Systems architecting for sustainability in high-tech industry

Canvas 2024 project report

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Summary

For industry, including high-tech manufacturing industry and OEMs, it is foreseeable that new regulations will be stricter on environmental sustainability and circularity indicators. The customers (who are businesses themselves) will face the same regulations and will therefore increasingly push their suppliers to comply. To prepare for this foreseeable future, companies should act now and integrate environmental sustainability in their development process.

Environmental sustainability and circularity (ESC) are more than just yet another quality. Their problem scope extends beyond the technical system, including uncertain future regulations, changing market demands, and dependencies across the value chain. Introducing ESC therefore requires integrating ESC considerations throughout the architecture, the business, and the wider ecosystem.

In this report, we show how to take the next steps in making environmental sustainability a key product aspect. Before, or in parallel with, applying and tailoring classical systems architecting and systems engineering methods, systems thinking techniques help in stakeholder alignment. We illustrate systems thinking can be uses to improve alignment among system architects and between system architects and R&D roles interfacing with the business. This paves the way for future alignments between R&D and business, logistics and manufacturing, and eventually with the external suppliers and companies in the value chain. In addition, we provide guidance for the early architecting phases for environmental aspects, especially for the roles of the architect and LCA assessment.

1 Introduction

1.1 Background

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 2024. The topic addressed in this project is systems architecting for **environmental sustainability and circularity (ESC)**. It is a continuation of the work started in the Canvas 2023 project [1].

1.2 Introduction to the problem

The high-tech manufacturing and OEM (Original Equipment Manufacturers) industry continues to face strong pressure to accelerate innovation to stay competitive, delivering increasingly advanced machines with higher performance and quality. In addition to the drive for better performance, sustainability and circularity have become increasingly significant in recent years.

The shift towards more sustainable and circular products is driven by several factors.
(1)   Regulations requiring reporting on sustainable and circular practices. Current trends indicate that regulatory bodies will ask not only to report, but also to reduce environmental impact and increase circular practices [2].
(2)   Customers are asking for machines that use less energy and are more sustainable; they themselves also need to follow the above-mentioned regulations.
(3)   The need to reduce dependency on raw material supplies and avoid supply chain disruptions.
In addition to these external drivers, there is the ambition of companies (and individual employees) to do good for society, as reflected in Corporate Social Responsibility (CSR) initiatives.

The topics of sustainability and circularity are not new. Companies have been working on various aspects of sustainability and circularity for a long time. More energy-efficient products and products using less material have been developed, but the main driver there was to cut costs. Nowadays, the regulations and customer demands have elevated sustainability and circularity to the status of important product qualities.

Given the trend in the coming years to not only report but also reduce environmental impact, it is important to integrate sustainability and circularity as the system quality into the (reference) system architecture. Considering the long development time and lifespan of high-tech manufacturing machines, these are becoming integral aspects, rather than mere cost-cutting measures. Considering sustainability from early development phases, including early architecting phases, products (and businesses) are better prepared for future regulations and customer demands related to sustainability.

To summarize, in current industrial practice, environmental sustainability and circularity (ESC) are not yet treated as a customer- or business-level "-ility" at the product level. Compliance with reporting requirements is often achieved through improvements at factory or

process level, such as energy efficiency measures, rather than through product-level architectural decisions. As a result, ESC is frequently approached as a constraint to be satisfied, rather than as a quality to be actively designed for. Ownership of ESC at product or system level is often unclear, and while large amounts of data may exist, relevant information for decision-making is fragmented. At the architecting level, connecting data to system choices and trade-offs, remains difficult.

At present, most high-tech manufacturing companies do not yet perform explicit ESC trade-offs at the architecting level. Initiatives are predominantly technology-driven and bottom-up, leading to local optimizations within machines or subsystems rather than system- or portfolio-level improvements. There is a growing understanding that an integrated approach across business, architecture, process, and organization (BAPO) [3] is needed; however, this is still emerging in practice. While boards increasingly set high-level CO_2 reduction targets, satisfying the reporting directives that are part of their external communication, translation to concrete product-level decisions is often missing. Current efforts focus primarily on CO_2 footprint reduction, which is a well-defined KPI and connects to the Scope 1 and Scope 2 emissions. Once these relatively straightforward improvements are achieved, more complex challenges are expected to emerge, especially those related to material scarcity, supply chain resilience, and circularity.

