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Project report
Sustainability assessment of the Dutch high-tech industry 2023

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Author : Wouter Tabingh Suermondt, Rosilde Corvino, Jelena Marincic, Joana Teixeira, Carmen Bratosin, Roland Mathijssen

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Contents

1 Abstract

Sustainability embodies the concept of responsible management and care of the planet's resources and the well-being of both current and future generations. In line with the European Green Deal (EGD), the high-tech industry wants to be climate-neutral by 2050 and is actively engaged in exploring methods to integrate sustainability into its product development processes.

While all companies have set up sustainability goals and provide ESG (Environmental, Social, Governance) reports at the corporate level, as required by regulations, there is a need to translate these corporate goals into actionable insights for architects and product designers.

In this report, the ESI sustainability study team presents the assessment of the status and practices of integrating sustainability within the TNO-ESI ecosystem of high-tech industries. The state-of-the-art assessment was based on a comprehensive review of the literature and web resources. At the same time, insights into the state of the practice were obtained through interviews and workshops involving TNO-ESI's Industrial and Academic Partners network. This document does not aim to be exhaustive or complete. Its purpose is to initiate building expertise toward understanding and actuating sustainability in complex system design and industrial environments.

In the assessment, TNO-ESI focused on adding the broader concepts of sustainability to the System Architecting domain, connecting business value, technical explorations, and organizational challenges. The vision is to have sustainability embedded in the Systems Architects' reasoning toolbox. For the (near) future, Design Space Exploration, balancing Product Qualities and decision-making processes must include sustainability aspects.

TNO-ESI has extensive Systems Architecting expertise and can show leadership by providing directions, means, and methods for taking the next steps. Since the sustainability domain is massive, value has to be found in taking the right steps at the right moment and providing noticeable benefits in the short term while focusing on long-term objectives. We realize that this may result in a tailor-made approach since all companies differ in markets, products, culture, and organization, bringing all BAPO (Business, Architecting, Processes, Organization) aspects into practice.

Acknowledgment

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2 Introduction

Sustainability embodies the concept of responsible management and care of the planet's resources and the well-being of both current and future generations. A global agenda on sustainability was set in 2015 with the UN's adoption of 17 Sustainable Development Goals (SDG), with a deadline in 2030. Since then, many governments around the world are acting. Specifically for the EU, the European Green Deal, adopted in 2021, assessed the aim to make Europe the first climate-neutral continent by 2050. Around the world, similar green deals are stipulated as the Biden plan for the USA. In addition, China, Japan, and South Korea's commitments to the UN are to reach total or almost total carbon neutrality by 2050.

As observed by Lyon et al [1], "*Corporate sustainability has gone mainstream, and many companies have taken meaningful steps to improve their environmental performance*" due to a new "*business leadership—driven by the market-for-virtue rather than by legal requirements*."

Although many definitions of sustainability can be found, there seems to be agreement on its three main components: environmental preservation, social equity, and economic viability [2]. This is depicted by Figure 1.

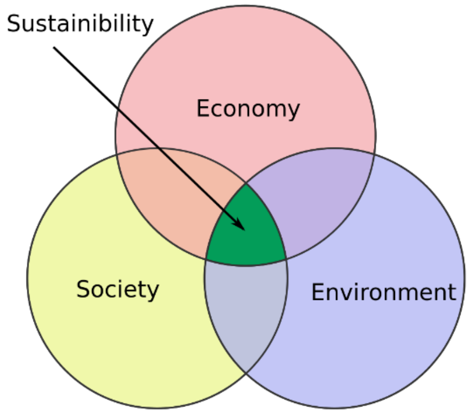

Figure 1: Sustainable is defined as the overlapping area of Environmental, Social, and Economic concerns. Source [2].

Sustainability is often viewed as a holistic and interconnected concept that requires a multidimensional approach. Achieving sustainability involves considering the interdependencies between economic, social, and environmental factors and finding solutions that balance these aspects for the benefit of current and future generations. Sustainable practices and initiatives are crucial for addressing global challenges such as climate change, resource depletion, and social inequality.

