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VALUE ASSESSMENT OF SUSTAINABILITY HOTSPOTS IN CONCEPTUAL DESIGN: AN AEROSPACE STUDY

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ABSTRACT

Nowadays, when designing structural aero-engine components, the engineering team does not only deal with aerodynamics and structural mechanics criteria. Rather, it needs to make more informed decisions based on the value and sustainability contribution of a design concept. This paper proposes a novel approach that combines qualitative sustainability assessment techniques, which are Environmental Impact Assessment (EIA) and Strategic Sustainability Assessment (SSA), with Net Present Value (NPV) analysis to facilitate early stage decision-making in design. A case study, related to the development of a new high-temperature aero-engine component, illustrates how EIA and SSA identify sustainability hotspots for a new product technology, and how NPV is used to assess alternative solution strategies within the hotspot. Within the studied case, the milling process was identified as a sustainability hotspot, therefore two process options - Electro-Chemical Milling (ECM) and Mechanical Milling (MM) - where benchmarked by calculating their NPV in alternative future scenarios, featuring different market and regulatory assumptions. The approach and its constituting models have been preliminarily verified with designers and process owners in co-located industrial workshops.

KEYWORDS

Strategic Sustainability Assessment, value assessment, conceptual design, engineering design, aerospace.

1. INTRODUCTION

The Strategic Research Agenda [1], published by the Advisory Council for Aeronautics Research in Europe (ACARE), clearly identifies sustainability as one of the most significant drivers that will influence current and future solutions within the aeronautic industry. The "Ultra green air transport system" is becoming a major high-level target for research in aviation [2], pointing towards reducing the environmental impact of aircrafts and associated systems during their lifecycle: from manufacturing to operation, maintenance and disposal phase.

This drives significant changes in the way aero-engine components are designed. In an early stage the engineering team does not longer deal with aerodynamics and structural mechanics problems only. Rather, sustainability considerations come into play, and the team must make more informed decisions about which product technology is the most sustainable, and at the same time the most valuable, for the company and its customers.

However, sustainability assessments are today conducted after significant design decisions are already taken [31]. This makes sustainability requirements to be perceived only as extra costs (e.g. generating additional design constraints that must be met or increasing testing and assessment costs) and not as an opportunity for innovation. This situation asks for a more proactive strategic that better positions the result from the sustainability assessment process within the engineering decision-making environment, which today is dominated by value and performance-based considerations.

1.1. Objective

When aiming to integrate sustainability aspects in product design, Thompson and others [31] discern between three main levels of intervention: the *operative*, *tactical*, and *strategic* dimensions. In this paper, the focus lies on the operative dimension. The objective of the paper is to propose a novel approach that combines qualitative sustainability assessment techniques, which are Environmental Impact Assessment (EIA) and Strategic Sustainability Assessment (SSA), with Net Present Value (NPV), to inform early stage decision makers about the sustainability-related consequences of their design options.

An aerospace case study, related to the development of a new high-temperature aero-engine component, illustrates how EIA and SSA are used to identify sustainability hotspots for a new product technology. NPV is later used to assess alternative solution strategies within the hotspot. The case has been used as main reference to discuss and verify the proposed methods/tools with designers and process owners in co-located industrial workshops.

2. STATE OF THE ART

The conceptual design phase of new products and services gives the best opportunity to influence sustainability performances along the product lifecycle. Nevertheless, in this phase, information about sustainability consequences is found to be weak from a decision support perspective.

For instance, at an aero-engine manufacturer level, the ACARE goals are early on turned into concrete targets on product functionality, such as lighter weight, noise reduction, emission reduction and high reliability [25]. These functional requirements are further decomposed to derive the requirements of the engine sub-systems, which dictate the development of components and technologies down the supply chain.

A major problem of such a target cascading process is that the design team tend to emphasise the achievement of technical performance targets, without considering deeply enough sustainability consequences when taking crucial preliminary design decisions [17]. Rather, engaging and investing in technologies characterized by such long lifecycles requires careful judgment at many levels inside the company: new products and services must comply with global future sustainability constraints to avoid running into negative surprises in the future.

2.1. Sustainability and decision-making

Sustainability indicators and composite index are increasingly recognized as a useful tool for technological improvement [28]. By visualizing phenomena and highlighting trends, sustainability indicators simplify, quantify, analyze and communicate otherwise complex and complicated information [8][23].

Within the realm of product development, the implementation of sustainability information has received increased attention in the last decade [3]. At the time preliminary design decisions are taken, engineers must not only consider the plausible negative effects of increasing prices on material and energy, but also the reduction of available resources and the introduction of harsher legislative restrictions on process and materials (such as REACH [13]).

