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A model-based approach for sustainability and value assessment in the aerospace value chain

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Abstract

In the aerospace industry, systems engineering practices have been exercised for years, as a way to turn high-level design objectives into concrete targets on system functionality (e.g. range, noise, and reliability). More difficult is to decompose and clarify sustainability implications in the same way and to compare them against performance-related capabilities already during preliminary design. This article addresses the problem of bringing the important—yet typically high level and complex—sustainability aspects into engineering practices. It proposes a novel integrated model-based method that provides a consistent way of addressing the well-known lack of generic and integrated ways of clarifying both cost and value consequences of sustainability in early phases. It further presents the development and implementation of such approach in two separate case studies conducted in collaboration with a major aero-engine sub-system manufacturer. The first case concerns the assessment of alternative business configurations to maintain scarce materials in closed loops, while the second one concerns the production technology of an aero-engine component. Eventually, this article highlights the learning generated by the development and implementation of these approaches and discusses opportunities for further development of model-based support.

Keywords

Engineering design, systems engineering, sustainability assessment, value assessment, model-based design

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Introduction

In an industry such as aerospace, which features the introduction of advanced technologies with long life cycles, it does not come with surprise to see sustainability listed as one of the most significant drivers[1,2] for the development of next-generation air transport solutions. For instance, the Strategic Research Agenda, published by the Advisory Council for Aeronautics Research in Europe, defines the Ultra green air transport system as a major high-level target for research in aviation,[3] pointing toward reducing the environmental impact of aircrafts and associated systems during their life cycle: from manufacturing to operation, maintenance, and disposal phase.[4]

This shift in direction stresses the need to reconsider methods and tools for design decision support. While systems engineering practices[5] have been exercised for years to turn high-level design objectives into concrete targets on system functionality (e.g. lightweight, noise reduction, emission reduction, and higher reliability), it

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is even more challenging to decompose and clarify sustainability implications in the same way and to compare them against performance-related capabilities in a product-planning phase.[6–9] While some aspects of sustainability are partially encompassed by the established drivers for design, such as specific fuel consumption, lifetime, and weight reduction, others are less readily quantifiable and more problematic to use as "goodness criteria" during development.

Even if sustainability includes a rich set of features important for the successful introduction of new solutions to the market, it is not evident which criteria and indicators should be used to guide the definition of design concepts and to support early stage decision making.[10] This problem is further emphasized when full life cycle responsibility is added: decision makers must be able to assess design alternatives both from an environmental and social perspective, looking at material extraction, production, usage, and component scrapping.

How to optimize sustainability aspects and be competitive on the market, is a major question for aeronautics and for the manufacturing industry in general. The answer lies in methods and tools that are able, already in a preliminary design stage, to balance sustainability requirements with economic interests, highlighting how sustainable design choices can create value for customers and stakeholders, hence generate market success in the long term. Overlooking the role of sustainability as a value-creating factor for future air transport solutions increases business risk and may result in expensive and time-consuming re-design efforts later in the product life cycle.

Objectives

Engineering teams are used to model problems and generate from them the necessary information for decisions to be taken; hence, the ability to apply a model-based thinking is critical for successful decision making. In this context, trade-offs may be solved by looking at what customers expect, which is how much they value certain capabilities against each other.

This article addresses the problem of bringing the important—yet typically high level and complex—aspects of value and sustainability into engineering practices. This is considered to be crucial to raise the ability of integrated engineering teams to take more informed decisions in the preliminary stages of design. Its objective is to illustrate how a model-driven approach was developed and applied to understand seemingly inconsistent, ill-defined design situations, and how it showed to improve the quality of early stage design decisions.

This article initially describes how sustainability aspects are considered today in the development of aerospace components, emerging from a review of the existing literature for decision support in engineering design. It further presents the development and implementation of a model-driven approach for quantifying the value of sustainability-related choices. The approach is exemplified in two separate case studies conducted in collaboration with a major aero-engine sub-system manufacturer. The discussion section focuses on the learning generated by the development and implementation of these approaches and elaborates on opportunities for further development of model-based support.

Method

Action research (AR)[11] best describes how research was conducted. AR is an iterative process involving researchers and practitioners working together on a particular cycle of activities, including problem diagnosis, action intervention, and reflective learning.[12] It involves a spiral of routines, look-think-act, or learning circles, in which researchers test a theory with practitioners in real situations, gain feedback from this experience, modify the theory as a result of this feedback, and then try again.[11] Lessons learned are grown from two case studies[13] conducted in collaboration with a major aero-engine subsystem supplier and in close collaboration (in the first case) with a large first-tier supplier of integrated metallic and composite assemblies for aero-structures.

The first case concerned the implementation of the model-based approach to benchmark alternative closed-loop configurations for the handling of scarce materials along the life cycle of an aero-engine component. Number of partners, material flows, ownerships levels, and activities were modeled to find the most optimal solution for keeping valuable materials (i.e. elements of a Ti-834 alloy) in closed loops. This benchmarking activity is based on the potential availability risks of the alloy elements, which might affect the economic performances of the component manufacturer in a long-term perspective.

The second case study looked at the use of Environmental Impact Assessment (EIA) and Strategic Sustainability Assessment (SSA) to identify and clarify sustainability hotspots along the life cycle of a new product technology. A Net Present Value (NPV) analysis was added to EIA and SSA as a means to quantify the value generated (for the manufacturer and the customer) by alternative solution strategies in the hotspot. After having identified the milling process as a potential sustainability hotspot, two alternative manufacturing processes, such as electrochemical milling (ECM) and mechanical milling (MM), were benchmarked by calculating their NPV in alternative future scenarios, featuring different market and regulatory assumptions.

Empirical data were collected between May 2012 and November 2014 through regular (bi-monthly) multi-day physical co-creation workshops and semi-structured interviews with managers, engineers, and information technology experts involved in the development of hardware and services related to aerospace products. Data gathering activities benefited from the part-time physical presence of the researchers at the industrial facilities.

Reflective learning was aided by the continuous participation in regular debriefing activities, which took the form of regular (bi-weekly) virtual meetings. The findings were iteratively discussed and validated with the project partners. Verification activities featured co-located focus groups with industrial practitioners. Both qualitative and quantitative data were gathered from such sessions and used to verify the feasibility and applicability of the proposed approach. Compiling visual representations and demonstrators of the emerging modeling concepts was an important means to validate techniques with stakeholders and to identify critical topics for modeling.

Sustainability aspects in the aviation industry

In the aviation industry sustainability challenges are typically addressed by introducing new technologies that are more efficient and have lower environmental impact for a certain performance than existing products. Fuel saving[14] and alternative fuels[15] are the focus of many research studies to improve the sustainability parameters for aviation. Air-to-air refueling,[16] open-rotor engines,[17,18] environmentally friendly propulsion systems,[19] and more efficient flight routes[20] are other proposed solutions that aim to pave the road toward more sustainable air transport systems.

The development of such solutions translates into new targets for design, both for system integrators and for all other partners in the supply chain. For instance, the development of a more fuel-efficient aero-engine suggests sub-system manufacturers to develop components able to increase the pressure in its core. This automatically leads to higher temperature, requiring the use of an advanced alloy in the construction. This seemingly simple choice has implications on the company sustainability profile and on its ability to deliver value to customer and stakeholders along the entire life cycle of the product. The scarcity of some metallic elements in the alloy might cause limited availability of the material in a medium- and long-term perspective. In turn, the manufacturer might be unable to provide spare parts, and this might raise the cost for maintenance operations. GE Aviation describes a similar situation, where challenges of using rhenium, a rare metallic element, became evident and demanded a new development approach.[21]

Already in a preliminary design phase, system and component manufacturers need to be aware of the sustainability consequences of their design choices and take a proactive approach toward them. In the example above, innovative solutions can open up from understanding the material flows in combination with the value flows of how products are developed, manufactured, operated, maintained, and re-cycled. The aircraft company Boeing, for instance, recently presented a proactive approach with the mission to create a closed-loop titanium cycle within their value chain,[22] to secure the access to high-value materials that otherwise are at risk of becoming degraded when traded on the general metal market.