In this report, we will focus on the environmental aspects that have a direct impact on product development and connect to the urgency of climate change. The report is the result of a one-year-long effort polling ESI partners to understand their goals, current actions, and existing white spots to reach environmental sustainability. This document does not aim to be exhaustive or complete. Its purpose is to initiate building expertise toward understanding and actuating sustainability in complex system design and industrial environments.

2.1 The ESI partners.

We build the conclusions of this report by involving the ESI partners through interviews and workshops. Seven industrial and five academic partners were involved.

Corporation	Partner	Market	Location
ASML	ASML	Semiconductor, lithography scanners	Veldhoven
Thermo Fisher Scientific	Materials and Structural Analysis Division	Electron Microscopes	Eindhoven
Philips	Image Guided Therapy	Medical	Best
Canon Inc.	Canon Production Printing	Printing	Venlo and Poing (D)
Toyota Industries	Vanderlande Industries	Logistic solutions	Veghel
Nexperia	Innovative Technology and Engineering Center.	Discrete semiconductor manufacturing equipment	Nijmegen
Thales (France)	Thales	Defense, radars, command and control systems.	Hengelo

University	Group	Research Domain
TU Eindhoven	Mathematics and Computer Science	Interconnected resource-aware intelligent systems
TU Delft	Embedded Systems Group	Sustainable Systems Lab
Radboud University, Nijmegen	Computer Science	Sustainable Digitalization
University of Amsterdam	Parallel Computing Systems	design of sustainable systems deployed in power-, thermal-, energy- and reliability-constrained environments
University of Twente	Applied Mathematics	Optimization and control problems for energy management and smart grids

2.2 The assessment

By the end of 2022, the TNO-ESI partner board agreed that ESI would assess the status of sustainable development in cooperation with all industrial and academic partners. This assessment includes the following research questions:

For the product development of the Dutch High-Tech industries, focusing on the Sustainability Domain …

RQ1: What are the most relevant tools, regulations, and standards?
RQ2: What is the actual state of embedding sustainability aspects into product development?
RQ3: What are the topics where TNO-ESI can provide leadership?

The TNO-ESI sustainability assessment project focused on learning how our industrial partners could achieve their sustainability targets concerning their products and life cycles. We build the answers to these questions on six approaches:

- Survey of literature, papers, articles, and reports
- Online interviews with the partners
- In-person and online workshops
- Participating in external workshops
- Connection to TNO in-house expertise
- Knowledge and insights from TNO-ESI projects

The workshops also facilitated networking through connecting partners and sharing knowledge and ideas between them.

The document is organized according to the three research questions. RQ1 will be addressed by chapter 3, while chapter 4 discusses the outcomes of RQ2. RQ3 connects to the overall conclusions and will be discussed in chapter 6.

3 Survey of available tools and methods

This chapter discusses an overview of the available tools and methods that we found relevant within an industrial context. We will assess the following questions:

For the product development of the Dutch High-Tech industries, focusing on the Sustainability Domain. RQ1: What are the most relevant tools, regulations, and standards?

When referring to sustainability, most companies use The United Nations Sustainable Development Goals (SDGs) [3] which are a set of 17 global goals adopted by all United Nations Member States in September 2015. The SDGs are part of the 2030 Agenda for Sustainable Development, which outlines a shared blueprint for peace and prosperity for people and the planet. The goals are designed to address various interconnected challenges, including poverty, inequality, environmental degradation, peace, and justice. The overarching aim is to achieve sustainable development by 2030.

Figure 2, the 17 UN goals for sustainable development. Source [3]

At the European Union level, the EU Taxonomy for Sustainable Activities [4] is the regulatory framework that sets up a common classification system for sustainable economic activities. The aim is to provide businesses and investors with a tool to identify environmentally sustainable activities and investments. The EU Taxonomy focuses on economic activities that significantly contribute to one or more environmental goals without significantly harming others. The taxonomy covers six environmental goals, which are climate change mitigation, climate change adaptation, sustainable use and protection of water and marine resources, transition to a circular economy, pollution prevention and control, and protection and restoration of biodiversity and ecosystems.

We organized the assessment of available tools into two groups: The reader finds the reasoning frameworks and protocols in chapter 3.1, while chapter 3.2 discusses the practical tools for accounting and standardization.