Lozano [22] has recently analysed the sixteen most widely used initiatives related to the use of sustainability dimensions in conceptual design (e.g. life-cycle assessment, eco-design, cleaner production, corporate social responsibility, sustainability reporting, etc.). The author concludes that relying only, or even mainly, on one initiative can result in a limited and narrow contribution to sustainability, with limited coverage of the company's system.

Hence, the literature proposes heterogeneous approaches to cope with the assessment of sustainability consequences in conceptual design. Bohm and others [5] propose methods that exploit computational concept generation and lifecycle assessment techniques to develop an automated mechanism for early phase environmental analysis. Rio and others [26] present an approach to get sustainability closer to the engineering environment, while Thompson and others [31] further propose an approach to integrate sustainability assessment into the conceptual design process. The latter adopts the set-based concurrent engineering notion, which systematically builds knowledge about multiple design concepts, and then successively eliminates concepts, so that the final choice is robust and reduces the risk of late changes [30]. This approach addresses two problems:

- robustness of a “sustainable design space” in the same manner as the early steps in a set-based concurrent engineering approach, and
- alignment of sustainability considerations throughout a generic design cycle.

Hallstedt and Isaksson [15][16] further point towards sustainability criteria as a key factors to identify constraints in the product requirement list. Similar ideas to define criteria and measurements for sustainable manufacturing are discussed by Haapala and others [14].

What the literature review shows is that, in order to use sustainability as a driver for these decisions, companies need to develop the ability of quantifying the “value” of being sustainable. This information has to be used alongside the requirements description to facilitate the selection of relevant product and technology concepts in an early stage.

2.2. Value assessment in design

As stated by Browning [6], “process improvements in product development cannot just focus on waste, time, or cost reduction, but the purpose should be to maximize the product value”.

Accordingly, decisions made during design should always add value to the solution space. Hence, linking value-based considerations to sustainability criteria is of crucial importance to highlight the role of the latter as decision-making driver in design.

In the domain of Systems Engineering, Value Driven Design (VDD) [11] has become a popular methodology to identify the most value-adding concept during preliminary design. VDD utilizes a single objective function, called value model, to determine the value of alternative solution options. A “value model” accepts a vector of attributes as its argument to assign a score (scalar) to rank a design.

Since “profitability” is by far the most intuitive dimension to assess the value of a system [11], the “best” design is the one that ultimately produces the best overall economic value. Hence VDD optimization is often addressed by utilizing an objective function that produces a Surplus Value (or Net Present Value) score, a surrogate object for profit that represents an unbiased metric of the ‘goodness’ of the final product [10][12].

Collopy and Hollingsworth [11] explains VDD using a cyclical view of the design process, as shown in Figure 1.

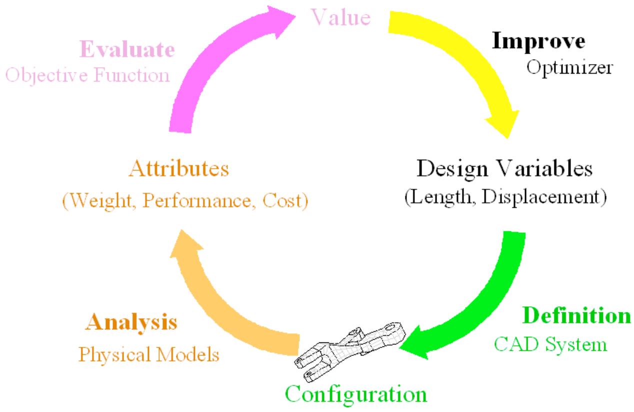

Figure 1: The Value Driven Design cycle [11]

As first step, the designers pick a point in the design space at which to attempt a solution. At the *Design Variables* step, they create an outline of the design, which is elaborated into a detailed representation in the *Definition* arc. In the *Analysis* arc, engineers produce a second description of the design instance, in form of a vector of attributes. While the design variables are defined to make sense to the design engineers, the attributes are defined to connect to the customer.

In the *Evaluate* arc the attributes are assessed with an objective function or value model, which gives a scalar score to any set of attributes. If the current configuration has a better score than any previous attempt, it is the preferred configuration to date. At this point, the design team can accept the configuration as their product, or try to produce an even better design by going around the cycle again.

VDD has been successfully applied in several design situations [9][10][12] to orient early choices towards value maximization. However, it has strongly focused on how customers make revenue or incur in costs while operating the product, without considering well enough those aspects – such as sustainability – which contributes to the overall value of a solution, but that are less intuitive to translate in monetary terms.

Apart from recent attempts to introduce more qualitative aspects in the VDD process [4][20][24][29], the literature review highlights a lack of approaches that combine sustainability assessment with value analysis. However, the integration of qualitative and quantitative aspects in the conceptual design phase is believed by the authors to provide better guidance when dealing with early design decisions.

