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Architecting for Sustainability: Bridging Business, Technology, and Organization in High-Tech Industry

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Summary

The high-tech manufacturing industry, dominated by large multinational corporations, faces pressure to innovate faster to remain competitive, producing more sophisticated machines with better performance and quality. In recent years, besides the push for better performance, sustainability and circularity have also gained importance, due to (1) **regulations** that are becoming broader in scope, stricter in thresholds, and more complex in requirements, (2) **customer demands** and expectations and (3) **internal** strategic objectives.

Environmental Sustainability and Circularity (ESC) are recognized as strategic, long-term goals which require both technical and business model innovations. Considering the long development cycles and lifespans of complex industrial machines, sustainability and circularity must be addressed early in the architecting process to prepare for future regulatory and market demands.

In this report, we present an architecting framework developed in close collaboration with Canon Production Printing department. It supports early-stage system architecting for a high-tech production machine, and aligns business, technology and ESC innovation strategies. It defines the scope and acts as the decision support framework when considering improvements for future machine generations.

We provide a multi-perspective modelling approach:

- **Business perspective** models the ecosystem (network) of collaborating businesses and ESC-related actors. It is modelled from the viewpoint of a high-tech manufacturer and its role in the ecosystem.
- **(Technical) architecture perspective** captures the trade-offs among top-level system qualities when introducing ESC improvements. It suports structured exploration of how technology innovations influence both value creation and sustainability outcomes.
- **Organizational perspective** reflects the roles and governance structures involved in ESC-related decision-making.

The perspectives are interconnected, so that changes in one perspective directly influence other perspectives, enabling holistic approach.

The framework is designed for collaborative use by systems architects, domain experts, business and organizational stakeholders. By integrating diverse perspectives and modelling approaches, it enables joint exploration of alternatives, transparent trade-off analysis, and alignment of technical decisions with business goals and environmental targets. This holistic approach ensures that critical interdependencies are addressed early, reducing risk and supporting the design of future-ready, sustainable system architectures.

Contents

1 Introduction

This technical report describes the learnings and the state of the Canvas project, a collaboration between Canon Production Printing (CPP) and TNO-ESI, at the end of 2025. The topic addressed in this project is **Systems Architecting for Environmental, Sustainability and Circularity (ESC)**. It is a continuation of the work in Canvas 2023 [1] and Canvas 2024 [2].

In Canvas 2023 [1], we explored the problem and gave directions for applied research; in Canvas 2024 [2] we zoomed in on the (1) process and information shared between Life Cycle Assessments (LCA) and early system architecting; and (2) the process of achieving common understanding between involved stakeholders. The findings revealed an opportunity in Systems Architecting research to better connect technical innovations and potential future business models in the context of ESC. This was the topic of Canvas 2025.

1.1 Sustainability and circularity

The high-tech-manufacturing industry faces pressure to innovate faster to remain competitive on the market, producing more sophisticated machines with better performance and quality [3]. In recent years, besides the push for better performance, sustainability and circularity have gained importance [4].

The key drivers for making more sustainable and circular products are:

(1) Sustainability and circular economic **regulations** are driving the industry to redesign products for repairability, component reuse, and compliance with eco-design standards, including Digital Product Passports [5] [6] for material and environmental data.

(2) **Customers demand** machines that consume less energy and comply with ESC-related expectations.

(3) **Supply chain resilience**, reducing dependency on raw materials, and mitigating disruption risks.

As an **internal** driver, companies and their employees seek to align corporate purpose with societal needs, demonstrated through ESC initiatives and sustainability programs.

While sustainability and circularity are not new topics, their role has evolved significantly. Historically, improvements such as energy efficiency and material reduction were primarily driven by cost considerations - lower energy use reduced operating costs for customers, and less material enabled more competitive pricing. Today, these qualities are recognized as strategic, long-term priorities, shaped by the abovementioned drivers, requiring innovations in both technical and business models.

Because industrial production machines are highly integrated systems with long development cycles and lifespans, improvements to key system qualities (including ESC-related ones) must be addressed early in the architecting process. This prevents costly redesigns in later development stages and ensures readiness for future regulatory and market demands.

Early-phase systems architecting for ESC works under the following constraints

(1) Market and regulatory uncertainty – markets and regulations are in flux, with regulations rapidly increasing in scope, becoming more stringent with tighter thresholds, and growing in complexity as they extend across entire supply chains and require extensive documentation. This makes it difficult to define stable requirements or anticipate compliance needs.
(2) ESC is not yet as deeply embedded as traditional quality attributes like productivity, costs or safety, which increases the risk of misjudging the trade-offs
(3) While sustainability and circularity goals are often well-defined on a high level, addressing them in the early architecting phase remains challenging. Key metrics include LCA [7], which is used for environmental performance assessment, and MCI (Material Circularity Indicator) [8], which evaluates circularity performance. However, such metrics typically require a detailed machine or product design which is not available in this phase.
(4) Priority misalignment and competing ESC objectives - performance and cost tend to get priority over ESC-related qualities. Moreover, even within ESC itself, objectives can compete; for example, designing for a long lifespan may require more robust materials, which can conflict with goals for minimizing material usage).

1.2 Problem statement

During the early phase of product development, system architecting serves as a bridge between customer value propositions, business priorities, and top-level system choices. For “classical” qualities, such as the machine productivity or output quality, the drivers to improve them and delivered value are clear. A faster machine or machine that creates a product of a higher quality directly enhances market competitiveness and customer workflow performance.

For ESC, this alignment is less straightforward. The drivers for ESC, such as regulatory compliance and resource efficiency, are obvious, but the beneficiaries of the ESC qualities are less clear. For ESC, the value proposition and whose benefits (customer, society, or both) can be less tangible (brand reputation, compliance, broad benefit for society). Also, its impact often materializes later in the product lifecycle, during use-phase (energy efficiency, maintenance) or end-of-life (recycling, reuse).

Furthermore, while sustainability and circularity goals are often well-defined on high level as a corporate goal, addressing them in the early architecting phase remains challenging, as key metrics, such as LCA or MCI, typically require detailed design data.

The absence of clearly defined beneficiaries makes it difficult to establish the scope for decision-making. If it is too broad, there is a risk of attempting to address global, highly complex systems that extend beyond the control of the high-tech company. If the scope is too narrow, there is a danger of focusing on local optimizations that may lead to rebound effects elsewhere in the system.

In the high-tech industry, during the early architecting phases, there is a need for a lightweight, yet precise/reliable enough, way to communicate with different groups of stakeholders to reach a common understanding of the problem along with coming to the initial architecting decisions. Current frameworks, e.g. CAFCR [9], TOGAF [10], for holistic problem definition are often difficult to apply in early architecting because it requires tailoring. There is a need for practical models that define the problem across business, technology, organizational, and sustainability dimensions, while helping set a scope that avoids drifting into global systems beyond company control and preventing too narrow optimizations at the same time.

Last year, following Canvas 2023 [1] that outlined the need to reason on the axes product-enterprise-ecosystem, Canvas 2024 [2] project identified areas where clearer roles, structured processes, and adapted frameworks could help integrate sustainability and circularity into early system architecting for the high-tech manufacturing industry. Building on these insights, in Canvas 2025, we zoomed in on the relationship between business and technical decisions, exploring how architects' understanding of the business context can further support the integration of sustainability and circularity in early system architecting.

1.3 Research questions

We addressed the following research questions:

Research question 1: How to effectively do business and architecture trade-offs and jointly innovate for ESC?