Last year, we identified the following challenges in architecting for sustainability and circularity [1].
- The need to have a scope broader than that of a product and involve other departments (such as manufacturing and logistics), as well as other companies in the ecosystem (suppliers, recycling companies, supply chain) [4]. In relation to these findings, we recommend explicitly distinguishing the scopes of *product*, *enterprise,* and *ecosystem* and clarifying the associated responsibilities.
- In the early architecting phases, many uncertainties (future regulations, future market conditions, future enabling technologies) make sustainability assessment challenging
- The transition to sustainability and circularity is not a purely technical problem; it also requires changes in business practices.

Our approach is to enhance existing architecting methods to effectively address sustainability. We envision a "toolbox" of methods and techniques to be used in different phases of architecting for sustainability, with guidelines what to use in each phase and for what specific purpose. As many companies are at the beginning of introducing ESC as a key quality, one of the first challenges is effectively working in the initial architecting phases. This report focuses on those early phases.

1.3 Research questions

We position our research question in the context of a high-tech manufacturing (or OEM) company/organization. ESC qualities have already been addressed as part of saving costs or energy. Now, ESC (as a set of qualities), is growing in importance: new regulations are coming, and customers (businesses themselves) start to ask for sustainable products to improve their own reporting obligations. There is no dire pressure at this moment, but in the future there will be. Most high-tech companies express the ambition to be ready, and even best in class, once the ESC-related regulations take full effect.

Our focus is on the early architecting phases; in these development life cycle stages, there are no system requirements and design yet (the ISO 42000 standard calls these phases concept development and initial system architecture definition [5]).

Environmental Sustainability and Circularity are each compound concepts on their own. Our approach is to start in more detail with the Environmental Sustainability of ESC, specifically focusing on the CO_2 equivalent of emissions, and gradually introduce circularity concepts. In our earlier case studies, circularity and related R*-strategies [6] were discussed as means to reduce the CO_2 footprint. However, fully covering circularity requires additional research and is planned as future work.

In this context, the overarching research question for this year is as follows:
RQ1: How to introduce ESC as a quality of high importance in future products, in the early stages of architecting and design?

We break this question into two parts:
RQ 1.1: When elevating the importance of ESC and introducing it as a set of highly important qualities, how to achieve a common understanding between business and architects regarding the sustainability problem?
RQ 1.2: What guidance is needed to support product architecting when creating environmentally aware solutions?

This breakdown reflects two concepts of the BAPO approach that recognizes that the product families development approach should find the best possible fit between interrelated aspects of business, architecture, process, and organization [3]. Ideally, business strategy drives architecture, which drives processes, which drives the organization. In a realistic, non-greenfield situation, bi-directional dependencies between them exist [7]. The Process and Organization concepts are planned as future work.

1.4 The audience

The audience of this document includes practitioners (architects and R&D managers in high-tech manufacturing and OEM companies) introducing ESC as a quality of high importance. It also includes researchers in the areas of sustainability and circularity for manufacturing and high-tech industry.

1.5 Report outline

The report is structured as follows. **Section 1 introduces** context, goals, and research questions. **Section** 2 **addresses RQ 1.1** and the topic of business architecting alignment. We will show how we applied system thinking techniques to make the first step towards business stakeholders' alignment. **Section 3 addresses RQ 1.2.** The focus is on guidance for the architect when making decisions on proposed concepts in the early architecting stages. **Section 4 concludes** the report.

2 Business-Architecting alignment for ESC qualities – first steps

This section focuses on the following research question.
RQ 1.1: When elevating the importance of ESC and introducing is as a set of highly-important qualities, how to achieve a common understanding between business and architects regarding the sustainability problem?

2.1 Introduction

Typically, companies have high-level sustainability goals, including environmental goals and CO_2 emissions reductions. Circularity is also part of the goals. In our study [8], we observed that within the organizational structure of our partners, there are multiple levels for translating top-level corporate pledges to UN goals and ESC targets down to the product level. This translation is still work in progress in many companies.

To support the ESC objectives, businesses need to understand what is technically possible, from architectural and design choices to developing and using new technologies. Conversely, architects need to understand the company's short and long-term strategy to achieve the ESC goals. To summarize, strategic alignment between architects and business helps architects focus on the solutions to achieve the strategy and assist the business in formulating realistic goals.

The techniques and methods of (model-based) systems engineering and systems architecting prescribe the architecting process as well as the process to relate capabilities to top-level systems requirements. But before that, different stakeholders within a company should achieve a common understanding of sustainability (problem). Given the complexity and broad scope of the sustainability topic, first different stakeholders within a company should achieve a common understanding of the sustainability (problem). To do this, systems thinking is needed before going to other more formal methods. Systems thinking helps understanding and structuring the problem; furthermore, it allows for explicitly showing interconnections of different concepts, stakeholders, drivers within the system; this can guide discussions in the early stages of introducing ESC in the company.