Recycling, remanufacturing, and more efficient materials handling are becoming increasingly important,[23] with the legislation also moving in this direction (e.g. the *Extended Producer Responsibility* and the *Registration, Evaluation, Authorization, and Restriction of Chemical Substances* regulations). Here, a transition from a good-dominant logic to service-dominant one is observed: in order to realize such closed loops, companies need to radically rethink their aftermarket activities and to consider themselves not only as product sellers but also as service providers.[24] This servitization trend[25] is described by many in academy: Industrial Product–Service Systems (IPS2),[26] Total Offers,[27] Functional Sales,[28] Servitization,[29] and Product–Service Systems (PSS)[30] are just few of the names given to the new paradigm.

All above-mentioned paradigms imply a radical change in how products are offered[31] and in how revenue streams are generated. In turn, they suggest a radical change in the way products are designed and developed.[32,33] Stressing the need to include service activities in the "hardware" design space[34] means that the focus of the design activity has to move from the definition of new products to the re-organization of existing hardware or service elements based on new needs and values.[35] Developing an integrated product–service solution is more than simply choosing the best technical option; instead, it entails identifying the preferred combination of products and services that enable maximization of value for customers and stakeholders, which may also include more thoughtful consideration of property rights.[36]

The challenge is eventually how to model such combinations of products and services to support design decision making. This means understanding how the product, the service, and the overall business can be represented as a model, so that it can be understood, simulated, and evaluated to find the "optimal" combination for both a sustainability and value viewpoint.

Model-driven decision support for sustainability and value

To predict product properties, engineers build different models. The evolution of computational software for performance analysis (computational fluid dynamics, multibody dynamics, etc.) has significantly influenced the development of algorithms, mathematical formulations, and, in general, the functionalities required to model different physical mechanisms in engineering design. The advancement in the simulation software area has now reached a stage where, for example, finite element analysis (FEA) is a commodity in the engineering toolbox and is used in regular design work. Also, knowledge-based approaches, such as rule-based simulations and knowledge-based engineering (KBE),[37] have found application in industry[38] to reduce time spent on design by automating routine tasks. These tools are closely coupled to the specific knowledge for solving engineering-specific problems and, by tradition, bound to geometry modeling. By looking outside the computational side of design, knowledge-enabled engineering[39] models have been proposed to capture both the formal and the tacit, unspoken knowledge to aid the design process.

The evolution of mechanical engineering and knowledge engineering models is important, but there is also a need for a broader view on how models are used in a business perspective to support not only the design of the technical hardware but of the entire system of products and services. An example of this is the product–service hybrid pyramid presented in Fritz et al.[40] The challenge is how to represent the properties of services since they no longer mean dimensions and tolerances of physical artifacts. Schmitt and Hatfield[41] suggest a systematic approach that incorporates customer operations based on quality management, much in line with Grönroos[42] and Fransson.[43] They point out how the provider can take advantage of learning from customer use by, for example, making invisible services visible. Modeling and simulation challenges for PSS lie then on validating the methods used for virtual verification, realizing multidisciplinary simulation, and taking into account the complete product life cycle including disassembly and remanufacturing.[44]

Many approaches and support tools for sustainability aspects in product development have been developed over the recent decades. Generally, they focus on certain aspects of societal sustainability challenges, for example, Environmental Management Systems (EMSs),[45] Cleaner Production,[46] Factor 10,[47] Eco-design or Design for Environment,[48] Life Cycle Assessment (LCA),[49] Framework for Strategic Sustainable Development (FSSD),[50] Method for Sustainable Product Development (MSPD),[51] Templates for Sustainable Product Development,[52] and a Sustainability Life Cycle Assessment (SLCA) matrix.[53]

The latter has been thoughtfully explored in the context of product–service combinations. A recent study[54] indicates that SLCA is capable of strengthening the strategic sustainability focus of PSS development in industrial practices. A case study conducted in the light tube industry[55] further shows the benefit of using an SLCA matrix to map the ecological and social sustainability aspects when PSS are proposed for long-life products.

Still, in the design stage, sustainability requirements are not discussed exclusively: in the aerospace sector, for instance, they are rather traded off with weight, purchase price, or fuel burn requirements. The difficulty of selling "sustainability" to technology developers is mainly due to the problem of showing numbers and "hard facts" related to the value generated by sustainability-oriented decisions. As explained by one of the respondents during the empirical study:

> If you do not have a trade factor between two things, then it is my experience that where you have a number on, it wins … If we cannot set a quantitative measurement for something during conceptual design, it sinks down simply. When we talk about qualitative measurements; there is a tendency to ignore them. (Systems engineer at the case company.)

Recent attempts to integrate sustainability with a value-based view remains at an organizational strategy level and do not dive into a design situation.[56] Sustainable value is a concept put forth by Figge and Hahn[57] and used on an European scale[58] to arrive at a return to cost ratio that considers environmental indicators as costs. The validity of this approach has been recently debated,[58–60] and a step change is required to spotlight the value creation opportunity of a sustainable choice and to better integrate sustainability and value considerations into the preliminary stages of design.[61]

The current research in the domain of value-driven design (VDD)[62] suggests a possible way forward. VDD is an approach that uses NPV and surplus value (SV) models,[63] which are surrogate objects for long-term profitability, to evaluate, early in the systems engineering design process, the "goodness" of a design.[64] Several authors[64–66] have applied VDD to optimize system design in aerospace. First, the designers pick a point in the design space at which to attempt a solution. Then, they create an outline of the design, which is elaborated into a detailed representation of design variables. Later, they produce a second description of the design instance, in the form of a vector of attributes that mirror the customer preferences or value scale.

These attributes are assessed against 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 may accept the configuration as their product or may try to produce an even better design by going around the cycle again.

This approach is of interest to avoid falling in the trap of focusing only on the nearest customer and targeting local optimal solutions, rather than on those dimensions that add value from a more system-level perspective. While VDD does not yet consider sustainability explicitly in the value analysis (mainly due to the difficulty of translating it in monetary terms), recent attempts to introduce more qualitative aspects in the VDD process[67–70] show the opportunity of exploiting VDD to find a win-win situation where sustainable improvements are aligned with business advantages.[71]

A model-based method for sustainability and value assessment in conceptual design

In order to bridge the gap between sustainability-centered and value-centered approaches, a generic method for integrated sustainability and value assessment in conceptual design has been proposed and described in Figure 1. The process emphasizes two main loops:

- The Qualitative Assessment loop follows the initial definition of the development program targets for a new aerospace technology or product. It is composed of two main activities, which aim to (1) raise awareness and (2) describe in detail sustainability hotspots along the technology or product life cycle. This loop brings to the definition of alternative design concepts (both in terms of product and processes) to cope with the hotspots. Data about such concepts, together with information and lessons learned gathered during the analyses, are used as inputs in the quantitative loop.
- The Quantitative Assessment loop benchmarks alternative concepts on the basis of the value