Traditionally, business drivers have been formulated in terms of profit and sales volume, with commercial success defined by return on investment and shareholder value.
Today, companies increasingly recognize that ESC ambitions are important, not only for societal impact, but also for maintain competitiveness, meeting regulatory requirements and mitigating business risks. This research question explores how organizations can balance and integrate ESC ambitions, enabling business and technical stakeholders to collaborate effectively and drive innovation for sustainability and circularity.

Research question 2: How to integrate sustainable design principles and circularity into an architecting framework?

For system architects, the primary focus has been on system functionality and established system qualities, such as performance, reliability, and cost. Sustainable design principles, however, are relatively new and often not yet fully embedded in the architect's toolkit. This research question addresses how ESC-related qualities can be defined, incorporated, and managed alongside traditional system qualities, ensuring that sustainability and circularity become integral parts of the architecting process.

1.4 Relating three perspectives

We propose a framework that integrates three perspectives relevant for architectural decision-making: business, technical and organizational. It is tailored for ESC considerations in the early architecting phases.

This framework does not eliminate the constraints mentioned in Section 1.1, such as external volatility and competing business priorities. The framework provides a systematic way to work within these conditions. By systematically connecting these perspectives, the framework enables informed trade-offs and holistic reasoning. Moreover, it makes the underlying challenges explicit, helping identify where targeted actions or organizational adjustments are needed to strengthen embedding of ESC in the long-term.

1.5 Report outline

In this report, we propose an integrated reasoning framework that supports architectural decision making in the early phases of architecting for ESC. The framework relates customers and markets, business models and technology innovations, with the aim to improve ESC, but also covering other architectural quality trade-offs. We start with the related work and our method description in Chapter 2 and then present the method in Chapter 3 conclude and outline areas for future research in Chapter 4.

2 Related work and methods we used

The INCOSE 2035 vision [11] identifies sustainability as a global megatrend and positions sustainability and circularity as central to the future of systems engineering. In their article [12], the authors outline the challenges and complexities of circular systems engineering, and point out the lack of frameworks for actionable insights, effective knowledge reuse, and systematic trade-off balancing. Current SE methods and tools including MBSE approaches, the V-model, the ISO/IEC/IEEE 15288 [13] standard for systems engineering, and the ISO/IEC/IEEE 42010 [14] for systems architecture, need tailoring to address these needs [15].

There is a lot of work being done integrating Lifecycle Environmental Assessment (LCA) [16] into Model-Based Systems Engineering (MBSE) tools. For example, these authors outline integration of LCA analysis into a SysML-based MBSE method [17]; The Capella/Arcadia tool suite has an add on to connect to standard repositories containing LCA data and selected LCA tools [18]; Siemens digital engineering tools connect MBSE models with LCA tools [19]. These improvements are applicable in later development stages, when the assumptions about the market and the business model are explicitly or implicitly fixed, and when the required data is already available.

In the other ESC-related, but not strictly SE disciplines, especially in the area of circular design, there are number of methods, but they are not integrated into systems architecting methods. For example, the circular business model canvas [20], circular business model pack [21], and the value hill model [22] all focus on future business models and circular value loops but do not connect to system architecting methods. As a result, the potential to translate circular business model insights into early architectural decisions is missed.

There is a growing and evolving number of circularity tools coming from research and practice [23]; whereas they explore business models in early stages, they do not connect to architecting methods. Prospective (lightweight) LCA and LCC combined with Material Flow Analysis and Carbon modelling give environmental insights but do not explore future markets or business models. Sustainability metrics and (emerging) circularity indicators, such as MCI [8] exist, but they are not integrated into architecture trade spaces methods.
The work of Bakker et al. (see e.g. [24]) and Bocken et al. connects product design to circular business models [25] and Bakker et al. put Circular Systems Thinking as one of the future key competences in a circular economy [26].

In our research, we focus on a step before the requirements are fixed, when assumptions about future markets are still being defined and when business models may still change. Looking at this challenge, we recognize that informal simple models are needed to integrate business and architecting trade space.

The methods and models we used we position within the principle of BAPO [27] (see the paragraph below) that emphasizes the alignment between business strategy, architecture, process and organization. These principles are also present in other frameworks, for example

TOGAF [10] relates business and enterprise architecture in details, MBSE in relation to requirements engineering methods connect system mission with the model-based system architectures. They go into details, develop methods and tools for these needs.

2.1.1 BAPO

BAPO (Business, Architecture, Process, Organization) has been introduced in the CoPAM (Component-Oriented Platform Architecting Method) for Product Family Engineering [27]. CoPAM stated that an important goal of any development method is to achieve the best possible fit between the following interrelated aspects (see Figure 1):

- Business, which includes the requirements of the market about the products and the way the company intends to respond to them.
- Organization, referring among others to the structure of the developing organization and the available people with their skills and experience.
- Process, which entails the different development steps and activities and their mutual relationships.
- Architecture, which refers to the structure of the products themselves.

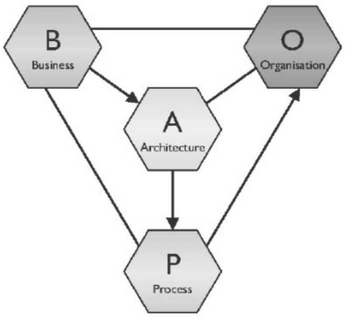

Figure 1: BAPO provides a holistic model that integrates the four aspects, ideally in the order of Business, Architecture, Process, and finally Organization. This is presented by the arrows.

We have used BAPO in a slightly simplified way where we have left out the process perspective, because the focus of the research was on business and architecture in the context of sustainability.

Another high-level conceptual structure we use to position our models is shown in Figure 2. It conceptually connects customer needs and business proposition with the system requirements [28] to emphasize the need for systems thinking in the early phases of development when requirements are not fixed yet.

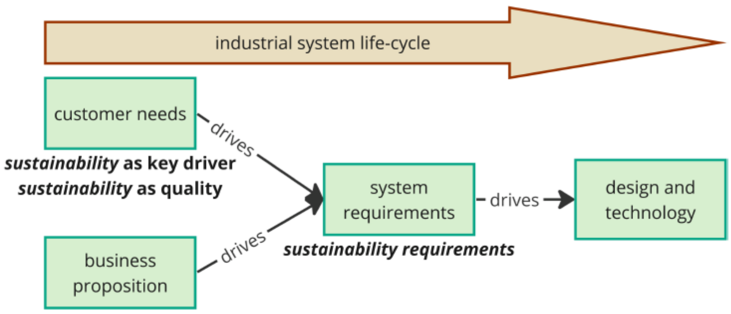

Figure 2: Connecting customer needs and business proposition to systems requirements and design and technology with the system lifecycle taken into account.

2.1.2 DAARIUS

DAARIUS is a structured, scalable methodology connecting stakeholder needs, top-level system qualities, and FCR (function, component, realization) views [29]. It complements MBSE by providing lightweight design reasoning and trade-off analysis that captures architectural design rationale, particularly in early phases of architecting.
Figure 3 depicts the DAARIUS reasoning structure.

At the highest level, we find a map of stakeholders that have specific interests or concerns in the System of Interest (SoI). The SoI is decomposed into a layering structure. Qualitative, as well as quantitative, sub methods [9] provide ways to reason over these layers.
The Aspects are mapped on system qualities and define how the systems main functions will perform. Usually, they are directly related to the system definitions of the system layer. Some examples of such qualities are energy consumption, manufacturing cost, productivity, serviceability, but they also may include ESC related aspects.