In the remainder of this section, we build on the systems-thinking structure proposed by [9]. We first introduce the conceptual models they used; next, we show how we used their structures to guide the stakeholders and how we extend it with concrete elements needed for early alignment in a high-tech manufacturing company setting.

2.2 A systems thinking perspective

In their paper [9], the authors provide a systems-thinking framework for analyzing how industrial organizations currently approach the integration of sustainability as a product quality. Their conceptual model (Figure 1) outlines the path from high-level sustainability ambitions, originating in international and national policy frameworks, to organizational goals and the resulting system-level requirements and qualities.

The authors address obstacles in the area of policies, engineering decisions and data availability, and complexity. By positioning organizational goals between policy ambitions and system-level requirements, the structure highlights where gaps and dependencies in current industrial practice emerge.

Together with their conceptual model in Figure 1, Figure 2 (adapted from Muller) shows how sustainability as a quality is integrated into system development. When identified as a key driver, sustainability maps onto system requirements and qualities.
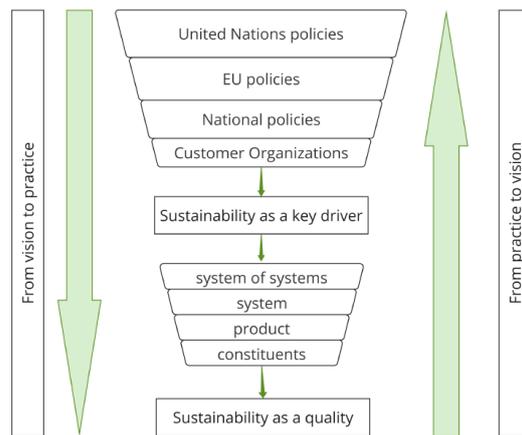
Figure 1: (copied from [9]) Relating high-level ambitions towards goals and (later) system requirements.
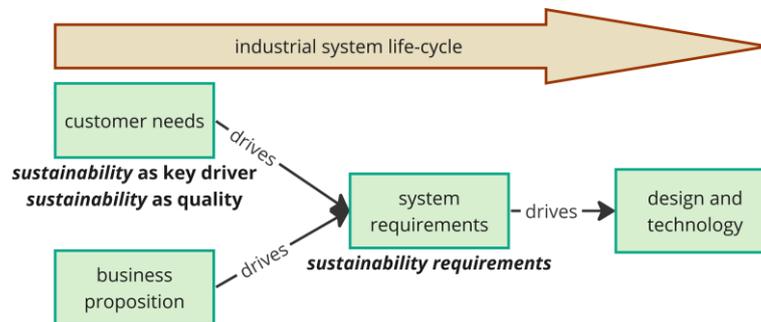
Figure 2: Sustainability as key driver and a quality (copied from [9])

Although the authors note that a collaborative environment is needed for stakeholders to discuss sustainability drivers and indicators, they do not describe how such sustainability-related discussion should be structured in a single organization, involving both business and architecting roles. In the next subsection, we apply and extend these conceptual models to support early stakeholder alignment within an organization.

2.3 An approach towards a common understanding of ESC

This subsection presents the approach we designed to help business and R&D stakeholders develop a shared understanding of Environmental Sustainability and Circularity (ESC) in the early stages of architecting. The approach was applied in a workshop setting with Canon Production Printing (CPP). The detailed outcomes are confidential, but the structure and rationale of the approach are generalizable to high-tech manufacturing (OEM) organizations.

The steps described below provide a practical structure for combining systems-thinking conceptual models with guided discussion steps. These models help stakeholders articulate drivers, pains, and interdependencies across the value chain, while the session format provides a focused setting to explore improvement directions. This format illustrates how the approach can be applied in an industrial context to translate high-level sustainability ambitions into shared, concrete insights.

The objective is to establish a common problem understanding, align different stakeholder viewpoints, and support interaction between business and architecting decisions related to ESC. The approach does not aim for completeness in a single session; rather, it helps organizations identify knowledge gaps, unknowns, and next steps.

Participants and preconditions. To achieve meaningful alignment, participation from the following roles is recommended:
- Business representative – they provide strategic context for jointly shaping product-level expectations.
- R&D manager(s) interfacing the business and owning sustainability goals
- Regulatory experts who clarify obligations and future trends.
- System architects who own the ESC problem at product and system level.
- LCA expert as support for quantification and interpretation

Organizations differ in their maturity in organizing ESC-related responsibilities; some may not yet have dedicated roles or committees. The essential requirement is to bring together people who influence ESC-related decisions

The guided discussion of four major (timeboxed) **steps**, each designed to surface stakeholder perspectives in a structured manner.