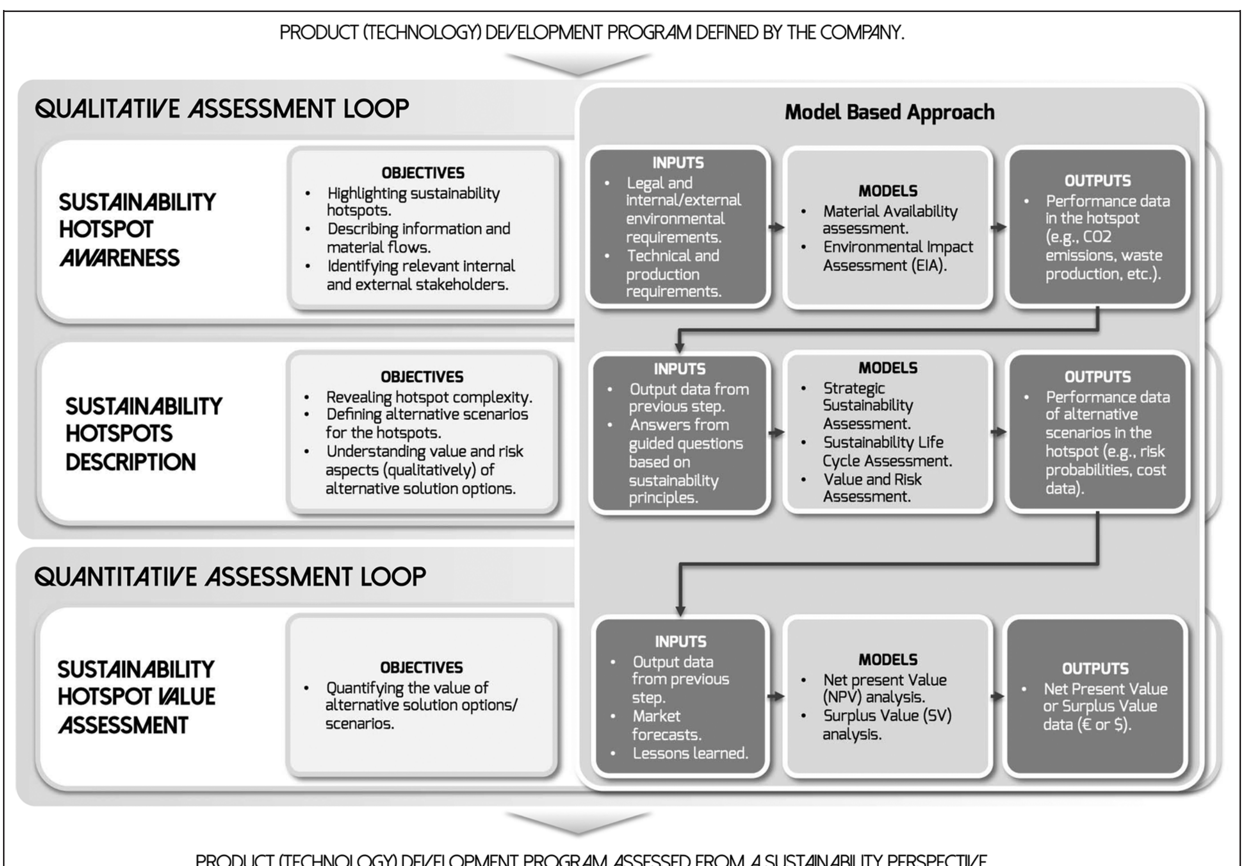

Figure 1. Generic method for integrated sustainability and value assessment.

they generate for the manufacturer in the short and long terms. Value reflects the ability of a solution to satisfy a range needs, concerning the immediate customers, other stakeholders, and society in general. This analysis looks into the customer environment to evaluate how a design (i.e. a combination of hardware and services) affects the operational process. At the same time, it encompasses a broader analysis of customer-of-customer and societal needs, which are modeled and translated into economic metrics.

The purpose of introducing models at this early stage is to support the design team in structuring the sustainability analysis of the customer operational process, which, otherwise, will be dominated by gut-feelings and intuition. A peculiarity of the method is that it does not prescribe one model but rather suggests a portfolio of tools, which can be selected depending on the context of the study.

Sustainability hotspot awareness

The Qualitative Assessment loop is triggered by the selection of a product concept from the pot of available technologies. This loop is conducted by focusing on the identification and evaluation of "sustainability hotspots" along the entire product life cycle. Hotspots are defined as environmental concerns of serious impact potential, along the entire life cycle of a proposed solution (i.e. from raw material extraction to the disposal phase).

The identification of such hotspots is conducted by introducing a set of models, which are as follows:

- Material Availability Assessment (MAA)
- EIA.

In the product development process, the MAA is used to verify availability (but also abundance) of given materials. This model features two main components, which are the Future Contamination Factor Index[72] and the Supply Risks Checklist.[73]

EIA further identifies significant environmental impacts generated from the resource extraction phase to the end of life. EIA is based on a simplified LCA developed in a Swedish industrial consortium (Verkstadsindustrier[74,75]) and uses a rating scale from 1 to 3 (where 3 has the highest significance) to judge the following four 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 or occurrence of the activity that are negligible (1) to requirements that are regulated in steering documents and quantity or 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 or no possibilities for improvement (3).

From this, EIA proposes measures to adjust impacts to acceptable levels or to investigate new technological solutions. It is often regarded as a local, point source–oriented evaluation of environmental impacts, which takes into account time-related aspects, the specific local geographic situation, and the existing background pressure on the environment.[76]

Both models take as input information about the customer operational process, the technical specification of a design concept, together with legal, internal, and external sustainability requirements. As outcome, they produce performance data related to the hotspot in question. These data are heterogeneous and might be related to the amount of emissions, energy consumption, or waste produced by a given activity.

Sustainability hotspot description

The second step of the qualitative assessment phase uses models to obtain performance data of alternative solution concepts within the hotspots. These data are in terms of probabilities of negative effects to happen, as well as cost data.

SSA is the reference model at this stage. SSA, by covering all the three pillars of sustainability (social, environmental, and economical),[77] aims at revealing the hotspot complexity and at clarifying its short- and long-term consequences. SSA is based on guiding questions inspired from a MSPD,[50,51] which is, in turn, based on backcasting[78–80] from sustainability principles. The principles state that in a sustainable society, nature is not subject to a systematic increase of the following:

1. Concentration of substances from the earth's crust;
2. Concentration of substances produced by society;
3. Degradation by physical means;
4. In this society, people are not subject to conditions that systematically undermine their capacity to meet their needs.

SSA is complemented by other models, such as SLCA, value assessment, and risk assessment. Their purpose is to expand on the SSA to reveal expected consequences with regard to an ideal sustainable situation (Figure 2). First, they support the design team in determining the benefits of alternative concepts, in terms of which individuals or entities will benefit from a change in the As-Is situation by introducing a new "solution." Then, they aim to provide a feedback on the likeliness of a concept to render the expected effects. Also, they indicate when in time is optimal to introduce such change.

The modeling activity aims to reveal the complexity of the hotspot, and when alternative solutions have been generated, it allows to understand value and risk aspects of such concepts.

Sustainability hotspot value assessment

When the information generated in the qualitative phase is not yet sufficient to drive decision making, a quantitative model can reveal with more precision the economic value generated (for the company, for the customers, and the other stakeholders) of the alternative concepts. The quantitative phase looks closer into the customer operational process and calculates (or simulate) how alternative solutions generate value during their life cycle. The quantitative model is based on a NPV or, alternatively, SV approach, which takes as input the results of the qualitative investigation, such as data for risk and cost, complemented by historical data (e.g. process models, technical documentations, and market forecasts).

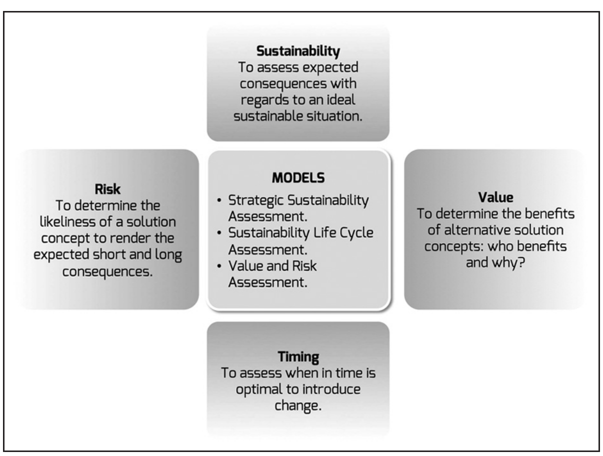

Figure 2. Combination of models in the sustainability hotspot description phase.

Figure 3 describes the process used to build and populate the NPV (or SV) models. Given the uncertainty that dominates the analysis at this stage, it is important to run the quantitative simulation under different assumptions or "future scenarios." Modeling scenarios mean for the design team to determine a limited set of parameters characterizing the overall context in which the proposed solution concepts will be operated in the future. These might relate to changes in the intensity of environmental regulations, in the price of materials, or in customer sensitivity toward a given dimension related to the product, and so on.

Once the links between the value model and the scenario-governing parameters have been described, the design team is asked to estimate the value of the latter. The model is run on the basis of three datasets that reflect:

- The As-Is context or situation (which is considering only very small changes in the given time period for the calculation);
- The assessment from the most confident stakeholders;
- The average assessment from the entire design team.

The results of the three models are later discussed with the stakeholder group until an agreement is reached on the best solution from a sustainability and value perspective.