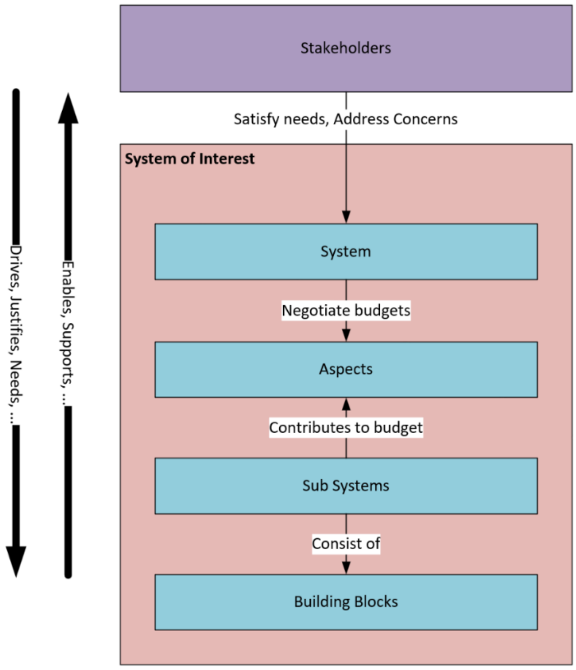

Figure 3: The layering structure that supports a system reasoning from stakeholders towards technology. These lines include, next to traditional objectives, the ESC related objectives. Our vision is to handle both in a similar way.

The Sub System layer and the Building Blocks define the system breakdown. For example, for a digital print system we can identify: Paper input module, print module, fixation module and paper output module. Each subsystem may contribute to the aspects of the Aspect Layer.

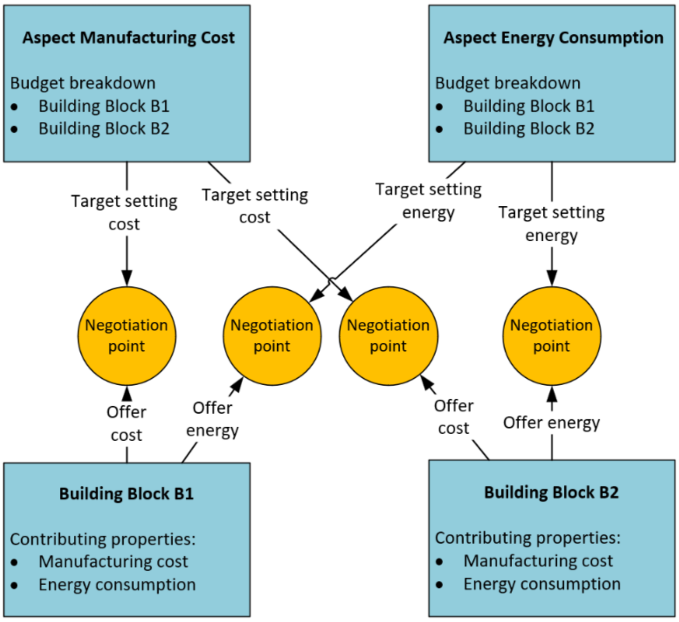

Figure 4: The layers are interconnected by a budget allocation. The owner of an aspect budget will assign a sub-budget to building blocks in a negotiation process.

Figure 4 presents how layers are connected. The owner of a design budgets [30] at aspect level will decompose it over the various sub systems, and further to Building Blocks. When budgets are conflicting, architects need balancing and dilemma thinking to find the most optimal solutions.

2.1.3 Modelling business value network

Several methods are available for business value network modelling. We selected the e3value model described below due to its simple language, graphical representation and possibility to automatically generate calculations of value exchanges, such as profitability, cash flows and the feasibility of scenarios, especially when the models become more complex. Other methods may be preferable in different contexts, for example BPMN [31] (future research is needed to check this) or specialized circularity tools. The work of [32] also addresses this kind of analysis.

The e3value modelling methodology is a conceptual modelling language for building and analysing business models of an ecosystem. The models describe how multiple actors create, exchange, and capture economic value through value networks and economic transactions We refer the reader to [33] for details on the e3value modelling method and the tool. Here, we describe the basic concepts of the business transaction, and in Section 2, we explain how we added ESC related actors and value flows.

Using concepts of the e3value modelling language, we model the business network, as actors consisting of businesses and other entities, and their economic transactions. One of the core concepts in this language is a (business value) transaction between the actors. For example, in Figure 5 below, a simple transaction shows transactions between the readers buying books in exchange for a certain amount of money. This transaction happens only if there is benefit, value for both sides. The bookshop sets the price for the book, and the reader buys the book. The value for the reader is more than the cost of the book, like cultural enjoyment, which the model does not depict. It depicts the monetary and object value exchange agreed between the actors.

The language allows for describing networks with value exchanges between more than two actors. These diagrams describe markets in different periods. Input, such as market size, prices, and investments, is needed to calculate the net flows. Based on these different inputs, it is possible to simulate, perform sensitivity analysis and assess viability of the business models.

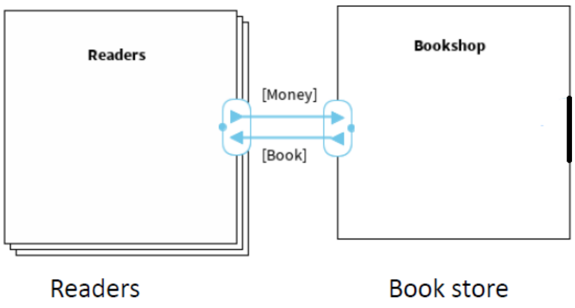

Figure 5: Example showing value transaction via value interface between two actors.

We used this method to model the business ecosystem of a high-tech manufacturing company, focusing on how ESC values are exchanged within that ecosystem.

3 Framework description

This framework supports architects in the initial phase of product development, when critical system architecture choices are made. It considers ESC-related improvements and aligns them with (future) business model and markets. Importantly, this framework helps to scope and focus discussions, especially in ESC-related questions, which are related to global and systemic issues and can move the discussion in multiple axes of complexity.

The framework is intended for both business and technical stakeholders. The goal is not to develop models in isolation (which should not be done in architecting anyway); rather, the value of this approach lies in constructing these models together, which improves mutual understanding and view of the problem. To facilitate this process, an expert modeller should guide and document the collaborative work.

3.1 Top-level structure and intended use

As shown in Figure 6, the framework integrates and aligns the three BAO perspectives and are represented with dark blue blocks (the process aspect of BAPO was out of scope)

(1) Business Perspective represents the market of the company offering the product (system of interest)
(2) The Architecture Perspective refers to the product definition and its structure. This product architecture could be incorporated into a product family architecture or even a platform architecture or refer to an overarching reference architecture.
(3) Organizational Perspective represents internal stakeholders. These stakeholders have an interest and influence in both the business and the architectural perspective.

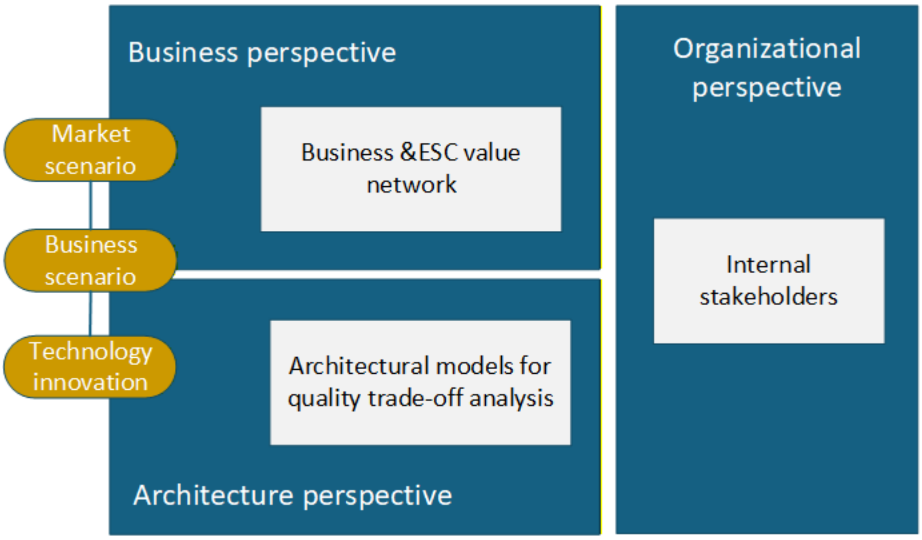

Figure 6: To enable innovations, for example on sustainability, Business, Architecture and Organization Perspectives must be aligned.