3. CASE STUDY

The case study, which was defined in collaboration with a major aero-engine sub-system manufacturer, describes a design situation where the design team is requested to take early-stage decisions on the architecture of a new high-temperature jet engine component. Engineers and designers are faced with the problem of deliberating on the product technology representing the best short- and long-term investment for the company. To support this decision, the authors have developed an approach that combines simplified Environmental Impact Assessment (EIA), Strategic Sustainability Assessment (SSA) and Net Present Value (NPV), as shown in Figure 2 and described in the sections below.

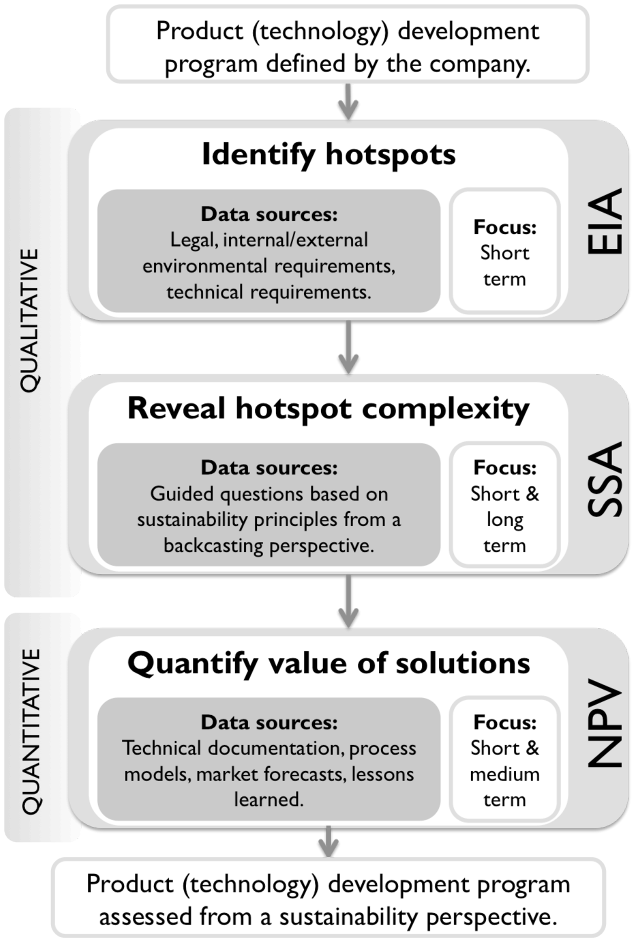

Figure 2: Approach for sustainability and value assessment

3.1. Identifying sustainability hotspots using EIA

The Environmental Impact Assessment (EIA) [18] is a simplified, qualitative, life-cycle assessment and eco-design tool, which, early in the development process, identifies significant environmental impacts generated by the product's life cycle, from the resource extraction phase to the end of life. Its purpose is to facilitate the identification of sustainability hotspots and to suggest corrective or recommended measures to improve the environmental performance of the product [19][21].

Within the studied case, EIA was applied to uncover environmental concerns of serious impact potentials along the entire life cycle of alternative component concepts (i.e. from raw material extraction to the disposal phase).

The EIA was lead by an environmental engineer. Its first step concerned the definition of the studied system, of the working group, and of the available data sources (such as legal, internal/external environmental requirements, technical requirements). In the next step the team carried out the assessment of environmental impacts using a form based on rating with a scale from 1 to 3 (where "3" has the highest significance) for the four following criteria:

- *Severity*: from negligible negative damage (1) to long-term or permanent severe negative damage (3).
- *Steering documents*: from no requirements in steering documents or quantity/occurrence of the activity that are negligible (1), to requirements that are regulated in steering documents and quantity/occurrence that are above a valid limit (3) - like a maximum level of emissions of carbon dioxide .
- *Interested parties*: from no negative effect on the company's environmental reputation (1) to severe damage to the company's reputation regarding the general public (3).
- *Improvement potential*: from good and quick improvement (1) to little/no possibilities for improvement (3).

The ratings of the criteria (done independently) were discussed in the working group and set by the environmental engineer. After the rating process, recommendations to identify corrective or recommended actions were suggested by the working group.

The EIA resulted in a few hotspots; the manufacturing process was further spotlighted as the most critical one. The company had initially identified Electro-Chemical Milling (ECM) as the most suitable manufacturing technology for the component. However, the EIA showed clearly that the company might not benefit from a long-term investment in ECM, even if today it is a very cost effective technology. The ECM process generates hexavalent chromium, nickel, and lead particles when applied for Nickel-based alloys. The already severe requirements on the process generate extra costs for the company, and an upcoming ban would strongly diminish the profitability of the investment in such a new technology.

From an engineering design point of view, the method did not provide enough support for active design decisions, rather further investigation was needed to clarify why the ECM process generated hexavalent chromium when applied for nickel-based alloys, and how this could be avoided.