3.1 The reasoning frameworks

This chapter discusses a set of reasoning frameworks as part of environmental sustainability. They are practices for communicating greenhouse gas emissions (GHG) and the circular economy.

The World Business Council for Sustainable Development (WBCSD) [5] brings together transformational organizations to form a global community that shifts the systems they work within towards a better future. Their goal is an economy based on true-cost accounting. The addition ‘true’ means that all direct and indirect costs of circularity are included in the product's value calculation. This gives an incentive and ensures that more sustainable companies are more successful. They deliver pioneering sustainable business solutions and connect companies, partners, and sectors to deliver results that no single company could achieve alone.

The ESG (Environmental, Social, Governance)

ESG stands for Environmental, Social, and Governance, and it refers to a set of criteria used by investors, stakeholders, and companies to evaluate and measure the sustainability and ethical impact of an investment in a business or organization.

Environmental (E): Environmental factors focus on a company's impact on the natural world and how it manages its use of resources. This includes issues such as climate change, carbon emissions, energy efficiency, waste management, water usage, pollution, deforestation, and biodiversity conservation.

Social (S): Social factors relate to a company's impact on society and how it manages relationships with its employees, customers, suppliers, communities, and other stakeholders. Social considerations encompass areas such as labor practices, human rights, diversity and inclusion, employee health and safety, community engagement, product safety and quality, and philanthropy.

Governance (G): Governance factors focus on the systems, processes, and structures that govern how a company is managed and controlled. This includes issues such as board composition and independence, executive compensation, shareholder rights, transparency, ethics, risk management, compliance, and anti-corruption measures.

The European Union (EU) has been actively developing and implementing regulations related to ESG factors, particularly within the context of sustainable finance. We mention some of them.

- EU Taxonomy for sustainable activities [6]
- Sustainable Finance Disclosure Regulation (SFDR) [7]
- EU Action Plan on Sustainable Finance [8]
- EU Green Bond Standard [9]
- Corporate Sustainability Reporting Directive (CSRD) [10]
- Non-Financial Reporting Directive (NFRD) [11]

Overall, ESG has become a critical framework for evaluating investments and businesses' sustainability, ethicality, and long-term viability in today's global economy.

To make environmental sustainability a system quality, we need tangible and quantification key elements. They supply a structured and measurable approach for understanding, monitoring, and improving the impact of activities on the ESG. Bastein and Lennartz [12] mentioned four aspects to consider when creating a quantification methodology:

- The assessment should create incentives and thus match company goals by choosing the appropriate indicators.
- Helps to scope the ‘problem’ by determining the environmental hotspots and development strategies.
- Should match the development stage. Modeling choices may result in certain circularity strategies not being reflected.
- Has its limitations. Initial modeling choices may result in certain circularity strategies not being reflected.

The Green House Gas Protocol

The Greenhouse Gas Protocol [13] supplies the foundation for sustainable climate strategies and more efficient, resilient, and profitable organizations. It is among the most widely used accounting tools to measure, manage, and report greenhouse gas emissions. Figure 3 presents a commonly used picture of greenhouse gas emissions across the value chain with the various greenhouse gases on the top and split across three scopes:

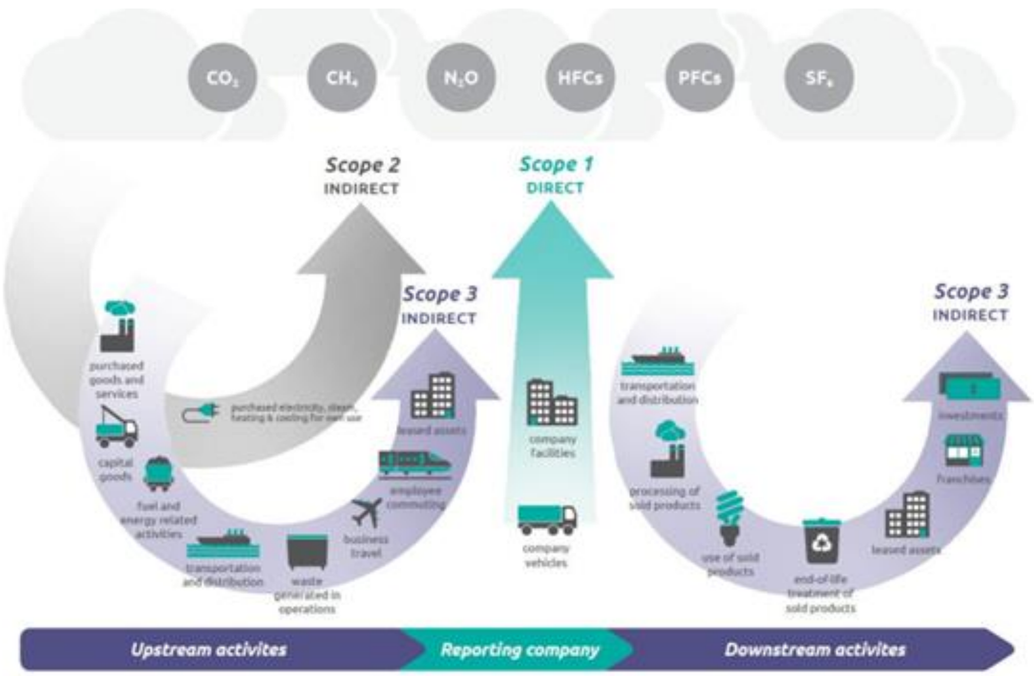

Figure 3, Greenhouse Gas emissions across the value chain. Source [14]

- Scope 1 emissions represent emissions owned or controlled by the reporting company. For example, emissions from combustion in owned or controlled boilers, furnaces, vehicles, etc.

- Scope 2 is an indirect emission and defines emissions from the generation of purchased or acquired electricity, steam, heating, or cooling consumed by the reporting company.
- Scope 3 is an indirect emission and defines all indirect emissions (not included in scope 2) that occur in the reporting company's value chain, including both upstream and downstream emissions. Examples are emissions caused by the production, transportation, or use of purchased products. This is the most difficult scope to handle because it is not always clear how purchased products are manufactured and transported to Greenhouse Gas Emissions by the supply chain.

Now, most focus is on carbon emissions, and all TNO-ESI partners pledged to be carbon neutral by 2050.

In summary, The GHG protocol provides a framework for organizations to categorize and quantify their greenhouse gas emissions across different sources and activities. Understanding and addressing emissions across all three scopes is essential for organizations to develop comprehensive strategies to reduce their carbon footprint, improve sustainability, and contribute to global efforts to mitigate climate change.

The circular economy

The Circular Economy, introduced by the Ellen McArthur Foundation, does not in itself represent a goal but, moreover, a means towards sustainability. It identifies action perspectives that have in common that they focus on reducing net material consumption—and thus its environmental impact—over the entire lifetime of goods.

A linear economy and a circular economy represent two different approaches to managing resources and waste within an economic system. In a linear economy, resources are extracted, used to produce goods, and then disposed of as waste after their useful life. In contrast, a circular economy aims to keep resources in use for as long as possible, extract the maximum value from them during their use, and then recover and regenerate products and materials at the end of their service life.

A shift from a linear toward a circular economy business model requires more than implementing new processes and activities. It also requires a new way of finding value and cooperation within the value chain, as well as a corresponding change in organizational culture [15].

Ellen MacArthur [16] proposes a definition of a circular economy: *"The circular economy is a system where materials never become waste and nature is regenerated. In a circular economy, products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting."*

To make circularity tangible, they developed the Butterfly model Figure 4. On the left side, the model stands for the biological cycle, while the right side represents the technical (non-biological) cycle.