Step 1: Introduction – creating a common starting point
The goal in this step is to gather and establish the following.

- Available ESC-related data,
- Known bottlenecks in the value chain,
- The product's position in the customer workflow,
- Relevant value network elements (suppliers, customers, end-users, recyclers).

In this step, the workshop organizer (someone with an assignment on ESC) provides information that creates a common starting point. The information encompasses the available data on sustainability and bottlenecks. For example, charts showing the biggest CO_2 contribution. If they are not available, rough estimates (based on traceable facts) should be made.

High-tech OEMs provide product families to their customers, covering different market segments. Many of them express their ambition to have a whole portfolio of their products sustainable. However, when introducing or improving ESC, we recommend focusing on **one specific product** in the early development phase. This provides concrete examples, and helps avoid the trap of speaking in vague, high-level terms. In later steps, the same workshops can be applied to product lines, platforms and portfolios.

This step also connects to the conceptual models introduced in Section 2.2. Figure 1 and Figure 2 connect high-level sustainability ambitions with organizational goals and system-level qualities. By providing concrete data on an example of one product for one specific ESC aspect, e.g. CO_2 emission reduction, and identifying the associated bottlenecks, Step 1 makes the relationships shown in the figures tangible for the specific context of the company.

Further application to understanding the context required additional conceptual models and diagrams. For the specific case, the following were used:

- The value flow in the market (business perspective), for example an overview of the value exchanges in the selected product line that the business provided as an informal value-flow map.
- A typical workflow at the customer premises, for instance showing how the machine operates alongside other manufacturers' equipment in the customer's end-to-end process.
- A typical, high-level product flow, for example a simplified outline of the product's main lifecycle stages to indicate where the company interacts with suppliers, customers, or other actors.

If the value network and workflows are not available, we advise co-creating them during the workshop. The value of these workflows is to understand where the bottlenecks are, what the waste streams are, and to shift thinking toward all actors in the value chain and their needs, rather than focusing on technical details of each participant's domain.

Step 2: Identify the sustainability drivers, pains, and concrete examples
After the value chain is understood in Step 1, in Step 2, the goal is to identify for each actor in the value chain the list of drivers, pains and concrete examples.
The structure of the output is as follows:

- Who – one of the actors in the value chain
- Driver – what is their driver, not only for sustainability but also for the business, related to sustainability
- Pain – what is difficult related to sustainability drivers
- Example – concrete example

The results can be grouped into short-, mid-, and long-term categories. This helps structure later concept generation and prioritization. When inventorying the drivers, besides sustainability, think of the following: (a) Customer Drivers and customer value proposition; (b) Business drivers and business proposition

Step 3 - Generate and Select ESC Improvement Concepts
3.1: Identify options to improve the situation (concepts generation)
Participants brainstorm potential improvements across the areas shown in the framing of Business value – Customer value - Top-level Requirements (qualities and KPI) – Design and technological solutions. Examples include business model adaptations, customer-value enhancing features, architectural or technology choices, and technological innovations.

Step 3.2: Concept selection
The group merges similar ideas and selects 3–5 concepts for further evaluation.
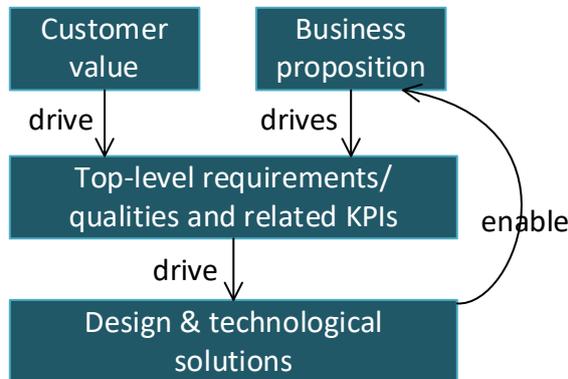

Figure 3 (redrawn from [9], adding that design and technology solutions enable business propositions)

At the workshop we held, when analyzing the improvement options, we found the following non-mutually-exclusive improvement directions.