3.2. Clarifying sustainability consequences using SSA

The findings from an EIA investigation were not able to clearly state the consequences associated to alternative design actions. As shown by Hallstedt and others [16], it is very difficult to take strategic decisions and choices without following up these findings. For this reason, a Strategic Sustainability Assessment (SSA) was introduced as a means to clarify and better understand sustainability consequences.

Strategic sustainability [27] is defined as backcasting from sustainability principles. These sustainability principles state that in a sustainable society, nature is not subject to systematically increasing of:

- concentrations of substances from the Earth´s crust;
- concentrations of substances produced by society, and
- degradations by physical means,.

Strategic sustainability highlights another important point, which is:

- in that society, people must not be subject to conditions that systematically undermine their capacity to meet their needs.

The SSA is based on guiding questions inspired from a previously developed Method for Sustainable Product Development (MSPD) [7]. The main idea of using guiding questions is to raise the awareness and knowledge about sustainable manufacturing problems, to highlight opportunities among project leaders and product developers, and to open up for a creative dialogue and innovation within basic sustainability constraints.

In the studied case, the SSA assessment was conducted in several steps. Firstly, the material flow, potential emissions, waste treatment and rest-product treatment were investigated as a means to clarify why the ECM process generated hexavalent chromium, nickel, and lead particles when applied for nickel-based alloys. The investigation was conducted mainly through a literature review and through meetings with potential suppliers of the ECM process. The investigation focused on the opportunity to avoid the emission of toxic substances and pollutants, as well as on the possibility to keep such emissions isolated and in closed technical loops.

In order to clarify short- and long-term sustainability consequences, a list of guided questions was used. Most answers for the short-term perspective did relate to present environmental, social and economical requirements, such as documented requirements stated by the company, customers, and in legislation. The answers from a long-term perspective included reflections and logical reasoning on the consequences of the ECM implementation.

From the economical short-term time perspective the analysis showed that choosing ECM was, in general, beneficial, because some investments had already been made and some work had already been performed in terms of investigation of suitable suppliers for ECM.

From the socio-and ecological perspective, the guided questions highlighted some aspects to consider more in depth, such as the importance of company image, and the risk of leakage and consequences if that would happen.

More in detail, the SSA resulted in the following list of reasons for not investing in ECM:

1. the use of carcinogenic and allergenic substances could be justified from a social perspective if there are alternatives to use;
2. according to the precautionary principle alternatives should be chosen when there are environmental- and health risks;
3. material lists showed a warning for a ban of processes that involve Cr VI;

4. the company might not take economic advantage of an investment in ECM, due to the introduction of new severe requirements and an upcoming ban;
5. only a few sub-contractors might be able provide support to the process in the long run;
6. the costly investment in new tools was not justifiable for a process that is not very developable.

Hence, the final recommendation from the SSA was to preferably use Mechanical Milling as an alternative manufacturing process. The investment in ECM could turn into an economical disadvantage in a long-time perspective if, for instance, the company had to change to another manufacturing process due to tougher legislation in the future. Although the MM processes is a more expensive to run and does not ensure the same quality as ECM, it involves only one hazardous substance (nickel) and produces less toxic material compared to electro-chemical manufacturing processes.

3.3. Quantifying consequences in hotspots using NPV

The EIA and SSA investigations clarified sustainability impact consequences of the proposed manufacturing process and suggested alternative solutions (i.e., Mechanical Milling) to address the sustainability problem. However, from an engineering design point of view, it did not provide the necessary clarification of consequences of the identified hotspots to provide the design team a solid base for decision.

Hence, the 2-step approach described above was complemented by a more quantitative assessment model, with the purpose of making more explicit the value of adopting the alternative design options, under changing future scenarios.

A calculation sheet in MS Excel® was developed to estimate the Net Present Value (NPV) related to the implementation of the ECM vs. the MM manufacturing process, with the aim to enhance a comparison of the two alternative solution options within the hotspot.

The model takes as input the result of the SSA investigation, a set of company´s historical data (e.g., process models, technical documentations and market forecasts) and is built on assumptions related to:

- the impact of new environmental requirements;
- the expected increase in waste management cost;
- the availability of suppliers for raw materials and consumables;
- the level of environmental consciousness among the customers, and
- the expected discount rate in the next 10-year period.

By acting on 5 controlling variables (Table 1), designers can simulate different future scenarios and increase their awareness on the consequences of their design decisions if such scenarios become true.

Table 1: NPV controlling variables

Expected increase in:	**Link with SSA**
Environmental requirements toughness	Deep risk of new severe requirements to be introduced to regulate the ECM process.
Waste management costs	Carcinogenic and allergenic substances are produced, which requires special waste management procedures.
Environmental consciousness	The production of toxic materials in the process makes the final product to lose appeal in front of customers.
Number of suppliers after 10 years	Due to upcoming constraints, it becomes unprofitable for sub-contractors to provide support to the process.