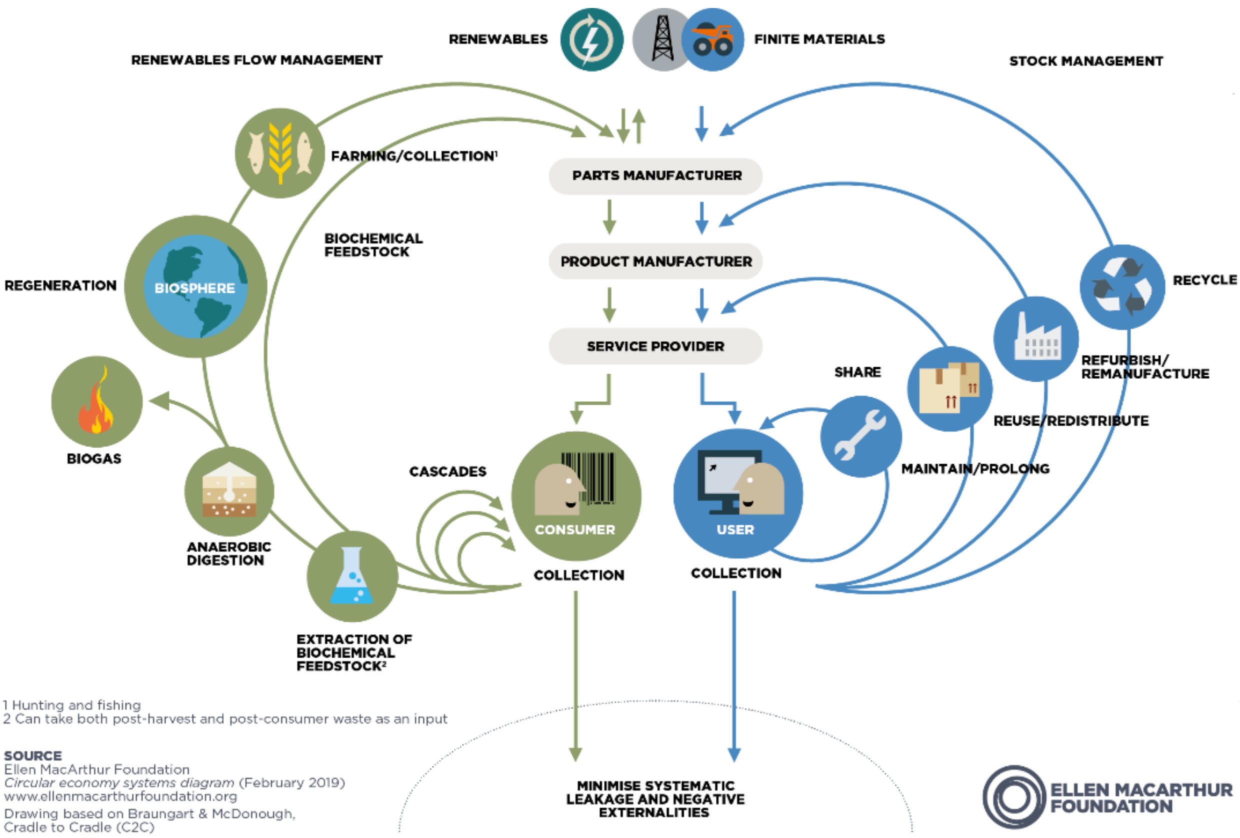

Figure 4: The Butterfly model of the Ellen MacArthur Foundation. Source [16]

In the technical cycle, products and materials are kept in circulation through processes such as reuse, repair, remanufacture, and recycling. In the biological cycle, the nutrients from biodegradable materials are returned to the earth to regenerate nature.

Another representation of the circular activities is the value hill, which was discussed by CirConnect [17]. Figure 5 stands for two kinds of value hills.