The **Business Perspective** models the ecosystem around the high-tech manufacturing company as a business offering the product. For ESC, it is important to consider the whole ecosystem, because product-level improvements depend on aligned incentives and value flows across all actors in the value chain (value network), not just the manufacturer. In this network, we focus on the high-level flow of monetary transactions and non-monetary ESC-values. The **Architecture Perspective** captures the trade-offs among top-level qualities, such as performance, cost and ESC. The **Organizational Perspective** reflects roles and governance structures involved in decision making related to ESC. Within these perspectives, we model the business network, the quality trade-offs and the stakeholders. This is presented by the white blocks in Figure 6.

The input parameters to the models are based on different scenarios that capture the following:

(a) Assumptions of how future **markets** will look like and how they will value ESC,
(b) Potential new **business models** for ESC, and
(c) **Technological innovations** that could provide ESC-related value at the market

The models within the three perspectives are constructed using different formalisms, tailored to their respective domains and using input from different domain experts. For example, the business value model uses network-based representations and economic transactions; technical architecture shows system engineering budgets, and related system design trade-offs; organizational models capture roles and governance structures.

In the framework, we connect perspectives through explicit parameters so that decisions in one perspective influence and constrain decision in the other perspectives.

3.2 The business perspective

Business decisions are driven by the creation and exchange of value, for the customers, within the organization, or across the broader ecosystem. Traditionally, this value has been measured in financial terms, such as product sales, service contracts or supply agreements. When taking ESC considerations, the definition of value expands to include ESC-specific aspects, such as emissions or reuse of systems or system components. By mapping the network of stakeholders and their interactions, engineers and architects can identify how sustainability solutions create, deliver, and capture value across the entire ecosystem.

While MBSE methods systematically capture customer and business requirements (also suggested in BAPO framework), they do not natively represent stakeholder networks using network-based languages. Instead, complementary tools, such as value modelling, can be used to map these networks, and MBSE models can be linked to them to ensure technical and business perspectives remain aligned and understandable for all stakeholders.

3.2.1 Value modelling - purpose and scope

The models created in this perspective represent an ecosystem of collaborating businesses and other actors that together (can) make a positive ESC impact. The models are created from the viewpoint of the architect’s company; in our case this is typically a high-tech manufacturing company. At the same time, the value exchanges described are made with the assumption that in such network *all* actors benefit economically from it (otherwise such network becomes economically unsustainable).

The purpose of such a model is to enable economic assessment of technology choices, considering both monetary and ESC-related flows. As this model is built in co-creation with other domain experts, it improves the communication and common understanding of the

ESC-related challenges. The questions addressed can be: Does the proposed innovation make sense from the customer perspective? Or: Is a specific business model for offering ESC value combined with the product and its services competitive and sustainable? Can projected ESC-focused technological innovations succeed in the market?

Ideally, the model is developed collaboratively by architects, business strategy experts focused on ESC, relevant domain specialists and those with expertise in technological innovations that contribute to ESC.
As we will show in the examples in subsections 3.2-3.4, the value models are constructed with one ESC aspect in mind. The scope of the model is then determined by the relevant external and internal stakeholders for this aspect.

3.2.2 Value network: flows and quantification

Using the concepts of e3value language and method [33], we model the value network. In these models, we represent:

- Who exchanges what with whom (actors and value objects),
- How exchanges occur
- Scenario-based value flows.

Economic value of transactions between actors (e.g. monetary amounts, costs, revenues) are expressed as quantities, resulting in net value for each actor, which enables estimating scenario profitability.

When applying this method, we identified the need to distinguish three types of value flows.

1. **Monetary values representing traditional financial transactions** such as payments for products or services between actors in the network.
2. **Monetary values specifically related to ESC**, such as costs or revenues directly tied to sustainability and circularity (examples include fees for recycling, subsidies for low-carbon products, or payments for compliance with environmental regulations).
3. **Non-monetary ESC values**, which represent benefits or impacts that are not directly reflected in financial terms. These can include reductions in CO_2 emissions, improvements in resource efficiency, or enhanced reputational value for participating in circular initiatives. This way, we aim to combine the economic and sustainability dimensions of business decisions.

The example in the diagram in Figure 7 shows a “snapshot” of the relevant market for Company A, using the example of one customer Company B. The Machines are sold to Company B, which makes products using the machines of Company A, and sells them to Customers. These are typical financial flows. Taking the old machine back when selling the new machine improves circularity indicators, assuming parts will be reused or refurbished or recycled. In this example of the business network representing business actors and the value they exchange, we add an additional “actor”, that is the Environment. This allows us to represent the ESC impact of the ecosystem represented.
This way we can show in this diagram if the program of buying back the old machines improves some indicator (for this prospective LCA estimate is used). The government’s legislations are represented to show that Company A fulfils reporting guidelines and regulations, and in return achieves compliance. We also represent investors and other stakeholders seeking opportunities in green companies.

In this example, all the value exchanges, monetary and environmental are quantified, with the exception of reporting and compliance activities. Additionally, the market size, investments into the new model of Company A, number of machines sold per customer, among other factors, are also quantified.

The inputs are based on the assumptions of market, business model, and technology innovation scenarios. Multiple scenarios can be explored. For example, a market scenario can be that of a market in which CO_2 emissions are highly-taxed and customers buy only machines with “green labels”; a business model scenario then accommodates this need in combination with technology innovations that enable this; Alternatively, there could be a scenario in which ESC is not valued at the market due to weakened regulations, but a business model still provides ESC improvements due to cost-related reasons.

The goal is to provide a rough but indicative estimate of the quantities, rather than a detailed financial or LCA analysis. The domain experts and stakeholders having knowledge of business and ESC-related concepts provide their inputs and assumptions here.

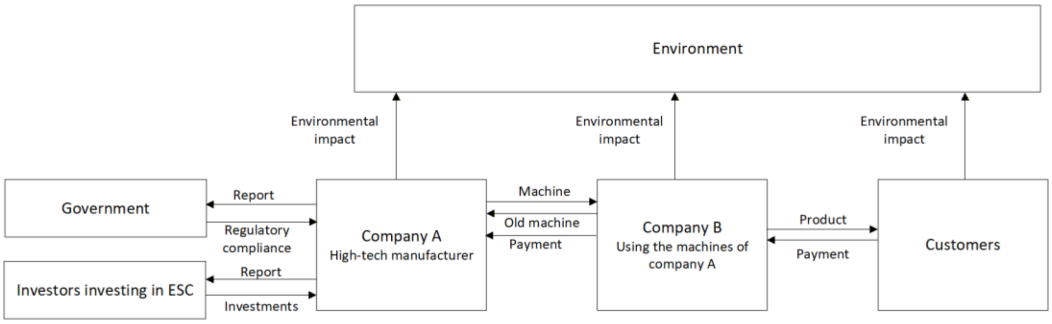

Figure 7: An informal diagram of a relevant business network for Company A

Note that the models are made at a high level of abstraction and are not intended to show detailed financial or technical analysis. The focus is on capturing the main value flows and the impact of introducing ESC-related changes, rather than exhaustively modelling every possible transaction or stakeholder.