Environmental requirements toughness relates to the introduction of guidelines, instructions, laws or regulations that constraint the usage of substances consumed or produced by the ECM and MM processes. The model foresees that the manufacturing process costs increase when environmental requirements become more stringent. Tougher requirements require more complex instruments and machineries, which are in general more expensive to purchase and to use. Also, setups might require more time (as the procedure is more complex), upgrades might need to be implemented more frequently (hence reducing the availability of the production line), and more specialized manpower is needed to manage a more complex/controlled process triggered by more stringent requirements. The latter is expected to generate higher costs for the company, because the necessary competencies to deal with a more complex might be difficult to find, and individuals do likely require more training. Last but not least, new requirements might be introduced to regulate the activities in the working environment, and to ensure safety of the individuals involved in the manufacturing process.

The introduction of more stringent manufacturing requirements is expected to increase *Waste management* costs too. Toxic and hazardous materials might require more complex and expensive procedures to be properly handled, and this has a direct impact on the profitability of the manufacturing line.

An important variable to consider is *Environmental consciousness*, which reflect the overall customers' attitude towards buying products that do not meet sustainability requisites. In an extreme scenario, the aircraft and aero-engine manufacturer may completely avoid to purchase components responsible for producing pollutants and toxic waste, to satisfy extremely environmental conscious passengers. In the model, designers can simulate the environmental consciousness evolution throughout the product lifecycle. The basic assumption is that increasing environmental consciousness decreases the appeal of the ECM-manufactured products; hence it forces the components manufacturer to reduce their price year after year.

A coefficient from 1 to 10 is set by the designers to indicate a weak, medium or strong increase of these 3 variables, with 1 meaning that the variable is not subject to any change (e.g., no new environmental requirements will be introduced in the next decade) and 10 meaning extreme changes (e.g., every year new and more stringent requirements will be introduced).

Another variable designers can play with to simulate future scenarios - and to base their decision about the use of ECM vs. MM processes – is the *Number of suppliers after 10 years*. Suppliers are intended as companies or entities that provide all the hardware, software and services needed by the ECM and MM processes to be correctly executed. As far as the number of supplier increases, competition is likely to push down the price of, for instance, consumables and support services. On the opposite, if their number decreases, costs will rise and the profitability of the manufacturing process will be reduced.

The rate used to discount future cash flows to their present value is another key variable of this process. The model accounts for variations in the *discount rate* and allows designers to calculate the NPV under different conditions.

The model also includes an "IF" condition related to the *ban of the ECM process*. A ban on the process will have severe negative consequences for the manufacturer, with regards to costs related the dismissal of the ECM manufacturing line, its conversion in MM, the disposal of its waste, the reduced manufacturing line availability during the conversion, and the training costs generated by the change in production process.

In general, it is beneficial for the manufacturer if the ban is introduced as late as possible. To make an extreme example, if the ban is introduced just after the ECM manufacturing line has been implemented, the company will not be able to gain back any of the investment costs. Hence, the model considers the year in which the ban is introduced as an important variable to calculate the NPV. It is assumed that, if the ban is introduced at year n, at n+1 the company will move back to MM (i.e., to its profitability curve). However, the MM process will likely be less efficient when introduced at year n+1 compared to a situation in which it is introduced at year 1. A penalty is introduced in the model to render such a loss of performance, which is due by the lack of lessons learned generated between year 1 and n+1.