Investing on the generation of quantitative models is a matter of finding the right trade-off between benefit and cost of the modeling activity because building and populating the model is both time-consuming and

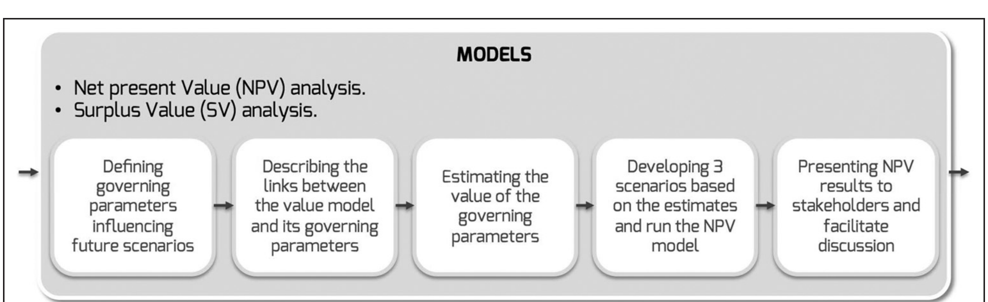

Figure 3. Scenario-based process to define quantitative value assessment models.

costly. The choice to perform a quantitative assessment is also dependent from the availability of the data. Not all design situations require designers to approach this last stage of the method, as shown in the case studies presented in the following sections. The first case study, in fact, only exploits the qualitative loop and details how models are used to raise awareness on existing hotspots for a new technology. It further proposes solution directions (in the form of different business model scenarios) to cope with such hotspots and evaluates them under a value, risk, and time perspective. The second case study exemplifies with more detail how the quantitative loop is deployed and how tools and data sources are used to quantify the value of alternative solution strategies in a hotspot.

Case 1: closed loops based on the availability of scarce materials

The first case study concerns the development and deployment of models for assessing different material-loop configurations for future jet engine components. The modeling activity only concerned the qualitative loop, which is the identification and description of the hotspots. Quantitative modeling was not part of the assessment in this case.

Sustainability hotspot awareness

During the design of a major aero-engine sub-system, the Ti alloy 834 was initially selected as preferred material because of its ability to withstand extreme heat and fulfill temperature requirements. Intuitively, this choice contributes in leveraging the sustainability profile of the manufacturer: higher temperature and pressure in the core of the aero-engine allow reducing fuel consumption and emissions.

In the first step of the qualitative assessment phase, the design team applied MAA and EIA to uncover tacit sustainability hotspots in the way Ti-834 is handled along the entire life cycle of the product. A first result came from the MAA model, which showed that some of the alloy elements—molybdenum (Mo), niobium (Nb), and tin (Sn)—are scarce in the earth's crust or have high supply risk. Material scarcity and remote extraction location were flagged as hotspots because they are likely to increase both purchasing and managing costs for these elements in the future.

Sustainability hotspot description

In the second step of the qualitative assessment, alternative solution options were conceptualized and further analyzed by the use of SSA, SLCA, and value or risk assessment. Given the long life cycles that characterize aerospace products (up to 30 or 40 years), the result of the first assessment step suggested either discarding the Ti-834 option or building closed-loop systems in order to increase the following:

- Material efficiency, which is reducing scrap production and optimize scrap management (which directly could give reduced costs);
- Material availability, which is making sure that there is enough (or affordable) amount of the alloy during the entire manufacturing period.

Which way such a closed-loop system should be configured was not evident at this initial stage, and several questions needed to be clarified to move forward with the decision. A few of such questions were as follows: How to ensure future availability of materials? How to secure material flows? How to build reliable cooperation with suppliers and customers? and How to define ownership of activities, products, and services?

Several alternatives of the closed-loop system needed to be built and further assessed. After having identified relevant stakeholders among the aerospace component manufacturer and among a value chain partner, a workshop was held to

- Get a better understanding of activities, flows, and ownership related to the handling of the studied elements at the two companies;
- Define relevant closed-loop business configurations to be explored more in depth from a sustainability and value perspective;
- Get a feedback on the companies' perspective at new suggested closed-loop configurations with regard to these elements.

These activities were conducted with the support of foresight tools, and accompanied by the analysis of flows, roles, and dependencies in the current business situation. The workshop participants contributed to the definition of an initial picture of attractive alternative business options, which was defined in more detail including the flow of materials, the roles of the value chain actors with regard to the handling of each material, and other aspects that the value chain depends upon (e.g. an actor may have knowledge regarding material handling that a direct material-handling actor is dependent upon, despite not handling the material directly). Once this initial picture was set, researchers and engineers investigated possible future value chain configurations. The configurations differ in terms of the following:

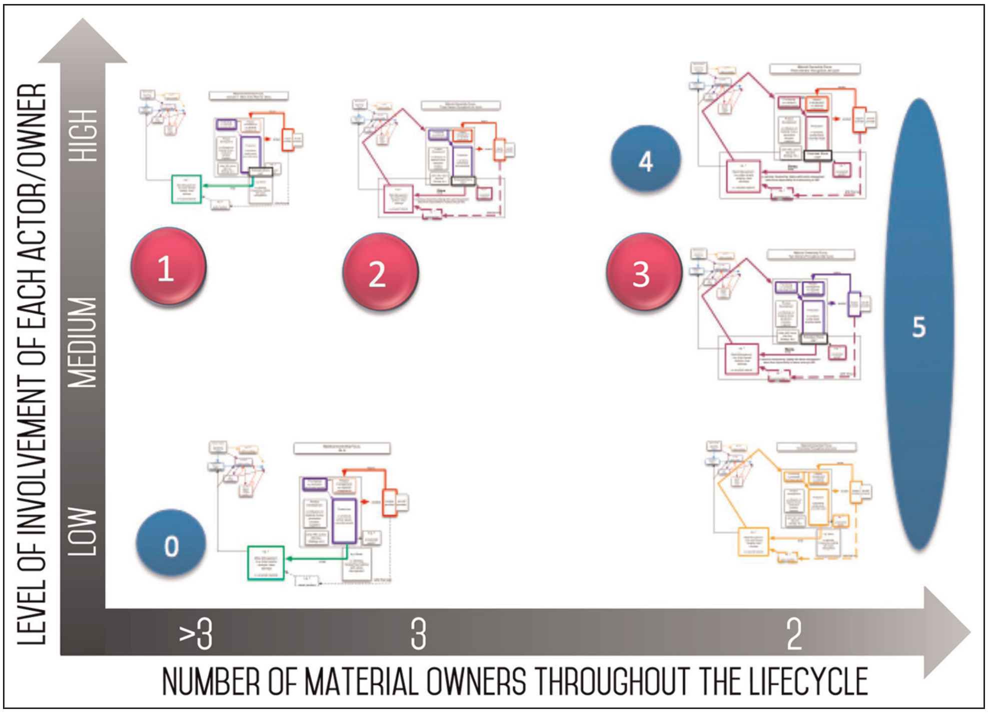

Figure 4. Proposed closed-loop configurations for Ti-834 handling.

1. Number of material owners along the life cycle (x-axis in Figure 4);
2. Level of involvement of each actor or owner in the loop (y-axis in Figure 4).

Five closed-loop configurations were eventually detailed. Among these, only three were chosen for further evaluation as they were considered to be the most realistic by the participants.

Concept 1 (Figure 5) is very similar to the As-Is situation but suggests that the materials handling company has more responsibility in helping out in sorting and in optimizing the recycling process. This loop features several players, but material ownerships aspects remain unchanged. The participants shortlisted it because of the short-term economic incentive it offers to reduce material losses and become more efficient in the way the different elements are managed.

The second concept (Figure 6) reduces the number of owners to three. Here, the material-handling company takes a larger responsibility of the sorting process, and suppliers are expected to take the ownership of the material throughout its recycling process. A totally closed loop (where the material goes back to the original manufacturer) can be realized if enough incentives are in place (which is, if the value generated for the engine component manufacturer by executing the loop justifies the investment). Otherwise, the material-handling company will sell the elements to the market to get the best price.

The third concept (Figure 7) is the same as loop configuration 2 in terms of the recycling flow of the material, but it suggests only two material owners. The engine component manufacturer becomes the sole owner of the material and takes back the product component after use, that is, possibly by selling the function and remanufacturing of certain parts.