3.2.3 Adaptation of e3value model to ESC

We used the key concepts from the e3value method, designed for the modelling and simulation of digital business value networks. The e3value approach itself encourages the use of informal diagrams (“cartoons”) to facilitate communication with stakeholders and avoid constraints imposed by formal language constructs. In our work, we followed this guidance by using informal diagrams as a “front-end” for stakeholder engagement, ensuring that participants were not hindered by the formal language of the method. The modeller’s role is to maintain rigor by translating informal representations into formal models.

While the paid version of the e3value tool can generate Excel files and supports semi-automatic calculation of net value flows, we manually calculated net flows in our case. As we move toward assessing a larger number of scenarios, we foresee the need to further automate and manage scenario-based models.

Although e3value is primarily suited for modelling one-to-one economic exchanges, we expanded its’ scope to include the environment as an explicit actor (external stakeholder) and to represent system-level impacts, such as the GHG (greenhouse gas) standard scopes [34]

Scope 1 (direct), 2 (indirect), and 3 (value-chain) emissions, using the insights from Life Cycle Assessment (LCA) and Material Flow Analysis (MFA). This enabled analysing both individual exchanges and overall environmental system effects. Future work will focus on deeper integration of these methods. Furthermore, in our previous work we linked technological innovation with customer workflows [35]. Future work is needed to investigate how these workflows contribute to analysis that connects business and architecting perspectives.

3.2.4 Example

Figure 8 shows the outcome of analysis of the business network of the high-tech company. This is one of the diagrams we used as an input for e3value model. Focusing on the ESC aspect of energy saving and CO_2 reduction, we explored a certain business model that relies on a technology innovation to reduce machine energy consumption; we assumed how the market will evolve in the next 10 years. The question focused on a certain combination of technology improvement, offered by a specific business model on the assumed market, if this will be beneficial for all the network actors. To follow the syntax of the e3value language, we need 2-way transactions, so for the Environment we put as a modelling “placeholder” zero values on the arrow that flows in the opposite direction.

The quantitative values were then used to project CO_2 reduction of the direct emissions, energy cost of the customer, as well as other values for the printer company from offering more green products. The quantitative analysis was done in Excel and served as basis for discussion (example in Figure 9).

The model executes by identifying value activities and value transfers between actors, and then automatically constructing scenario paths that represent how a predefined consumer need triggers a chain of value exchanges through the network. These scenario paths are evaluated under the assumption of economic reciprocity (each transfer must be matched by a counter-value), and the tool aggregates these exchanges over a given time period (e.g., per year) to calculate metrics such as revenues, costs, and profitability for each actor. In other words, the “trigger” is a stakeholder need, and the model computes the resulting value flow chains rather than simulating continuous behaviour or time dynamics.

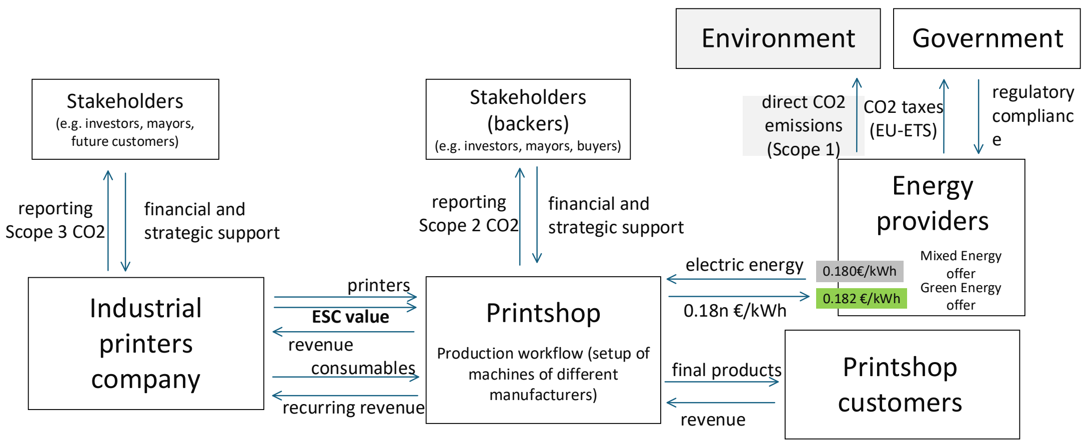

Figure 8: Value network example (to avoid the double booking, the total impact of energy usage of the machine in use is represented by the direct impact of the Energy provider)

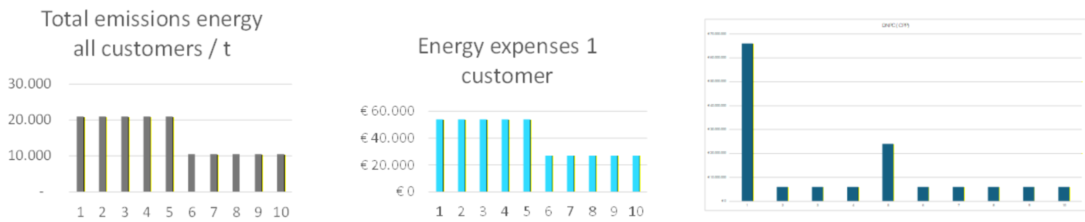

Figure 9: Examples of a quantitative analysis of years 1-10: revenues of the company with a new business model offering technological improvements that save energy, how the customer benefits in their revenues and CO_2 savings

3.2.5 Summary

It is essential to recognize that we are modelling a value network rather than a simple linear value chain. Here, value is not confined to one stakeholder (represented as an actor in the value model); it is often co-created, shared, or influenced by several ones. The way stakeholders (actors) are connected (their interactions, agreements, and exchanges) can change the overall value and impact within the network.

Additionally, scenario simulation is a key aspect of our approach: by modelling uncertainties and exploring various scenarios, we can identify the most relevant factors and ensure that these scenarios are analysed across the entire system.

As additional ESC-related value dimensions are incorporated into the analysis, the value network (model) naturally expands. Each newly considered sustainability or circularity quality introduces additional relationships, dependencies, and value exchanges among actors. As a result, mapping value flows become increasingly complex. Future work will therefore focus on modelling multiple ESC value dimensions simultaneously, allowing for a more comprehensive assessment of sustainability impacts within such networks.

3.3 The Organizational Perspective

As we transition to the organizational perspective, our focus shifts to identifying the internal stakeholders who own ESC-related business models and technical requirements.
ESC is not limited to one organisational unit. Goal setting for ESC (Environmental, Social, and Circularity) is structured across multiple organizational levels, with each layer adding detail and specificity as objectives are translated into practice [28]. At the corporate level, organizations articulate broad, publicly stated ESC ambitions, such as carbon neutrality targets or circularity commitments. These high-level goals are then translated at the division level into more specific objectives, such as developing new ESC-oriented business models or implementing targeted sustainability programs. They are tailored to the division's context and responsibilities. At the product level, these objectives become concrete requirements and key performance indicators (KPIs), including measurable targets like energy consumption limits, the use of recycled materials, or compliance with defined ESC standards. This layered approach demonstrates how strategic intent is progressively refined into actionable requirements, with the level of detail increasing closer to the product.

These stakeholders typically include departments such as R&D, business units, and purchasing, as well as individuals and teams responsible for developing ESC business models and offerings. Stakeholders can be positioned across various organizational segments. Example of their roles are R&D manager and sustainability committee which nowadays is typical in large organizations.