Improvement direction	Description
Quantifying sustainability aspects	1. For reporting: This step is meant to help customers to address sustainability reporting needs – to learn their (future) needs and ensure proper system development planning 2. For Steering/improving (Next increment): The next step is to advise when/how use the system at the customer's business to be more sustainable 3. For eco label certification & Sustainability branding Adding sustainability reporting as a feature has relatively low barriers for creating a business case, and it lies within the company's control. It complements ongoing initiatives such as reducing energy or material usage.
Modular approaches	Modular approaches already exist in platform design. Introducing additional modularity that supports both platform and ESC goals is a mid-term approach and lies within the company's control
Reuse and recycling strategies	This category is likely to have the highest sustainability impact. However, it extends beyond the company boundary and requires an ecosystem approach.

Step 4: Define evaluation criteria and assess selected concepts
4.1 Create Evaluation Criteria:
Participants propose criteria such as sustainability impact, development feasibility, business value, customer appeal, technical difficulty, and the effort needed to develop them. These are condensed into 5–10 key criteria.

4.2: Assess the top concepts

In this step, a table is created with the list of concepts and criteria in rows and columns. Participants should rate them on a scale of 1-5. These ratings are by any means not the final result. Their averages should not be taken as the final direction which concepts to select.
The ratings are only the first step in their assessment; they support discussion and reveal assumptions and disagreements.

Step 5: Reflection and synthesis
In this last step, the group looks at the concepts and the assessment results and discusses them. Participants reflect on surprising insights from the ratings, missing information or unclear assumptions, implications for business strategy and technology development. This step transforms the workshop from brainstorming into structured alignment

2.3.1.1 Summary

The approach described in this section provides a structured way to align diverse internal stakeholders' perspectives, by applying systems-thinking concepts to actionable company-level discussions. It provides the basis for further work on architecting for ESC. As the approach has so far been applied within a single company context, further validation across additional industrial settings is needed.

3 Guidance to support environmental-aware architecting

This section focuses on the **Research Question RQ 1.2**: "What guidance is needed to support product architecting when creating environmentally-aware solutions?

The project paid particular attention to environmental impacts to ensure sufficient study depth. Circularity aspects were investigated less and are suggestions for future work. Given this focus and the project learnings, the **answer** can be summarized as:

> "Architecture frameworks (such as CAFCR) provide sufficient space for integrating environmental impact concerns into the solution. The nature of architecting wouldn't change much. Yet extra guidance is desired to address the solution complexity. It includes: (1) principles, (2) conversion assumptions, metrics, scope, lifecycle decisions, (3) company policies, and (4) and information exchange support."

The latter two points (policies and information exchange support) will provide inputs to the company's processes, which is a topic of a follow-up section.

Importantly, a specific focus on such a broadly understood topic as sustainability will introduce new connections and stakeholders. It will call for architects who, empowered by the listed guidance to handle the complexity, will elicit, consider, and address diverse stakeholder concerns. In this way, the nature of architecting work will not change.

This section is **structured** as follows:
1. Overview of *architecture frameworks* known and used in the high-tech domain;
2. Selection of *a subset of the frameworks* that are particularly relevant for (product) architecting for sustainability;
3. Methodology how the project addressed the research question;
4. An outline how the subset of frameworks can support environmental impact concerns;
5. A list of *topics* that would benefit from having additional information/guidance.

After providing conclusions, the section ends with recommendations for future work.

3.1 Background: Overview of architecture frameworks

This subsection briefly overviews several architecture frameworks recognized in the high-tech industry. The term 'architecture framework' is used in a broad sense according to [10]: 'conventions, principles and practices for the description of architectures established within a specific domain of application and/or community of stakeholders. This section does not

differentiate between (architecture) 'model' and 'framework', as the models listed below can be perceived as frameworks by practitioners. After briefly outlining the frameworks for the interested reader, the next subsection relates them to (high-tech) product architecting tasks.

4+1 view model can be used to describe the architecture of software-intensive systems, based on the use of multiple concurrent views [11]:
- **L**ogical view: functionality the system provides, e.g., as the object model of the design;
- **P**rocess view: system processes and how they communicate, e.g., the concurrency and synchronization;
- **P**hysical view: deployment, topology, connections, e.g., mapping(s) of the software onto the hardware;
- **D**evelopment view: programmer's perspective, e.g., the static organization of the software in its development;
- **S**cenarios (as '+1'): a small set of use cases.

A3 method, initially developed for lean manufacturing, has been adapted for system architecting to capture and communicate architectural information. Each side of an A3 page provides either model or text view to close the 'gap' between a model and text description of a system [12]. The A3 text view helps to create an independent, self-contained view of the system. A set of A3 architecture overviews forms a repository of architectural knowledge.