This configuration becomes of interest if the same alloy is used during the product's long market life (in this case 30–40 years). Some incentives for loop configuration 3 that need to be considered are, for example, the likelihood for the company to shift from producing artifacts to delivering services or the likelihood that tougher legislations or requirements from customers will require closed material loops to reduce material degradation. However, there are also disincentives for this concept that need to be considered, such as the likelihood for new materials to be introduced and replacing the alloy.

Workshop participants expressed the need to apply a more structured approach for assessing the expected consequences related to the implementation of each concept as a means to take a more confident decision. Sustainability-related hotspots were further described using a SLCA matrix[54] and a value assessment matrix, as shown in Figure 8.

The SLCA ranking is considered from two perspectives: (1) relative (i.e. the sustainability aspects of a proposed concept relative a baseline) to know whether a loop configuration is better or worse than the current

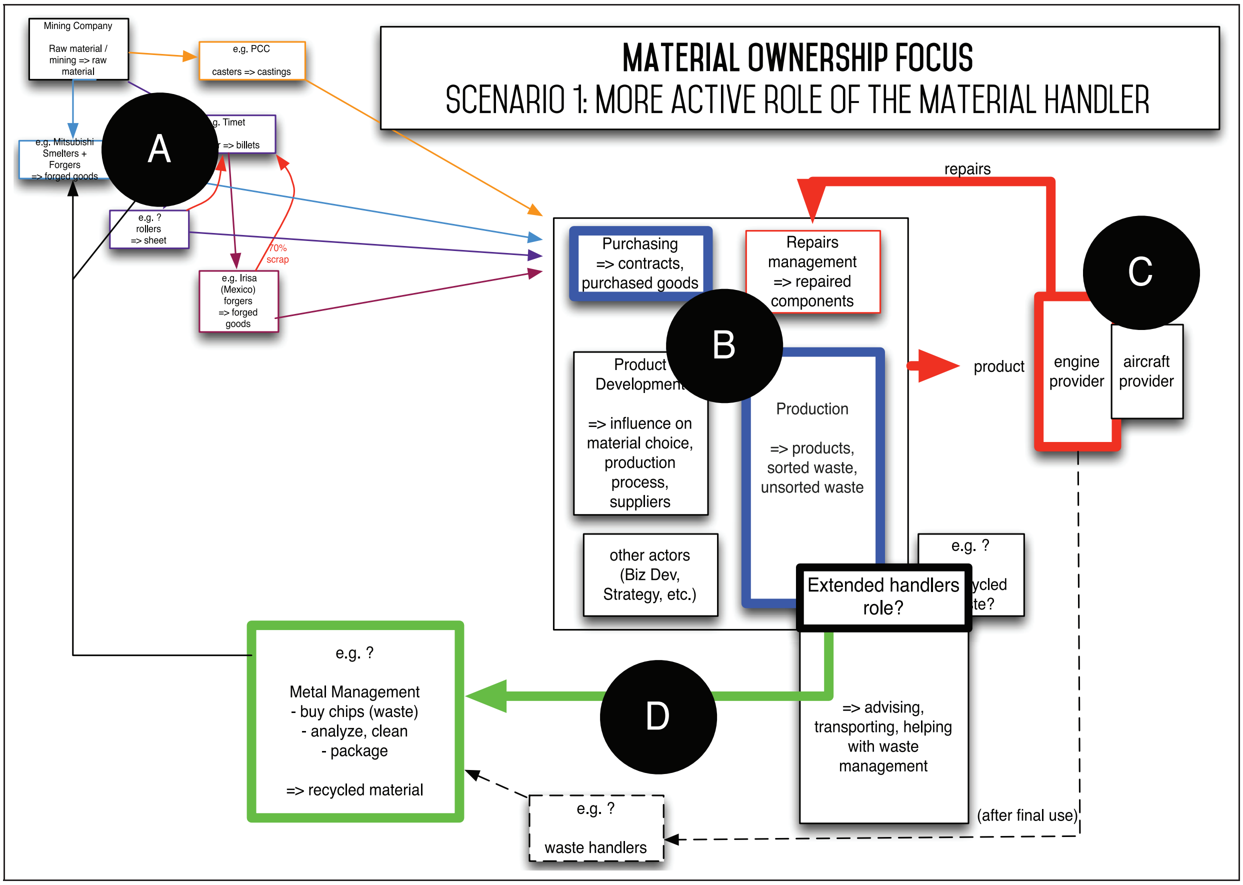

Figure 5. Loop configuration 1.
A: raw material producers; B: engine component manufacturer; C: engine manufacturer; D: material handler.

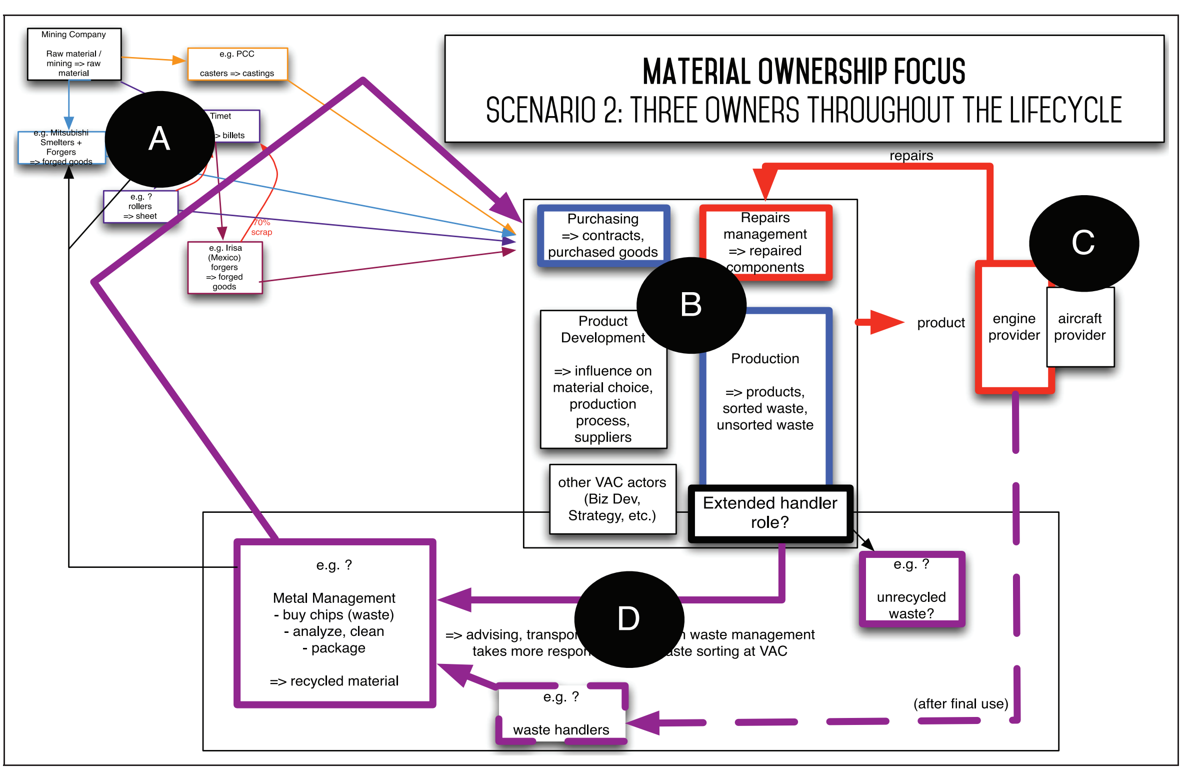

Figure 6. Loop configuration 2.
A and D: raw material producers or material handler; B: engine component manufacturer; C: engine manufacturer.