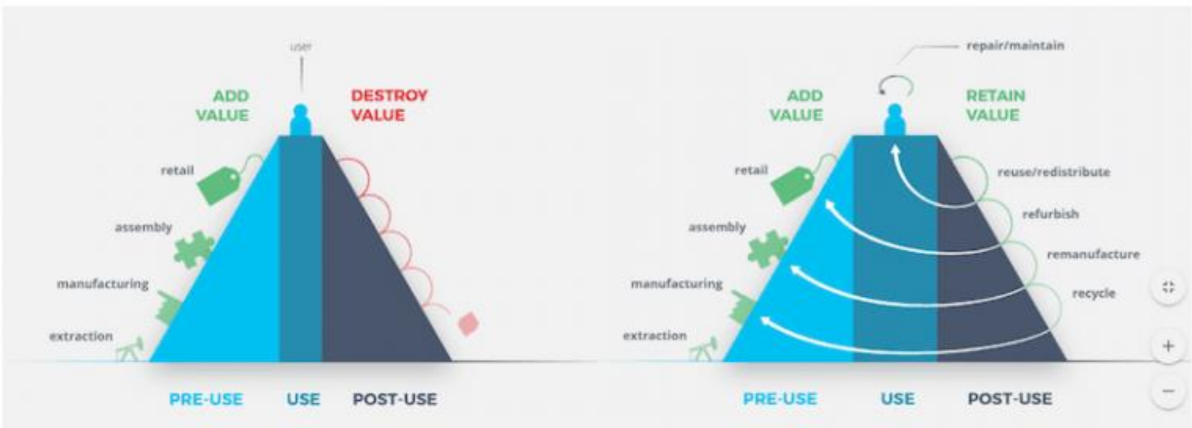

Figure 5: The value hill, left the linear and right the circular economy. Source [17]

The hill stands for the value of materials, where materials closer to the top have the highest economic value. The value hill on the left side stands for the development of value in one-off products, where materials are trashed, and their value is destroyed after their useful life. The value hill on the right-hand side stands for the circular economy, where final goods are reused or refurbished to obtain the highest possible value in every product life. An example is the refurbishment of smartphones after their first use, which supplies the highest value. On the contrary, dumping them into a landfill after use supplies the lowest possible value.

From a business perspective, the circular economy may make sense in combination with True Cost Accounting (TCA): reuse of materials can save costs, and service models can deliver new business propositions and revenues [17] [15]. Circular businesses aim for products to stay at their highest level of value for as long as possible.

The Capital Equipment Coalition (CEC) [18] has been started as part of the Platform for Accelerating the Circular Economy (PACE). PACE is a public-private collaboration co-chaired by the CEO of Philips, the heads of the Global Environment Facility (GEF), and UN Environment, currently hosted by the World Economic Forum [15]. The CEC is a group of nine forward-thinking businesses that have committed to applying circular economy principles to preserve and recover value across the lifecycles of their respective products. Many TNO-ESI industrial partners engage in this initiative by issuing a pledge statement. The referenced document focuses on the two areas prioritized by the CEC in 2018:

1. Establishing the business case for implementing circular economy projects and business models.
2. The organizational changes required to implement these projects and models successfully.

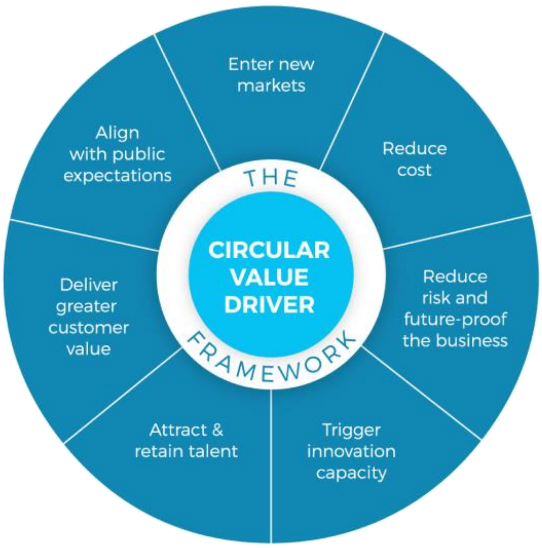

Figure 6: Circular value drivers for closing the loop. Source [18]

The circular value driver framework [18] of Figure 6 highlights seven key considerations that member organizations consider when developing circular business proposals. It represents a discussion at CEC that helps organizations find and capture value from circular economy initiatives. It supplies a structured approach for businesses to assess the potential economic, environmental, and social benefits of transitioning to circular business models. The framework typically consists of several key elements or "value drivers" that contribute to the overall value proposition of circularity. These value drivers help organizations understand how circular practices can create value across different business dimensions.

Overall, the Circular Value Driver Framework supplies a holistic perspective on the potential benefits of circular economy strategies and helps organizations show opportunities to create value while advancing sustainability goals. By using the various value drivers of circularity, businesses can unlock economic, environmental, and social benefits that contribute to long-term value creation and resilience.

3.2 Tools

This chapter discusses a set of more practical tools for computing and accounting of sustainability aspects.