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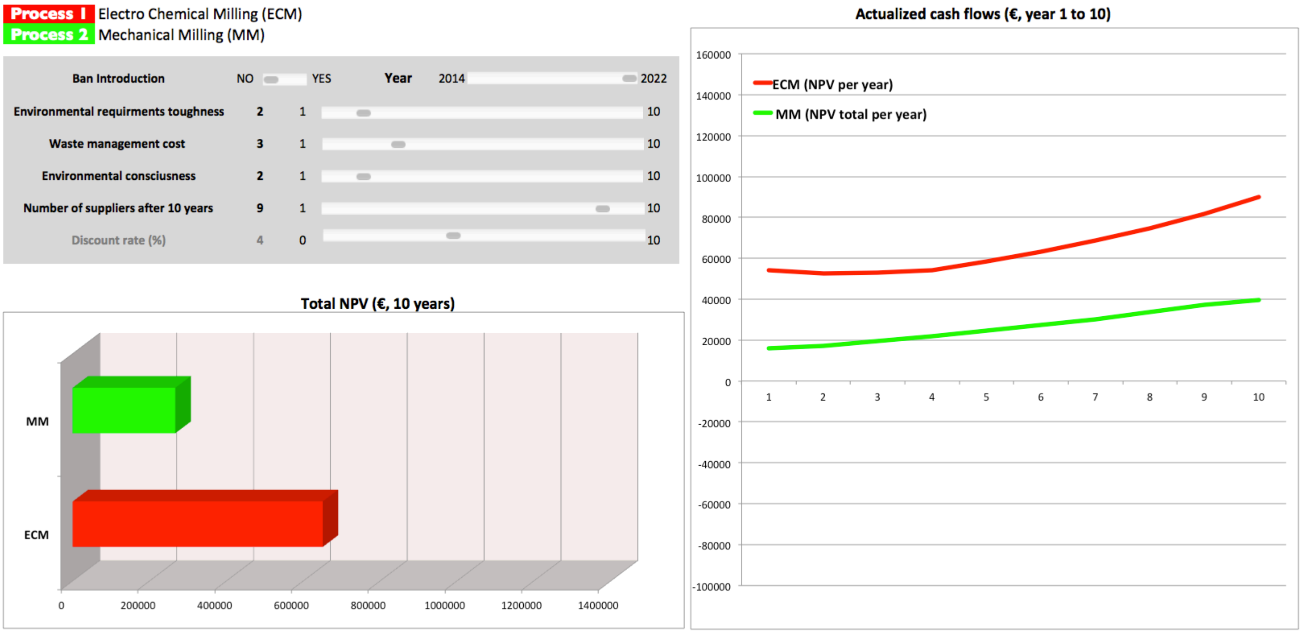

Figure 3: ECM vs. MM Net Present Value calculation for the static scenario 4.1

4. CALCULATING THE NPV OF SUSTAINABILITY DECISIONS

The purpose of this section is to exercise the NPV model by presenting the results associated to three alternative scenarios, where the 5 main scenario variables (*Environmental requirements toughness, Waste management costs, Environmental consciousness, Number of suppliers after 10 years, Ban of the ECM process*) are tuned to observe changes in the Net Present Value generated by the ECM and MM process.

The calculation sheet considers a time span of 10 years (2013-2022), after which the machines used in the process are considered to have achieved the end of their life. The NPV is calculated in Euros and, for simplicity purposes the discount rate is kept equal to 4% for all 3 scenario presented. Please note that the data used as input in the calculation sheet (as well as its results) have been scaled and used for illustrative purposes only.

4.1. Static scenario

The first example considers a static scenario, where very small changes in the existing regulations are foreseen within the next decade, and where the ECM process is not going to be banned. More in detail, this scenario considers new environmental requirements to be updated and introduced at a very slow pace in the next 10 year. Also it considers waste management costs to remain stable and similar to the ones experienced today. Customers are considered not to be particularly environmental conscious, and final users are not influential enough to orient the engine and aircraft manufactures purchasing choice. Eventually, it foresees an increase in the number of companies operating in the market at the end of the 10 years period, and able to provide support to the ECM process.

Under these assumptions, the future looks favourable for the implementation of the ECM process (Figure 3). The calculation sheet, under these assumptions, reveals that ECM is much more profitable than MM throughout the entire decade, providing higher actualized cash flows from year 1 to year 10. On the one hand, the investments and costs needed to run and maintain the ECM production line are similar to the ones featured by MM. On the other hand, in this scenario customers value more performances than sustainability, and this is reflected by the purchasing price (which is higher for components realized with ECM).

From the economical short- and long-term time perspective, the model reveals that it is much more beneficial to choose the ECM compared to MM. If the societal consequences (company image, risk for accidents, etc.) are minor, the design team is likely to orient its choice towards such first option.

