and technological scenarios	Lack of impulse and budget at high hierarchical level to get human resources
	Few cross-disciplinary meetings on environmental issues	Daily work structured in silo
	Circular economy not fully mobilized in the upstream design phases	Circular economy not in line with company's business model
#7 - Staff	Insufficient staff skilled in eco-design	Lack of impulse and budget at high hierarchical level to get human resources
	New employees known in their domain siloed or by the organization chart	No broadcast channel for these information
	Architects reuse parts of systems designed in the past = Design as usual	Slow diffusion of new knowledge High shifting jobs over time project Historical activities and technologies

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It is important to highlight that the failure modes can be common to non-environmental concerns, such as " New employees known in their domain siloed or by the organization chart " or " Architects reuse parts of systems designed in the past = Design as usual ". Those specific to environmental concerns include one or several key words listed alphabetically: circular economy, eco-design, environment(-al), exemption and life-cycle.

The data in Table 1 do not appear systematically in projects. They occurred at least once during the experience of the actors interviewed. Moreover, they are mostly common to the project owner and the industrial project manager in most cases and were summarized in one table. The differences between DGA and Thales concern the different environmental concern addressed within each of them and, their translation into themes and tools in the design framework. For example, on one hand the translation of eco-design by DGA is global to the life cycle and refers to the control of polluting discharges in use and at the end of life, to the control of risks, to dangerous energy frugality and to energy. On the other hand, Thales focuses mainly on the carbon footprint of its products by modifying the amount of mass and energy according to the nature of the use (kinetic or stationary).

The failure modes are used later to identify barriers and drivers of eco-design integration.

4.4 Barriers and drivers for eco-design integration

The SWOT matrix is used to identify the barriers and drivers to integrate eco-design into complex system projects. It helps to identify the strengths and the weaknesses surrounding design activities and to identify ways of improvement. According to Gürel (2017), "While external analysis focuses on the environmental threats and opportunities facing an organization, internal analysis helps an organization identify its organizational strengths and weaknesses." The "positive forces" column is filled based on internal documents and interviews. No distinction is made between the project owner and industrial project manager cases. Thus, a wide range of internal (i.e., strengths) and external (i.e., opportunities) origins are aggregated. The themes "#2 - Financial Resources" and "#3 - Maintenance" were not specified nor in document neither during interviews. The "negative forces" column is filled in with the information contained in Table 1 and are split according to their internal (i.e., weaknesses) or external (i.e., threats) origin.

Table 2. SWOT analysis of a long-term integration of eco-design in defence projects

	Positive forces	Negative forces
Internal origin	Strenghts	Weaknesses
	#4 - Management - project approach • Integration of system engineering and tracing of: technical documents, design process, engineering resources and responsibilities • Realization of project post-mortem on operational, design, industrial, etc. #5 - Materials • Internal discussion network on environmental issues • Traceability of technical documents, design process, engineering resources and responsibilities • Democratization of eco-design good practices: limit multi-material components, improve material grades and recyclable design, impulse frugality of functions to meet a need etc. • Capitalization of information on products: substances, processes of manufacturing, bill of materials, etc. #6 - Methods • Qualitative answer to environmental questions: energy and material oriented, • Quantitative and qualitative response through tools centred on technologies products and management of eco-design by suppliers and through environmental specifications • Creation of an internal page referencing tools and guides on eco-design • Trying to tool upstream design phases for people with no environmental knowledge and requiring low volume of hours to appropriate it #7 - Staff • Integration of environment issues in projects through voluntary requests of capacity (no reglementary) during upstream design phases • Conducting environmental training for architects, project manager, etc.	Refer to the failure modes of topics from #2 to #7 in Table 1

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External origin	Opportunities	Threats
	#1 – External environment • Integration of environmental dimensions, e.g. climate change; • Valorization of good relations project owner - industrial project manager; • Keeping annual industrial exchanges on environmental issues; • Keeping historically strong relations and creation of partnerships with SMEs.	Refer to the failure modes of topic #1 in Table 1

The diagnosis of positive and negative forces was useful to know how integrate eco-design over the long-term in defence projects. They respectively help to identify good practices and areas of improvement. The panel of improvement is wide: the processes (#4), the tools (#5), the methods (#6), the stakeholders (#7) etc. according to the external environment (#1).

4.5 Discussion and recommendations

To make some recommendations on the engineering process, it is important to integrate eco-design from the upstream design phases, so-called "Conceptual design" on Figure 3, which is also acknowledged by the literature. Also, the value analysis is strongly used in the observed processes, and it could therefore be an entry point to better integrate the environment by including environmental criteria. Also, the conclusion of the interviews, the discussions and the observations are that approaching the environment through risks aspects (environment risk analysis) could be a good idea because the notion of risk is usual in the defence sector. It would mean preventing environmental impacts by looking at them as potential risks, without waiting for the life cycle analysis which comes in at the very end.

The second recommendation is to focus on the people side of change of Hiatt and Creasey (2003), which plays a primordial role on the unwritten knowledge of structures. Beyond tools and methods, it is important to raise awareness and train people, if not eco-design will not be integrated in the long-term.

This interest of this study is to be an overview of the barriers and drivers to efficiently eco-design complex systems, in the applicative case of the defence industry. Even if the paper is specific to the applicative case of the defence domain, it can be useful for other industries that are designing complex industrial systems in a project owner / industrial project manager relationship. For instance, it is the case in the automotive industry, aerospace, energy, pharmaceutic, building, etc.

The strength of this study is the adoption of an "action-based methodology" through the systematic identification of elementary systems and the validity of pieces of information. This information is collected through semi-structured interviews and internal documents of two different companies: one is a project owner (DGA) and the other one is an industrial project manager (Thales company).

Improvement can be done on the scope of the emblematic eco-design projects. Criticisms can be made on the projects selected because they do not fit the ISO/TR 14062:2002. They integrate no more than three environmental themes (often one), and they are not integrated from the beginning of the project. They represent some of the best-in-class projects integrating environment in this ecosystem.

5 CONCLUSION

The study shows that the improvement that must be done to reduce environmental impacts of systems is huge. Papers have been found on the barriers and drivers of eco-design integration in diverse domains, but few have been found in the defence domain. There is a real challenge to integrate eco-design in this domain. We have deployed a method to identify these barriers and drivers in the context of complex system development involving multiple stakeholders (project owner and several industrial project managers). It has been highlighted that the design ecosystem of military systems can be represented as a socio-technical system. In this study, it is intended to integrate eco-design within each elementary elements involved in this socio-technical system, which is a key to promote a successful and long-term integration of eco-design. The design process studied is structured into key phases, to which are associated design activities and interactions with industrialists (applied to emblematic eco-design projects). They make it easier to support and identify the failure modes for eco-design integration in the projects according to: External environment; Financial mean; Maintenance; Management– project approach; Material; Method; Staff. These themes are used to assess the positive and negative forces to act over the long-term to integrate eco-design in defence projects. Strengths must be capitalized, and opportunities must be taken. Ignoring the environment during the upstream design phases introduces weaknesses and leads to threats during the life cycle. The coming work is to complete the diagnosis of

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the French defence socio-technical system with a focus on the emblematic projects. It will be centred on design activities through a systematic study of tools, actors, processes, results, etc.

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