This perspective is not influenced by scenario variations; rather, it provides an explicit overview of where ESC responsibilities are strongly or weakly enforced within the organization. By mapping ownership and accountability for ESC business models and offerings, we can pinpoint areas of strong enforcement as well as potential gaps, ensuring that ESC requirements and expertise are anchored appropriately in the organizational structure. In the next section, we show the relation between stakeholders and top-level system qualities.

The organizational breakdown is depicted in Figure 10. The corporation maintains a relationship with society through their markets, branding, and reputation. It consists of corporate entities that set objectives and constraints to the product divisions.

At the lowest level, we find the product families consisting of individual products. They are part of a product ecosystem with an upstream supply chain as well as a downstream chain of customers. They need the products to support their own business. Research on circular economy explores how organizational structures must evolve in future circular economies; this is beyond the scope of our work.

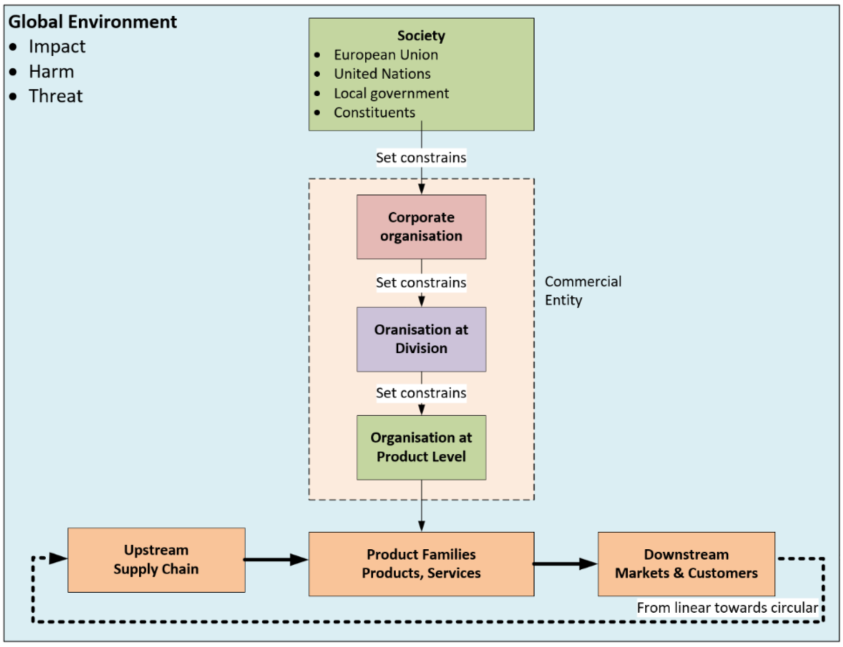

Figure 10: Almost every Dutch high-tech company is now part of a bigger global corporation. This may increase the complexity of dealing with changes, for example more focus on ESC to reduce impact on the Global Environment. Changing from a linear to a circular business model dramatically reduced impact, but this requires involvement and alignment at all levels.

3.3.1 Example

Today, many Dutch High-Tech industries are incorporated into a larger globally operating corporation. Companies that are part of these corporations must comply with the corporate objectives, policies and strategies. In the organizational breakdown structure, as presented by Figure 10, a division has a product portfolio which has a clearly distinct position within the corporate level. For example, within Canon Inc. this refers to the Canon Production Printing (CPP) division, headquartered in Venlo, with additional sites in Poing and Timisoara.

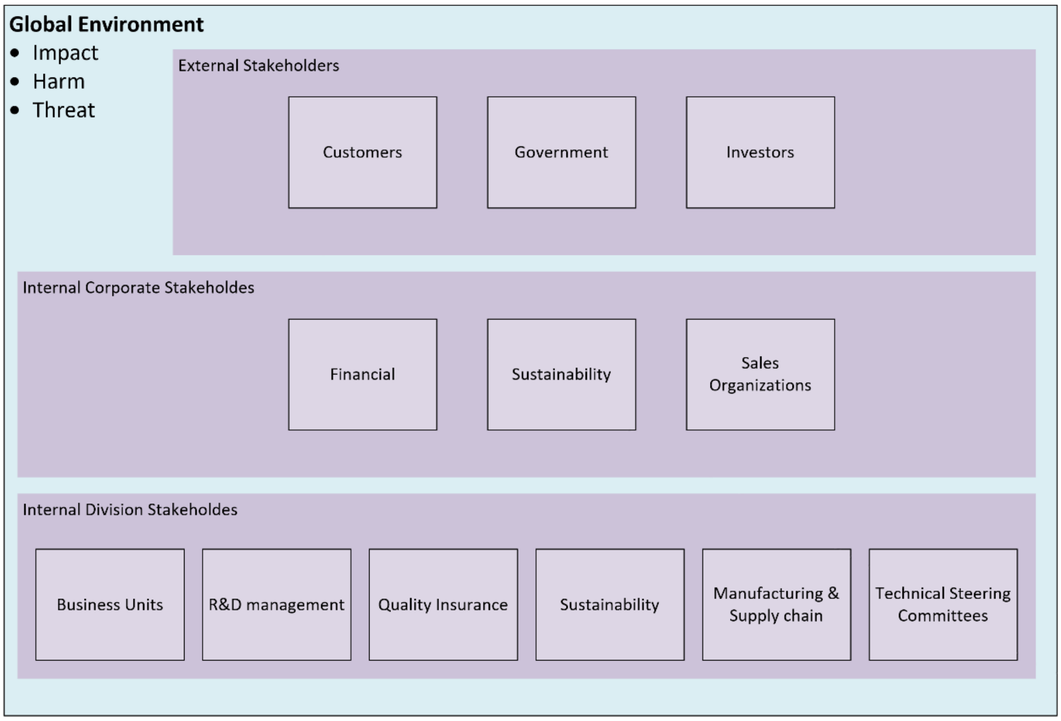

Figure 11: A map of stakeholder map from a typical high-tech company which is pursuing for more ESC related focus on their business and product portfolio.

Figure 11 depicts the stakeholder map as we found by our research. The number of stakeholder classes within the corporate body is substantially larger, compared to the amount of external stakeholders. A first observation is that for a substantial change in policies, for example more support to ESC related subjects, the internal alignment requires much more effort. On the other hand, we might have oversimplified the external stakeholders map because there is not a single government, customer or investor.-Future research on the organizational aspect in support of B-A alignment for circularity is needed.

3.3.2 Summary

This perspective connects the view of the business context in which the company operates to the technical system qualities chosen to satisfy the market needs. The roles and owners (or lack thereof) are important to identify as they are the ones giving requirements and budgets.

3.4 The Architectural Perspective

In the Architecting perspective, we start from a system level model, which includes requirements and parametric definitions. Through the aspects, we can reason to the realization, which is defined by the sub-systems and the building blocks. We present this in Figure 12 by the left structure. The linking pin are the aspects, which includes the system qualities and other important concerns, for example various kinds of costs. Defining the most optimal solution results now in balancing these aspects in a trade-off and decision-making process. A proven approach is quantification and budgeting.

The Logical Sub-systems and Building Blocks are the realization structure of the SoI, where the Building Block include the technology components. These components are assessed on ESC during the initial stages of such innovations. A typical approach is the Life Cycle Assessment (LCA). However, in the early phase this method is far from being precise, as it requires a high level of detail to provide meaningful results - a level of detail that is typically unavailable in the early development phase. Consequently, technical properties are usually specified within broad ranges resulting in substantial uncertainties, which directly influence the involved aspects and trade-off and dilemma thinking.