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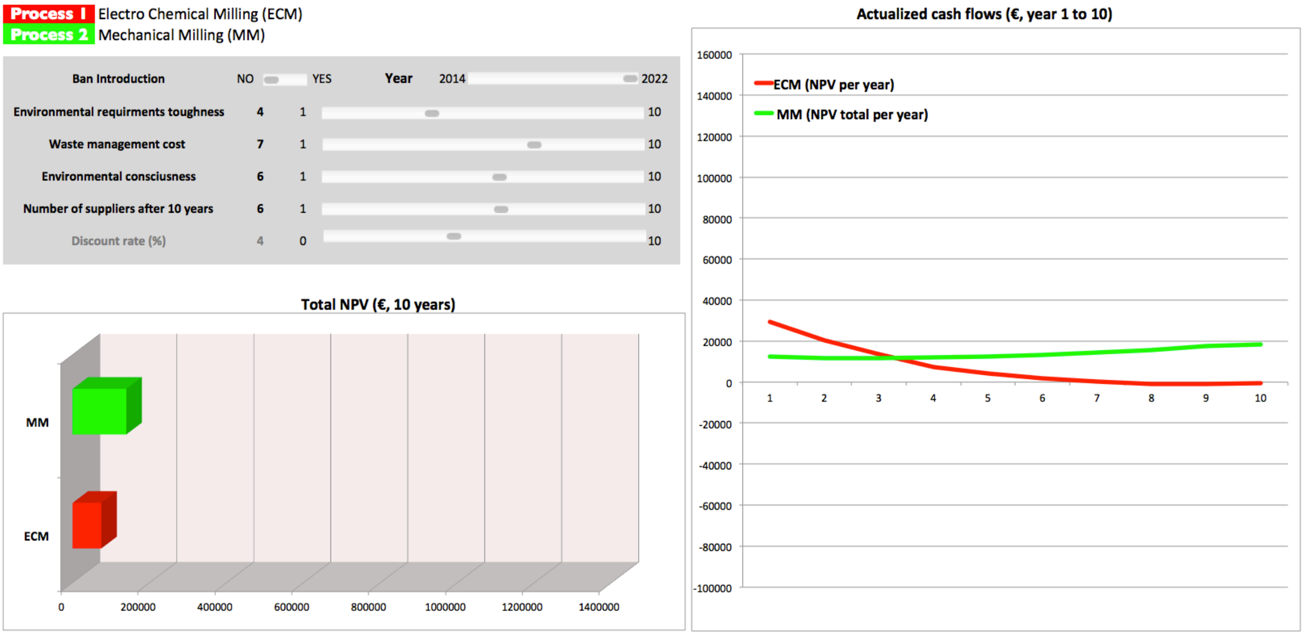

Figure 4: ECM vs. MM Net Present Value calculation for the fast changing scenario 4.2

4.2. Fast changing scenario

This scenario, as the one presented above, considers the ECM process not to be banned at least within the next decade. However, it foresees significant changes in the way environmental requirements are set and introduced in industry, together with a steady increase in waste management costs and in the number of environmental conscious customers.

During year 1 and 2, MM is still a losing option (Figure 3) even if higher waste management costs reduces the overall profitability of ECM. At year 3, the gains obtained in terms of manufacturing time and costs are levelled out by the increased costs related to the management of waste and hazardous material, as well as by a lower appeal of the product among the customers. They now prefer more sustainable options, forcing the company to sell components produced with ECM discounted.

From year 4 onwards, the combined effect of waste management costs, new environmental requirements and better consciousness about the environment, together with the reduced competition among the suppliers, strongly impact ECM profitability. In Figure 4, the actualized NPV for ECM progressively levels down to 0, while MM increased thanks to more optimized procedures that increase efficiency and lowers the production costs. As a result, with severe societal consequences expected, the company is likely to orient its choice to MM.

4.3. ECM process banned

This scenario considers the introduction of a ban for the ECM process starting from year 7 (2019). Furthermore, it considers a medium increase in the introduction of new environmental requirements, a strong increase in waste management costs, a low increase of environmental conscious customers and only 4 suppliers available at the end of the decade.

In such a scenario, as show in Figure 5, the ECM process is profitable until year 4. From year 5 onwards, the investments needed to comply with the severe environmental requirements, together with the lower appeal of the product among customers, and the high cost for waste management, make the MM process to be the most profitable choice. The investments needed at year 7 to convert the manufacturing line from electro-chemical to mechanical strongly impact cash flows and the expected NPV. As explained in section 5, from year 8 onwards the actualized cash flows curve for ECM follows the MM one.

In such a scenario, ECM is of economical disadvantage in the long-time perspective; hence MM is preferred from the start.