CAFCR model is a decomposition of an architecture description into five views [13]:
1. **C**ustomer objectives (*what* the customer wants to achieve);
2. **A**pplication view (*how* does the customer realize their goals);
3. **F**unctional view (*what* the product does, incl. non-functional requirements);
4. **C**onceptual and **R**ealization views (how does the product does what it does).

This approach ensures a comprehensive understanding of the system in its context, facilitating better alignment with customer needs and more effective communication among stakeholders

IEEE 42010 standard [10] provides a comprehensive framework for the description of system, software, and enterprise architectures. Architecture viewpoints, architecture frameworks and architecture description languages are introduced for codifying conventions and common practices of architecture description. It specifies the required content of architecture viewpoints, architecture frameworks and architecture description languages.

MBSE (Model-Based Systems Engineering) is the formalized application of modelling to support systems requirements, design, analysis, verification and validations activities. It begins from the conceptual design phase. Applying MBSE provides significant advantage to project performance [14], if:

- the systems engineer holds a leadership role over engineering processes and
- an enterprise already has mature, well-documented, and enterprise-wide systems engineering processes.

The Scaled Agile Framework **(SAFe)** is a methodology to help large organizations implement agile practices at scale. It integrates principles from Lean, Agile, and DevOps to enhance productivity, quality, and time-to-market. It contains the levels of teams, programs, and portfolio, as well as the optional value stream level [15].

Six Sigma programme was developed in 1986 to improve quality and reduce defects in products [16]. Focusing on reducing variability based on data, it follows DMAIC (Define,

Measure, Analyze, Improve, and Control) procedure for quality and process improvements. Design for Six Sigma (DFSS) spans the entire development process from the identification of customer needs to the final launch of the new product or service. The use of statistical tools and designed experiments are seen as particularly helpful. Six Sigma can be closely connected to Lean Manufacturing to eliminate long cycle times or waiting times between value-added work activities.

TOGAF (The Open Group Architecture Framework) is a well-known framework for enterprise architecture [17]. It supports creation, planning, implementing, and governing enterprise information technology architectures. This framework is divided into four architecture domains: Business, Application, Data, and Technology, ensuring a holistic view of the enterprise. At the center of the framework is Architecture Development method, which can be tailored to the organization's needs. Enterprise Continuum includes both the Architecture and Solutions continuum (as implementations of the Architecture Continuum with defining reusable Solution Building Blocks).

V-model relates each phase of the development life cycle to its associated phase of testing [18]. The purpose of the model is to improve efficiency and effectiveness of system/software development. V-model can be related to management of system (and system documentation) elements. Commonly recognized concept pairs in the model are:

- Requirements analysis – Acceptance testing; then,
- Specifications – System Testing; then,
- Architectural design – Integration testing; then,
- Detail design – Unit testing.

The **Zachman framework** [19] is an enterprise-level ontology. It is organized as a 2-dimensional scheme that interrelates historical classifications of: 'Why-How-What-Who-Where-When' and 'Context-Concept-Logical-Physical-Detailed' (the way an abstract idea is transformed into an instantiated). The result provides the total set of descriptive representations relevant for describing an Enterprise.

3.2 Frameworks for architectural discussions on environmental impacts

Architecture frameworks have different goals and scopes. This project focused on answering the research question in relation to (high-tech) product architecting tasks through a case-based research. The A3 method and CAFCR fit that category. The following frameworks can be excluded based on scope and organization specifics:

1. Due on the framework's *scope:*
   - IEEE 42010: the standard can assist in creating architecture framework with diverse viewpoints. Being a higher-level framework, it is less connected to direct architecting tasks, such as architecture conceptualization and elaboration.
   - SAFe: due to its focus on synchronization of teams, rather than a system quality like sustainability;
   - Six sigma: the focus on eliminating defects and variability can be too early for new and less well-formulated system qualities like sustainability;
   - TOGAF and Zachman frameworks were excluded due to their focus on *enterprise architecture;*

      ☐   V-model: although this model is often cited in relation to system decomposition activities, it does not include many architectural concerns and supports architecting tasks less well;

2. Due to the specifics of an organization that collaborated on the case study:
   - ☐ 4+1 view model: often recognized by software architects, this approach is less used by high-tech system architects in the company;
   - ☐ MBSE: chosen to be investigated in more details later.