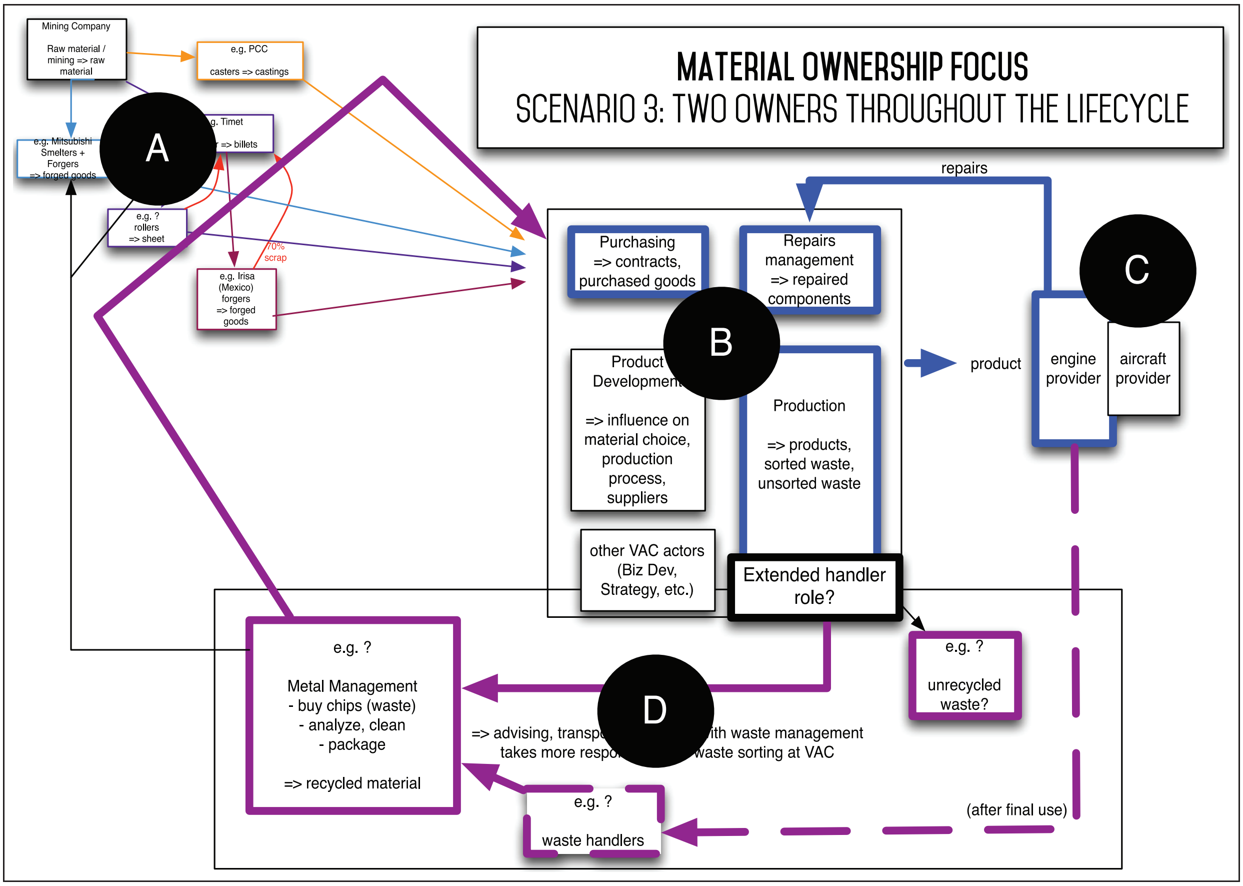

Figure 7. Loop configuration 3.
A and D: raw material producers or material handler; B: engine component manufacturer; C: engine manufacturer.

SUSTAINABILITY PRINCIPLES

LIFE CYCLE PHASE	1	2	3	4
RAW MATERIALS	SIMILAR	SIMILAR	SIMILAR	SIMILAR
PRODUCTION	SIMILAR	WORSE	SIMILAR	SIMILAR
USE AND MAINTENANCE	SIMILAR	SIMILAR	SIMILAR	WORSE
END OF LIFE	SIMILAR	SIMILAR	SIMILAR	SIMILAR

VALUE DIMENSIONS

LIFE CYCLE PHASE	OPERATIONAL RELIABILITY	MAINTAINABILITY	WEIGHT	VALIDATION COST	ROBUSTNESS IN MANUFACTURING
DESIGN	SIMILAR	SIMILAR	SIMILAR	BETTER	SIMILAR
RAW MATERIALS	SIMILAR	SIMILAR	BETTER	SIMILAR	SIMILAR
PRODUCTION	SIMILAR	SIMILAR	SIMILAR	WORSE	SIMILAR
USE AND MAINTENANCE	SIMILAR	SIMILAR	SIMILAR	WORSE	SIMILAR
END OF LIFE	BETTER	SIMILAR	SIMILAR	SIMILAR	SIMILAR

Figure 8. Extract of the Sustainability Life Cycle Assessment matrix and value assessment matrix from the Ti-834 alloy study.

value chain configuration and (2) from a full sustainability perspective (i.e. relative to first-order principles for a sustainable society[81,82]) to raise awareness on the long-term implications of the concept in a sustainability context.

Value assessment activities consider availability and price of materials, together with the impact of such changes on the value chain. The assessment is qualitative at this stage, and it is performed with the help of a value assessment matrix, featuring a list of "value drivers" that represent major aspects affecting the desirability and profitability of each concept.

The classification of risks based on sustainability hotspots follows the work on value dimensions. The risk assessment is based on possible consequences of changing from one loop configuration to another, the likelihood of these to happen, and estimated costs if they happen. The reason for adding a risk assessment step is that it could enhance a comparison with other risks and facilitate the communication of the result within the company and in the value chain.

The results of the qualitative assessment pointed to option loop configuration 2 as the preferable closed-loop configuration. The modeling activity showed that this concept represents the best trade-off between the ability to generate economical benefits for the manufacturer and the risks for unavailability of valuable materials. Compared to the other options, this configuration is safer from the perspective of ensuring availability of the material Ti-834 for usage in the industry value chain. Also, given that the dependency of the valuable material is less risky and it will take longer time for the material to be unavailable, the company will benefit from a more stable material price.

Case study 2: comparison of production technologies for a new aero-engine component

The second case describes a situation where the design team is requested to take early stage decisions on the architecture of a new high-temperature aero-engine component. This case features the use of both qualitative and quantitative assessment models, in particular:

- EIA, to raise awareness on sustainability hotspots;
- SSA to clarify potential sustainability consequences for a new product technology;
- NPV, to benchmark, using monetary units, alternative solution strategies in the hotspot.

The case study description mainly focuses on the quantitative assessment phase: the purpose is to highlight its main characteristics and to exemplify the use of economic models in a real-world situation.

Sustainability hotspot awareness

EIA was conducted focusing on the entire life cycle of the component and resulted in a few hotspots; the manufacturing process was further spotlighted as the most critical one. The EIA analysis was first done independently and then the ratings were discussed in the expert group with the facilitation of an environmental engineer. The model not only highlighted ECM as the most effective production technology but also showed that ECM processes generate hexavalent chromium Cr(VI), nickel, and lead particles when applied for nickel-based alloys. Upcoming environmental requirements related to production and management of Cr(VI) are likely to generate extra costs and to reduce efficiency of the manufacturing line. This information suggested the expert group that the ability to benefit from a long-term investment in the proposed option needed to be understood more in detail in the hotspot description step.

Sustainability hotspot description

First, the material flow, potential emissions, waste treatment, and rest-product treatment were investigated to clarify why the ECM process generated Cr(VI), 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.

From the socio- and ecological perspective, the SSA resulted in the following list of reasons for not investing in ECM:

- The use of carcinogenic and allergenic substances could not be justified from a social perspective if there are alternatives to use;
- According to the precautionary principle, alternatives should be chosen when there are environmental and health risks;
- Material lists showed a warning for a ban of processes that involve Cr(VI);
- The company might not be able to take economic advantage of an investment in ECM, due to the introduction of more severe legal requirements;
- Only a few sub-contractors might be able to provide support to the process in the long run;
- The costly investment in new tools was not justifiable for a process that is not very developable.

The final recommendation from the SSA was to choose a design concept manufactured using a more traditional MM process. MM has the drawback of diminishing the surface characteristics of the component, hence its performance in operation. Also, MM components are more expensive to be manufactured. Still, MM involves only one hazardous substance (nickel) and produces less toxic material compared to electrochemical manufacturing processes.