Compared with existing products (that include limited ESC related concerns), we found that there is no fundamental limitation to include more ESC related design decisions as long as stakeholder needs and concerns could be expressed in requirements and constraints. This is depicted in Figure 12. On the left side shows the description of an existing system. The right side illustrates an imaginary change case. New stakeholders add additional ESC related needs and concerns to the existing SoI.

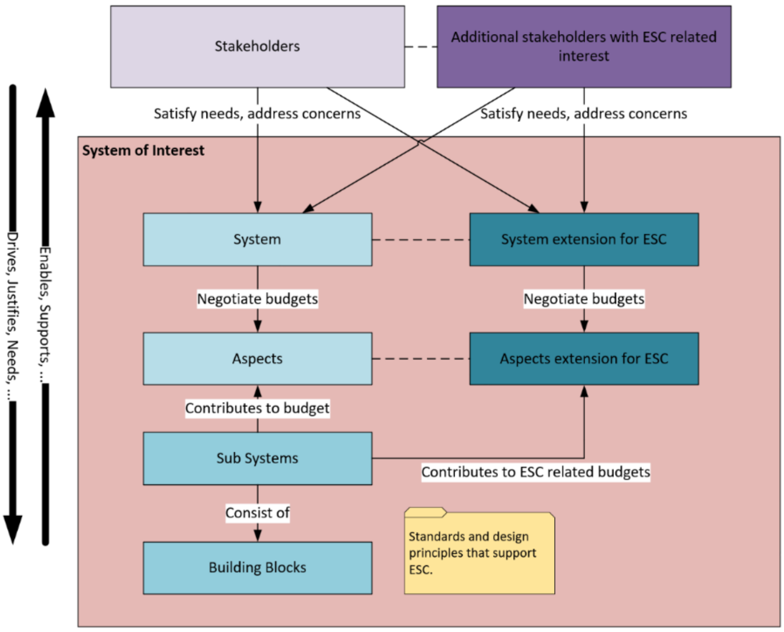

Figure 12, When we extend an existing architecture with ESC related concerns, this may result into new system demands and new aspects driven by existing or new stakeholders. However, the approach is unchanged.

Now the balancing, dilemma thinking, and decision making must be done over more aspects, but the principle remains the same.

Architects incorporate these aspects in the DAARIUS reasoning structure by adding them to the system level requirements. Furthermore, this may introduce new aspects that previously were not relevant. In response, the architects of the subsystems must take these new aspects into account. Building blocks may be affected and in some cases, existing technologies must be replaced. This requires substantial redesigns of building blocks. These changes could be supported by new design guidelines, technical standards, or design constraints. For example, an existing SoI could be made more sustainable by removing toxic materials, reduction of energy consumption during its use phase, or enforcing recirculation of used materials after decommissioning.

3.4.1 Example

We consider an existing industrial print system that is already in the market, depicted by Figure 13 on the left. Due to a new stakeholder, environmentally unfriendly materials must be replaced by more eco-friendly alternatives. This need arises from the Sustainability Department and may enforce new government regulations. Consequently, a new aspect “Environmental Friendliness” is added. This new aspect sets new budget constraints that must be considered in trade-off analysis by relevant Sub Systems and Building Blocks.

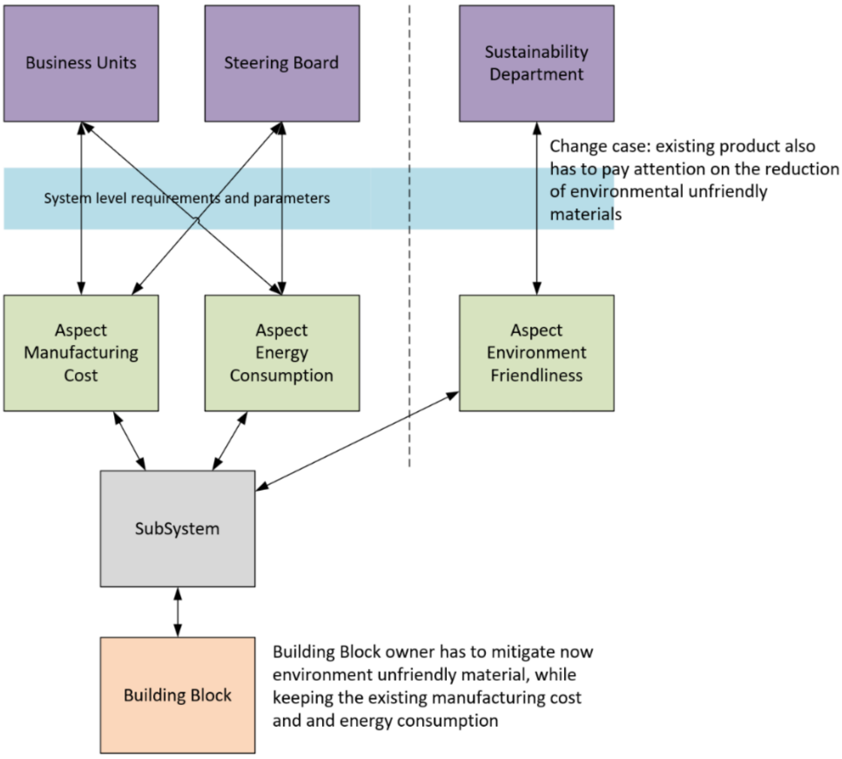

Figure 13: Example of a reasoning network. A Building Block owner must mitigate environmental unfriendly materials, because a new stakeholder (the Sustainability Department) issues new needs and concerns. However, needs from existing stakeholders must be respected.

The trade-off space is more complex since a new aspect on environmental friendliness must be considered as well, but the approach applied can be the same. Making ESC a mature aspect with early-phase estimation models is still a challenge and remains an area of future research.

3.4.2 Summary

This perspective connects internal stakeholders representing market and business priorities to the domain of technical trade-offs between top-level system qualities considering their priorities and budgets. It also connects these top-level system qualities to properties of technological innovations that are detailed in relation to the realization architectural layer.

Whereas such frameworks already exist, what is new here is that the insights gained in the analysis of the business network directly reflected in the requirements for top-level qualities.

We discussed the use of DAARIUS to structure the FCR side of CAFCR to support development in (large scale) R&D organizations. We found that DAARIUS could support more demanding ESC related concerns.

3.5 Connecting three perspectives

The Business, Organizational, and Architecture Perspectives are modelled using both formal and informal methods and tools. For the Business Perspective, we used the e3value method, for the Architecture Perspective the DAARIUS methodology and the Organizational Perspective was modelled with informal diagrams based on the company high level organigram. This brings us to the question how to integrate the concepts from the three perspectives shown in Figure 6, and more specifically how do they interface with each other?

The DAARIUS methodology recognizes **stakeholder maps** while the e3value modelling recognizes **actors**. We made the connection to map the actors of the corporate entity (Figure 8, Industrial Printer Company) over the External Stakeholders (Figure 11, upper layer). In this way, this corporate entity can be seen as a **black box** interfacing to its context while the stakeholder map to open this black box and show what is inside. More detail is provided by the other stakeholder layers and further by the DAARIUS reasoning structure (Figure 13). This distinction will be made explicit in future refinements of the stakeholder model.

There is a difference in semantics between value exchanges and stakeholder concerns that affects how they can be mapped. In e3value modelling, actors exchange monetary and non-monetary values, whereas in DAARIUS we represent stakeholders' needs and concerns. If both related to the same quantitative property, the mapping is straightforward. When needs and concerns are more qualitative, partial mapping is possible through appropriate translations. However, for needs and concerns that cannot be translated directly into value exchanges, needs addressing in future work.