The remaining frameworks are the A3 method and CAFCR. They are particularly relevant for the study, as:

1. These frameworks are recognized by architects in high-tech industry and are used in the company that collaborated on the project.
2. CAFCR can be directly connected to the broader structure of BAPO (Business-Architecture-Process-Organization, see [20]. CAFCR's Customer-Application-Functional form commercial views, linked to the Business aspect. Functional-Conceptual-Realization views have a technical nature. The Functional view can be directly related to use cases. The Conceptual and Realization views cover design topics like functional decomposition and performance analysis correspondingly.

3.3 Methodology to answer the research question

To answer the research question, the project investigated (1) how CAFCR can help with architecting activities in the solution space (i.e., F, C, and R views) and (2) addressing which topics can help to guide an architect in their work.

The project focused on investigating CO_2 Equivalent (CO_2e) environmental impact (not explicitly on circularity). It included numerous (weekly) work meetings with a diverse group of experts. Experts included a reference architect, sustainability experts, food contact materials experts, and systems engineering experts.

To create insights, this project conducted a case study to answer a generalized question 'how might CO2e emissions change with a new function?'' The case assumed that introducing a new function is desirable. As Customer values and details of Application were not detailed out, the case scope concerned the *solution* (not a problem) domain of product architecting.

The case study followed several steps:

1. Choosing a use case.
2. Creating a template for how architecting and assessing specialists interact in the use case.
3. Collecting assumptions that the architect and the assessor should agree upon.
4. Identifying improvement 'hotspots' in the case based on flows of materials and energy.
5. Creating a CO_2e emissions estimate formula based on materials and energy consumption, and the amount of travels needed.

The next subsections elaborate on the answer to the research question.

3.4 Applicability of architecture frameworks to consider environmental impact

This subsection elaborates on the part of the answer: "Architecture frameworks (in particular, CAFCR) provide sufficient space for integrating environmental impact concerns into the solution."

The case study discussions are related to F, C, and R views of CAFCR as follows:

1. Functional: the case addressed a particular question 'h*ow do* CO_2e *emissions change if a system gets a 'pre-treatment' function?*" The Functional view of the CAFCR is directly concerned with such functions. The view assisted in specifying a function description with inputs (e.g., ink, paper, energy, travels for servicing) and outputs (e.g., printed media, waste and emissions).
2. Conceptual: the case considered a specific pre-treatment concept, which was worked out as a lab model. The using of a particular pre-treatment approach led to inter-relations between saving consumables (ink) by increased energy consumption.
3. Realization: The case worked out CO_2e emission estimates. Particular values like [kWh] per hour of printing, consumption [Liter/m2 print] were discussed and assumed. Then, conversion rates like [CO_2e kg per kWh] were detailed out. This provided CO_2e budget estimates over the printer's lifetime.

The discussions around F, C, and R views of CAFCR touched the (interrelated) topics important to the environmental impact. They resulted in structured answering the study question.

The A3 method can also support discussions on the listed topics. The A3 core overview includes Functional, Physical, and Qualification overviews [12]. The introduction of a new function fits into the Functional overview, the specific pre-treatment concept can be, e.g., related to the Physical overview, and the CO_2e discussions can be indicated in the Qualification overview.

In sum, a case study indicated that architecture framework like CAFCR and A3 can support structured discussions on environmental impact concerns.

3.5 Architectural guidance: topics

A system architect considers multiple topics when addressing environmental impact concerns. That architect can benefit from some guidance. This subsection elaborate on the following part of the answer: "extra guidance is desired to address the solution complexity. It includes: (1) principles, (2) conversion assumptions, metrics, scope, lifecycle decisions, (3) company policies, and (4) and information exchange support."

During this project several topics relevant to architecting decisions were discussed by the interdisciplinary project team. The team recognizes that sustainability can be seen as a collection of diverse concerns perceived differently by stakeholders. Aligning and addressing such a diverse set of concerns results in increased complexity of the topic. The increased complexity is a consequence of bringing together different perspectives, and it highlights why guidance is helpful for structuring discussions and supporting decision-making. This

subsection lists topics that were seen as useful to address in conversations with stakeholders. The list is not exhaustive.