The modeling activity further showed that from an economical short-term perspective, choosing ECM would have been beneficial for the component manufacturer because some investments had already been made, and some work had already been performed in terms of investigation of suitable suppliers. Given these contradicting results, it was decided to further investigate benefits and drawbacks of the proposed solution concepts in the quantitative assessment phase.

Sustainability hotspot value assessment

To visualize and better understand the consequences from a value perspective, ECM and MM were benchmarked using an NPV calculation. Growing from the SSA analysis, five parameters were found to affect the value of the two processes.

The first one captures information about present and future environmental requirements coming from the legislation. The ECM process is the most exposed toward changes in legislation, while MM is almost immune. For ECM, new requirements mean introducing more complex instruments and machineries in the process, 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 or 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 more sophisticated equipment and processes might be difficult to find, and individuals do likely require more training. New requirements might also be introduced to regulate the activities in the working environment, to ensure safety of the individuals involved in the process.

The second parameter concerns waste management costs. These are expected to grow due to the introduction of new norms regulating the handling of toxic and hazardous materials. In turn, this will require more complex and expensive procedures for material management, affecting the profitability of the manufacturing line.

The third parameter, named Customer Environmental Consciousness, indicates the likeliness that engine manufacturers (i.e. the system integrators) choose another supplier because of the company not fulfilling internal requirements for supplier selection (i.e. the company is black-listed). This variable mostly affects the profit generated by the ECM solution: the company will either see their selling volumes reduced as customer progressively move to other manufactures or will be forced to reduce the selling price of each component to maintain the same market share and production volume.

The fourth parameter concerns the availability of suppliers for the new process. They might be discouraged to supply consumables and spare parts to keep the ECM process up and running if the legislation becomes more stringent. Fewer suppliers would mean higher purchase prices and lower flexibility.

Eventually, as fifth parameter, the group highlighted that a ban on the ECM process would have severe negative consequences in terms of profitability: cost would grow due to the necessity of dismantling the ECM manufacturing line and converting it to MM, to the reduced line availability during the conversion, and to 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 year 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 year n + 1.

Scenario 1 NPV results: As-Is context or situation

The NPV calculation considers a time span of 10 years (2014–2023), 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 8% for all three scenario presented. (Note that the data used as input in the calculation sheet have been scaled and used for illustrative purposes only.)

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. This scenario considers new environmental requirements to be updated and introduced at a very slow pace in the next 10 years. 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 manufacturers purchasing choice. Eventually, it foresees the same number of companies (3) operating in the market at the end of the 10-year period and able to provide support to the ECM process. In this scenario, customers value more performances than sustainability, and under these assumptions, ECM-manufactured products are more profitable than their MM counterpart throughout the entire decade (Figure 9). The ECM process renders a higher cumulative NPV after 10 years, and the break-even point is reached at year 6, about 1 year before MM. If the societal consequences (company image, risk for accidents, etc.) are minor, the design team is likely to orient its choice toward ECM-manufactured components.

Scenario 2 NPV results: assessment from the most confident stakeholders

This NPV calculation uses as input special values of the governing parameters of the scenario. These are set to reflect the opinion of those design team members who expressed high confidence on how the scenario is likely

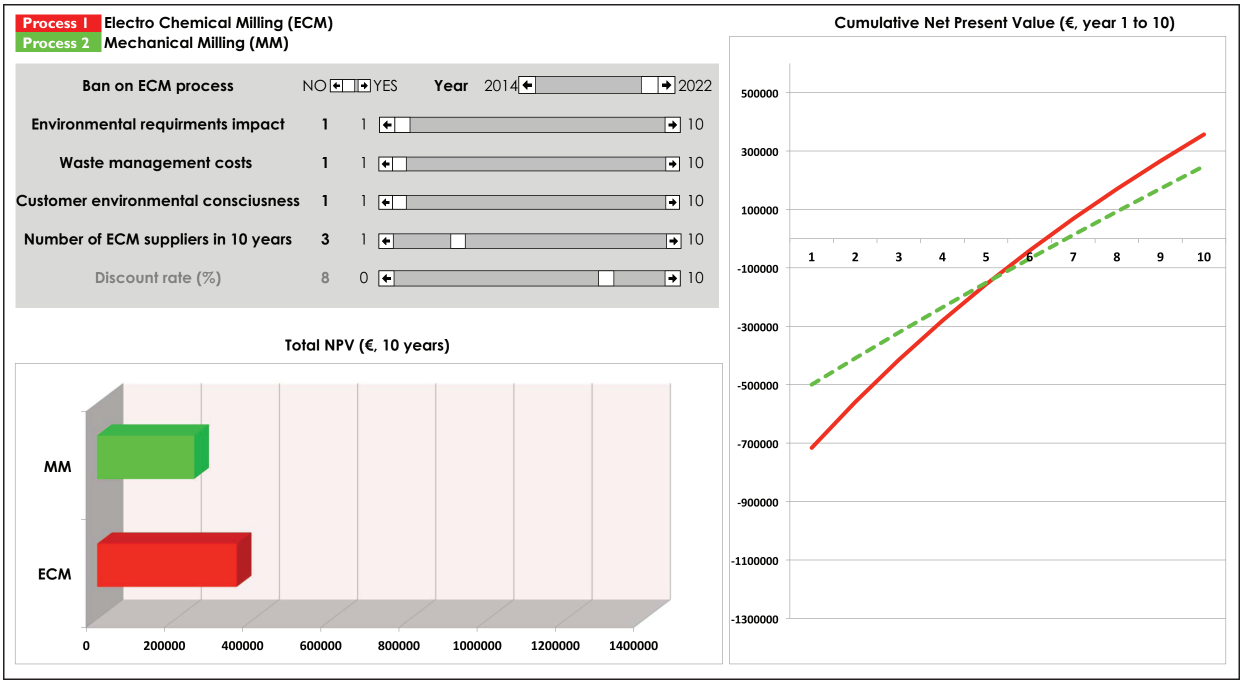

Figure 9. Scenario 1 results—As-Is context or situation.

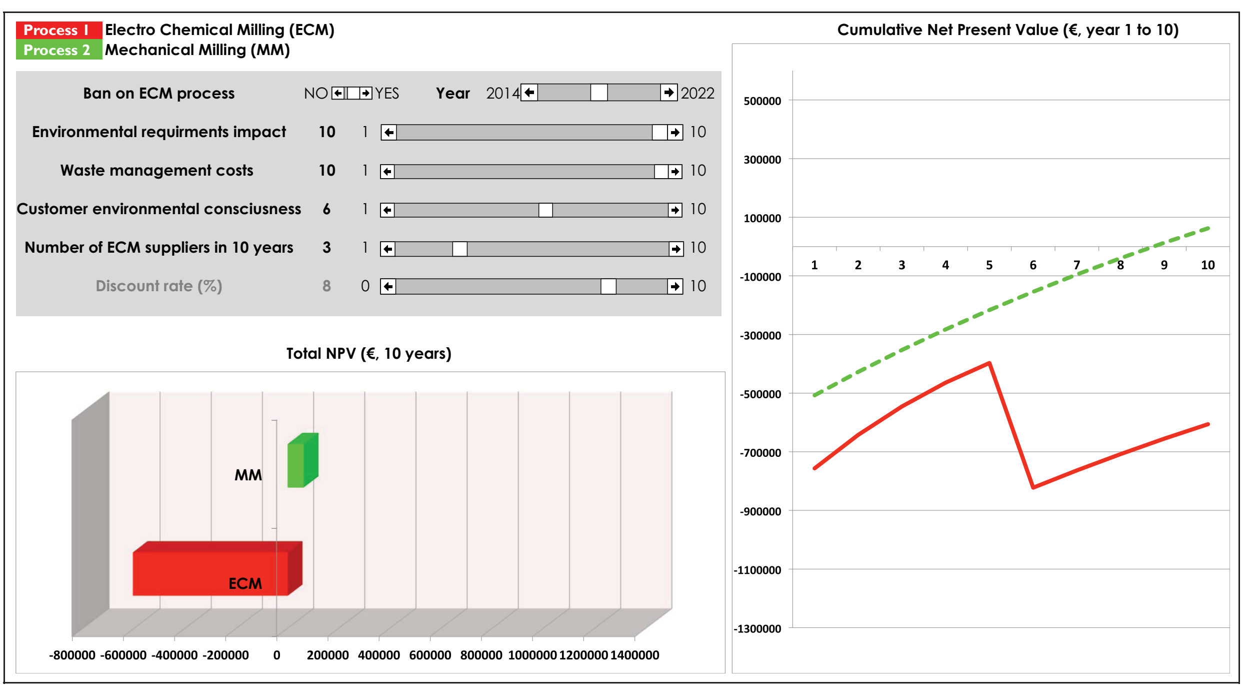

Figure 10. Scenario 2 results—from most confident stakeholders.

to look in the 2013–2023 period. According to them, it will feature the following:

- The introduction of a ban for the ECM process starting from year 5;
- A very quick increase in the introduction of new environmental requirements;
- A quick increase in waste management costs;
- A slow increase in environmental conscious customers;
- Three suppliers available at the end of the decade.