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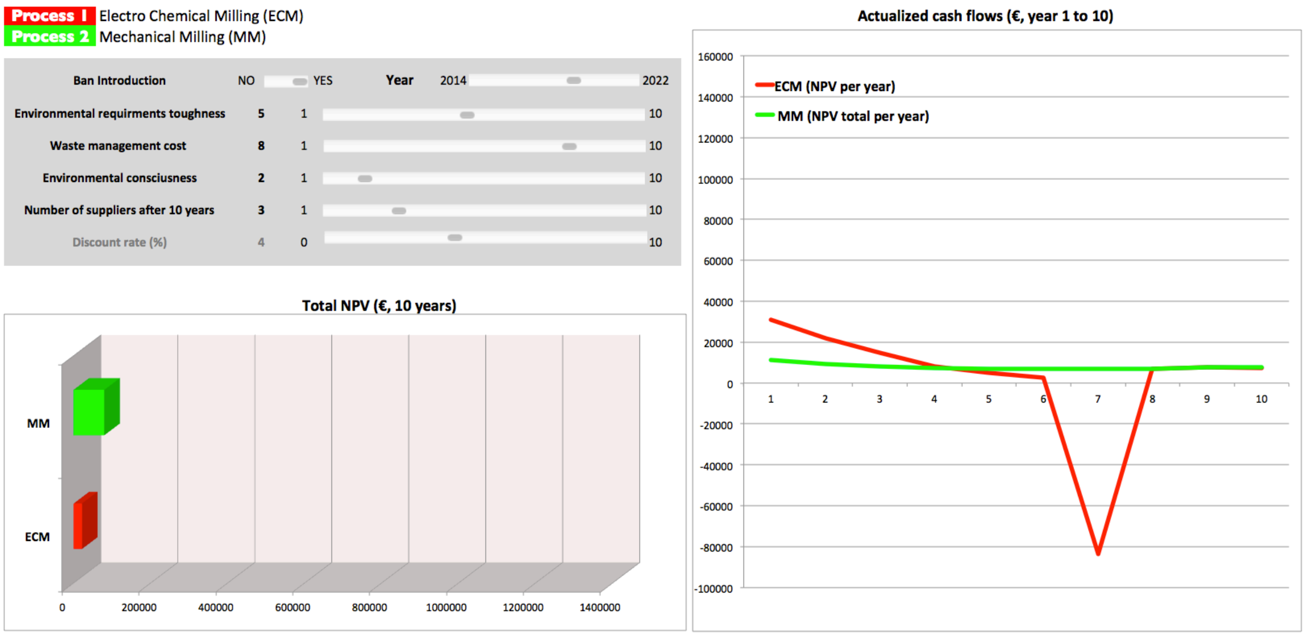

Figure 5: ECM vs. MM Net Present Value calculation for scenario 4.3 (Ban of the ECM process)

5. RESULTS AND RECCOMENDATIONS

The approach aims to explicit key variables and phenomena that determine the balance between value and costs that sustainability-related choices entails. In the first scenario, decision makers can deliberate with good confidence about the use of ECM. Although this choice does not look optimal from a sustainability point of view, it ensures higher monetary returns given the As-Is regulatory constraints and market conditions. In the second and third scenario, MM is slightly preferred, even if in the short-term it is far from being a winning option.

Strategic foresighting workshops might provide further details about the likeliness of each scenario, and all these data can be eventually aggregated to the requirements description to support concept selection activities at the decision gates. Given a 80%-15%-5% likelihood for scenario 1,2 and 3, the recommendation is eventually to proceed with ECM. On the opposite, a 20%-60%-20% likelihood plays in favour of the adoption of MM.

6. DISCUSSION

It has to be noticed that the purpose of this assessment activity is not to have an exact measurement; rather is to make sustainability consequences more concrete and understandable during design concept selection activities. The NPV result is a sort of "common denominator" for the different members in the team, and in this way it triggers the debate about the different perceptions of sustainability, especially when opinions differ. Although the adoption of a simulation approach is claimed to be counterproductive, as it hides away the complicated nature of the sustainability problem [17], undergoing the proposed steps is believed to guide the actors in making explicit assumptions, restraints and statements, rather than allowing them to remain implicitly inherent in high-level statements. In this way the quality and completeness of data and assumptions can be systematically improved, i.e. moving from opinions and intuitions to evidence-based statements.

7. CONCLUSIONS AND FUTURE WORK

The overall expected results of this research include increased knowledge and efficiency through introducing support tools and working procedures for sustainability integration in the early phases in the product-service innovation process.

The industrial relevance of this work is twofold: (a) increased capabilities to mitigate risks and take informed decisions early on, (b) increased opportunities to bring new, sustainability-driven innovations to the market. These include the definition of best practices, criteria and tools for how to efficiently introduce conceptual design support for sustainable innovations in a development organization.

In this spirit, the paper proposes a novel method that clarifies consequences of sustainability hotspots in conceptual design. The approach complements the qualitative analysis tools previously proposed, which is Environmental Impact Assessment (EIA) and Strategic Sustainability Assessment (SSA), with a quantitative value assessment model based on a Net Present Value (NPV) calculation. The conjoint use of these three methods is intended to help the design team in clarifying sustainability consequences when dealing with the assessment of a product or technology in a preliminary design phase.

The approach and its constituting models have been verified with designers and process owners in co-located industrial workshops. Further work will be dedicated to its refinement and integration in the existing decision making environment at the company. Two are the aspects that need clarification from a company perspective. Firstly, more in-depth studies are requested to understand how to position the method in the frame of the existing Risk assessment methodologies, and how the results of the sustainability-value study have to be balanced with other risks. This next step in the descriptive study research will be conducted in form of workshops where the authors will observe and collect feedback about the way developers and expert use the proposed model when dealing with design decisions.

Furthermore, the model itself has to be refined with more realistic data, and sensitivity analysis has to be performed to test the model robustness in the presence of uncertainty. Eventually, the authors plan to complement the model with a feedback related to the probability of each alternative scenario to happen, calculated on the basis of information gathered from internal databases and external sources.

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