To mention, the project team earlier identified and addressed two relevant topics:

1. **Principles** [21]; In this context, principles refer to high-level design rules, such as slowing, closing, and narrowing resource flows, that help architects structure discussions, focus on sustainability-driven decisions, and ensure alignment between business strategies and technical design choices.
2. **Techniques** to engage diverse stakeholders (e.g., design and communication tools);

After that, the project identified (based on the case study) other topics that can benefit from guidance:

3. Which **metrics** to be used. It includes expected law-required reporting. An architect should agree with stakeholders and experts on a **common denominator** and **conversion rates** (e.g., 1 km of travels leads to X kg of CO_2e emissions). An option: start with CO_2e for the initial iteration, then: consider rare materials.
4. Shared view on the **scope** of concerns (e.g., if energy consumption of high-tech equipment users should be included). Preferably, the scope should have a clear relationship to reporting structures, such as greenhouse gas (GHG) protocol and material lifecycle stages (e.g., extraction of rare materials);
5. What product **lifecycle options** are desired, incl. life duration and end-of-life options.
6. How **company policies** are operationalized as requirements on material footprint per product; energy consumption; and recyclability of high-tech products and the products they create.

Also, some guidance is desirable on which **information** (items) to use in:
1. cross-discipline collaborations, e.g., when an Architect and a sustainability Expert collaborate to effectively estimate environmental impacts.
2. ecosystem-wide discussion, such as supplier-originated information on environmental impact of subsystems.

To ensure effective communication, it can be desirable (subject to company-specifics) to improve architects' understanding/skills of life-cycle assessment (to communicate with experts and stakeholders). E.g., completing a course/certification.

Together, guidance can help an architect to consider (eco-friendly) functions of the system, such as:
- Support renewable energy integration into products through scheduling (due to its intermitted nature);
- Design for thermo-efficiency (e.g., advanced cooling);
- Incorporate data feedback on energy/sustainability impact from the field to the development.

3.6 Summary and recommendations for future work

This section outlined guidance that can support environmentally-friendly product architecting decisions. Based on a case study, it indicated that architecture frameworks (like A3 and CAFCR) can provide a structure useful for discussions about the solution space. Then, the subsection listed concrete topics where some guidance is desired.

Future research is desired to position this work in a larger context and assist high-tech companies in advancing their architecting practices. Topics to investigate (preferably, using a use cases-based approach) include:

1. How can Enterprise Architecture Frameworks, e.g., Zachman and TOGAF, assist (reference) system architects in resolving sustainability concerns in product development?
2. What guidance can help to make circularity-friendly architectural decisions?

4   Conclusions

In this report, we provide general findings from the Canvas project, a collaboration between Canon Production Printing (CPP) and TNO-ESI, at the end of 2024. The topic addressed in this project is architecting for environmental sustainability and circularity (ESC). It is a continuation of the work we started last year, by the Canvas 2023 project (TNO 202312091).

The context is a high-tech OEM company, introducing environmental sustainability and circularity. This year we focused mostly on the first, and partially on the second. Due to current and future regulations, companies and their customers (and their customers' customers) will have to give focused attention to reducing CO_2 footprint and improving circular practices. The problem is that customers are not asking for it yet, so it is not part of the current business practice and strategy. Companies pledge to UN sustainability goals, but as we go from these high-level goals of the top organizational layer, towards the projects and programs working on actual products, these goals are not yet concrete enough. There has to be alignment between the business and architects in transforming the business, the organization and architectures to integrate sustainability and circularity as key qualities.

In this report we focused on the following:
- Business-architecting alignment (first steps). We describe the workshop method and systems thinking approaches we used to align different stakeholders. Furthermore, we provide categories of approaches to consider when coming up with concepts for ESC improvement.
- Guidance for the architect in the early phases, when design options are still open, and LCA analysis cannot provide precise numbers.

For the Business–architecting alignment (RQ 1.1), we asked: When elevating the importance of ESC and introducing it as a set of highly important qualities, how to achieve a common understanding between business and architects regarding the sustainability problem?

The systems-thinking approach to co-create a shared understanding among the internal stakeholders helped establish a shared understanding of the ESC problem by structuring discussions across the value chain, exposing drivers and pains for different actors, and generating concrete improvement concepts. This demonstrated that early-phase alignment is feasible and valuable, but also that maturity varies across organizations and that further validation is needed across broader industrial settings.

For the Architecting guidance (RQ 1.2), we asked: What guidance is needed to support product architecting when creating environmentally aware solutions?

Architecture frameworks (in particular CAFCR and A3) can sufficiently accommodate environmental considerations in the early architecting stages. However, architects require additional guidance on principles, assumptions, metrics, lifecycle scope, company policies, and information exchange, to navigate the complexity of sustainability concerns effectively.

As the approach for RQ 1.1 has so far been applied within a single company context, additional validation involving diverse industrial environments is needed to confirm generalizability.

In the future work, we plan to conduct research to fully cover circularity of ESC aspects. Furthermore, we plan to focus on the architectural aspects of combining ESC with other qualities, and alignment with business goals.

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