The actors identified in the Business Perspective can be businesses (companies), their customers that can be also other businesses or individuals; suppliers; investors, legal entities. By exchanging values, each actor benefits by getting revenues or by getting products and services they need. One of the actors, the high-tech company, offers new products or features, that may be based on the technological improvements. In the value model, we estimate how this can bring the company revenues. If there is no solid architecting underpinning by the Architecting Perspective, these offerings stay assumptions.

The business value network (e3value model) is constructed from the viewpoint of the organization in focus, using the best available information, with added where necessary, assumptions or abstraction. When additional detail is required, the model can be extended incrementally as more information becomes available or as collaboration opportunities arise.

3.5.1 Scenario-based input and what-if analysis

The quantified properties in the models created in the business and architecting perspectives take input based on the assumptions on the future market, business model, ESC parameters and technology innovation.

An input from **a market scenario** takes assumptions on the market needs and related quantities. It reflects assumptions on future regulations, stakeholder interests, customer wishes and their valuation of ESC-related features. For example, a market scenario can be that CO_2 emissions are taxed with a certain amount of money and that the customer will buy only products with some green labels. Or it could be a market in which the customers do not see value in ESC and regulations do not ask for CO_2 reduction or repairability or recyclability. Or any other scenario in-between these two extremes.

An assumption about a **business model and specific ESC offering** describes what ESC value the business offers and how, and at what approximate price, and assumed costs. For example, a business can offer a product optimized to speed up production when the weather is sunny and solar cells on the customer's roof provide green energy, as an ESC feature. A business model can be product as a service or exchange of an old product for a new one, so that the old one can go into a remanufacturing program.

The **technology innovation** selects one technology improvement and its technical quantified characteristics, for example a component made of 50% lighter material, or a coating made of recycled plastics.

Figure 14 shows the dependencies between the scenarios. Based on the assumptions on how the future markets will look like, selected business scenarios are applied to models. This can go top-down from the market need and check if there is the technology innovation needed. Or it can go bottom-up, to check if there is a market for the technology innovation.

While architecting is more focusing on the definition and manufacturing of cutting-edge high-tech solutions by technical innovations, the business has a strong focus on value creation by understanding the markets with their customer needs. Business scenarios play a role in connecting both worlds.

The scenarios play a role with dealing with uncertainties and making explicit assumptions about three aspects.

Figure 14: The business scenarios play an intermediate role between market scenarios and technical innovation.

Quantitative relationships are established by linking the properties of the technical architecture, such as machine features and ESC benefits, to business offerings and market requirements. For example, an ESC offering like a machine with reduced energy consumption translates into top-level system qualities, such as power, cost, performance, and CO_2 reduction. The specific values offered to the market are based on technical capabilities quantified through architecting analysis. Improvements in ESC aspects, such as reduced component weight or refurbished parts, result in measurable benefits like lower emissions or enhanced circularity indices for both the company and its customers.

3.5.2 Summary

Answering the research questions from Chapter 1.3 we integrate business, organizational and technical perspective through qualitative and quantitative relationships, scenario-based modelling to reflect assumptions related to uncertain aspects in all three perspectives.

The aim is to enable the product architect and his stakeholders to discuss, scope, quantify uncertainties related to introduction or enhancement of ESC related properties, and to align technical capabilities and market opportunities, so that the decision-making is explicit and informed.

4 Conclusion and future work

We presented a way to combine insights from Business, Organizational and Architecting perspective, in the context of ESC, in the early stages of product architecting. The input from the assumptions of market, business and technology scenarios determined the scope and quantitative values in the individual methods, and it also related them. We used the methods of e3value, combined with the concepts of sustainability engineering, and DAARIUS methodology.

Coming back to the research questions from Chapter 1.3, we discuss the learnings, limitations, as well as pointers for where future research.

Research question 1: How to effectively do business and architecture trade-offs and jointly innovate for ESC?

As discussed in Chapter 2, existing approaches range from extending MBSE toolchains with LCA capabilities, to using circular business model frameworks, to applying systems engineering standards such as ISO 15288 or architecture frameworks such as TOGAF. These methods each address parts of the challenge, such as quantifying environmental impact, modelling business propositions, or structuring architectural decisions, but none provide an integrated way to reason jointly about business models, organizational roles, and architecture trade-offs in the early stages of ESC innovation. Our work positions itself in this space by combining lightweight ecosystem modelling, architectural reasoning, and stakeholder mapping into a coherent framework tailored for high-tech product development.

We propose a reasoning framework that connects reasoning about future markets, business models with technical innovation in architecting context. The first validation shows that the framework helps scoping and structuring the ESC-related problem analysis. This problem analysis contributes to specifying and aligning stakeholders' needs and concerns.

Research question 2: How to integrate sustainable design principles and circularity into an architecting framework?

Our findings show that using the framework, it is possible to translate ESC concerns into requirements and relate them to the product design. We found that the architecting framework as discussed in Chapter 3.4 can address ESC related concerns and technical solutions. If ESC concerns can be translated into requirements, architects, designers and engineers can handle this and bring it into the product design, applying design principles and technical standards. The same holds for the e3value business network model, with added ESC information they can visualize relevant network and value exchanges. Our learnings are as follows.

1. **Scoping:** The framework is useful for identifying relevant actors in the business ecosystem and the value exchanges that matter for ESC aspect at hand.
2. **Stakeholders explicitly described**: It makes the relationships between market and business view and internal organization stakeholders explicit and visible. Existing owners and the strength of requirements enforcement makes it explicit what ESC requirements are present, and which lack an owner.

The complexity and interdependencies of these require further research.
3. **Decision-making transparency:** By relating properties of technology innovation solutions, system qualities and market offerings make these relations explicit. The assumptions, especially those applied to future uncertainties are documented and visible, so that decisions can be traced.
4. **Value networks influence architecting decisions**: The framework demonstrates how the insights from the value network influence architecting decisions.

So far, the framework has been designed and validated on a case related to the energy reduction aspect of ESC. Next to further validation, we envision future research activities in direction of circularity.

Further research directions are as follows. Our approach has limitations and we identified questions that require additional investigation. For clarity, we group these directions into three themes.

Circular strategies

- Representing non-monetary ESC values, such as environmental or social impacts, or brand reputation, is important because it influences decision-making. However, translating them into quantified value flows is not straightforward. Future research should address how these important “intangible” ESC values can be incorporated into early architecting decision-making within our framework.
- A natural next step is to investigate how the framework performs when applied to broader R-strategies [36] [37] [38], such as Reduce, Reuse, or Remanufacture. The main question is how to scale the framework to more complex value networks that involve multiple circularity KPIs.

BAPO

- We used the BAPO structure to position models of business value networks, internal stakeholders in the organization, and architectural trade-off models. The Process aspect was out of scope in this project; however, the process aspect and development workflows are an important aspect of successful introduction of new ESC qualities. The next step is to investigate what process elements need to be modelled to support the framework goals.
- Stakeholders in the organisation are important for ESC governance. Our current modelling relates stakeholders' needs and ownerships to the “weights” of system qualities in the trade-off space. Further research is needed on how to deepen stakeholder modelling, understand their influence and combine socio-technical aspect with the reasoning framework.

Tools

- For this work, we used (domain) modelling methodologies and tools. The question remains how to combine them with MBSE tools.
- Although not explicitly mentioned, this framework may relate to multiple objective decision-making processes, with more detailed formulas. The questions to investigate are: Could they use our finding as an input or a framework. Could we connect to their detailed formulas in the early phases of architecting?

In summary, future research should focus on validating and scaling the framework to extend to broader circular strategies and process and organizational aspects that affect both business and architecting activities.

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