Figure 10 shows that profitability of ECM-manufactured products decreases year after year, in line with the introduction of new legislations. The NPV curve is flatter than in the first example to reflect the higher costs for equipment, labor, consumables, and waste treatment, as well as the diminishing appeal of ECM-manufactured products. The investments needed at year 5 to convert the manufacturing line from electrochemical to mechanical strongly affect cash flows and the expected NPV. From year 6 onward, the actualized cash flows curve for ECM approximately 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.

Scenario 3 NPV results: weighted average assessment from the entire group

This scenario builds on the average of the values given by all respondents to the governing parameters for the scenario. This average is weighted looking at the self-expressed confidence of the design team members. This scenario 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.

From year 4 onward, 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 affects ECM profitability (Figure 11). The actualized NPV for ECM progressively reaches break-even at the end of year 10, while MM between year 7 and year 8. As a result, the company is likely to orient its choice to MM.

The results from the three different scenarios were discussed with the stakeholder team, and a consensus and agreement was taken that the second scenario was the most likely alternative to happen in this case. Thereby, in this case, MM could be chosen as the best manufacturing process from a sustainability and value perspective.

Discussion

Sustainability consequences are difficult to trade-off with classical technical and business requirements in an early design phase and to relate to profitability and customer value fulfillment. The development and implementation of a model-driven approach, which aims at simplifying, prioritizing, and systematically asking what is important in the sustainability analysis, is believed to be useful to undertake sustainability assessment in a more structured way than what happens today.

The method enables a broader exploration of the design space using a quantified set of data, providing a sense of what impact key factors may have. Undergoing the proposed steps forces the actors to make these assumptions explicit, rather than allowing them to remain implicitly inherent and high-level assertions. Correctly implemented, the focus turns to the quality and completeness of data and assumptions

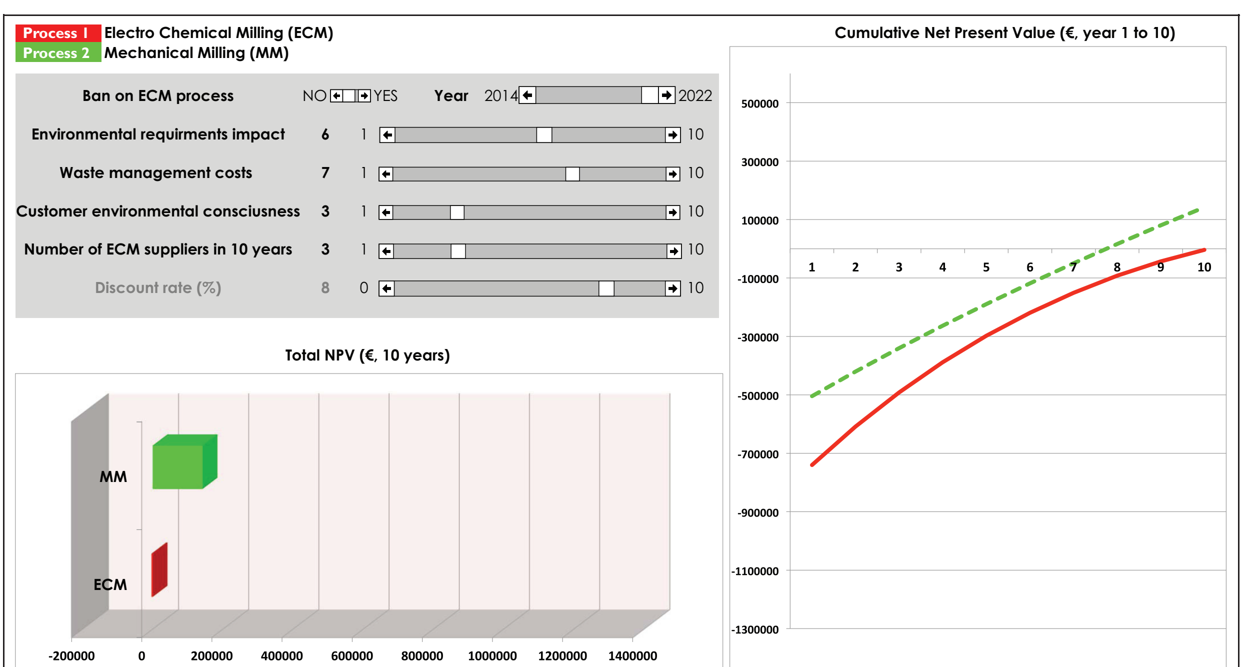

Figure 11. Scenario 3 results—weighted average assessment from the entire group.

made in the underlying model. In this way, quality and completeness can be systematically improved, that is, moving from opinions and intuitions to evidence-based statements.

Eventually, this makes sustainability consequences more concrete and understandable during design concept selection activities. Decision makers can then treat sustainability at a comparable level as other design parameters, which are, in general, more technical and more established and hence prioritized when making decisions.

Interesting phenomena can be highlighted in both case studies, in relation to the application of a model-based approach to support decision making:

- In the first case, the Ti alloy, which is initially discarded due to the scarcity of the elements it is composed of, becomes attractive again when a closed-loop value chain configuration is chosen, so that also purity of the Ti alloy can be maintained. This shows that a material-based question, which is typically addressed through the modeling of a technical product system, may benefit from an approach that includes modeling and simulating the value chain configuration;
- In the second case, the NPV results work as a common denominator for the design team members to confront on sustainability matters when opinions differ. Highlighting trends by altering the model input data becomes more important than obtaining precise output figures, even just because the latter suffers from lack of data in such an early phase. The model mainly helps experts to avoid looking only at a static scenario but rather to grow understanding among a range of possible scenarios. The most correct (or realistic) one is likely to emerge from a dialogue between the stakeholders, and supporting this dialogue is the main purpose of the quantitative model.

The method supports the transition from qualitative to quantitative, while keeping as much of open information as possible. For this reason, it does not prescribe the modeling approach to be used; rather, due to the complicated nature of the sustainability problem, a generic process is proposed from which designers can pick up specific models on the basis of their situation. This way of working is in contrast with more classical approaches, such as LCA, which adopt a simulation approach more directly (where the team inserts data in a computer and obtains figures).

The authors believe that openness will make the method more transparent to the final user. In the second case study, for instance, if the design team does not understand why certain parameters are chosen in the NPV model, they can go back to SSA to understand the rationale through qualitative and descriptive results. Openness is crucial also because the adoption of a simulation approach risks to be counterproductive, as it disguises the complicated nature of sustainability problems (i.e. leading to reductionism[82]).

Conclusion

This article presents and demonstrates a novel model-based approach where sustainability aspects are assessed and expressed in value-related terms for effective decision making. It shows how heterogeneous models for sustainability and value can be linked in a flow to support decision makers in accounting for these dimensions already in the preliminary stages of design. The benefit of the proposed method lies in the ability to make sustainability consequences more concrete, understandable and transparent, by linking them with economic metrics even before entering the detail design phase of a new product. By clarifying value of sustainability consequences earlier in the development process, through the systematic and consistent use of models, companies can reduce the risk of "late discovery" of sustainability issues, which are accompanied with rework and cost overruns.

This work has succeeded on building the method and has demonstrated its applicability through practical examples. In the future, the method will be validated further, by means of additional case studies, also outside the aerospace sector. Sensitivity analysis will be performed to test the models' robustness in the presence of uncertainty. More in-depth studies are also needed 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.

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