Life Cycle Assessments

Quantification is key; Life Cycle Assessment (LCA) is the most well-known and most adopted framework used to evaluate a product, process, or service's environmental impacts throughout its life cycle in terms of eco-costs. This life cycle typically includes all stages, from the extraction of raw materials through production, distribution, use, and end-of-life disposal or recycling. By systematically quantifying environmental impacts across the entire life cycle, LCAs help to find opportunities to reduce resource consumption, minimize emissions, and enhance the overall environmental performance of products and processes.

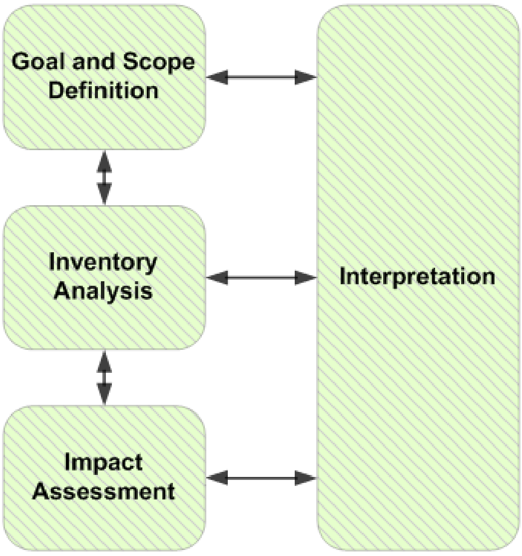

Figure 7, LCA process (Wikipedia) [19]

The ISO 14000 [20] series of standards describes the reporting process as presented by Figure 7. In addition, the Product Environmental Footprint (PEF) is a methodology developed by the European Commission to assess the environmental impact of products throughout their life cycle. They describe how LCAs have to be calculated and are based on four steps.

Goal and Scope Definition:

- Define the purpose of the LCA and set up its boundaries.
- Figure out the functional unit or reference unit for comparison (e.g., per kilogram of product, per kilometer traveled).
- Find the life cycle stages to be included and the environmental impact categories to be assessed.

Life Cycle Inventory (LCI):

- Compile a detailed inventory of all inputs (e.g., raw materials, energy, water) and outputs (e.g., emissions, waste) associated with each stage of the product's life cycle.
- Collect data on resource consumption, emissions to air, water, and soil, energy consumption, and waste generation from relevant sources such as suppliers, manufacturers, and databases.

Life Cycle Impact Assessment (LCIA):

- Evaluate the potential environmental impacts associated with the inventory data collected.
- Apply impact assessment methods and models to quantify the extent of environmental damage or resource depletion across various impact categories, such as global warming potential (carbon footprint), acidification, eutrophication, ozone depletion, human toxicity, and ecological toxicity.

Interpretation:

- Analyze and interpret the results of the LCA to find significant environmental hotspots, trade-offs, and opportunities for improvement.
- Consider uncertainties and limitations associated with the data and assumptions used in the assessment.
- Use sensitivity analysis to explore the effects of variations in input parameters and assumptions on the results.

LCAs require a quantitative dataset. Many datasets exist, both commercial and public [21]. OpenLCA is an example of an open-source software tool, capable of using the (public) databases.

An example of a lightweight LCA approach is the Fast Track LCA (FTLCA) (a.k.a. Quick Scan LCA or Lightweight LCA). Sustainability Impact Metrics (SIM) provides a method for Fast Track LCS calculations [22]. They supply an approach based on Eco-cost/value ratio and True Cost Accounting methods. It maps on the GHG protocol, scope 3 (the upstream/downstream indirect emissions of the supply chain). The purpose of these Fast Track LCA is to support product innovation, by making design choices where eco-costs are a relevant aspect. Systems Architects typically perform this type of LCA. This makes Fast Track LCA reasoning fit into the System Architects toolbox. For easy calculation, SIM provides the Idemat smartphone app [23].

Standards

Sustainability frameworks, quantification, and legislation are tightly connected because they collectively supply the structure, guidelines, tools, and incentives necessary to promote and enable reaching sustainability goals. In addition, there are ISO standards in place, which make it easier for companies to implement sustainability aspects in their products. These standards are generic, and companies need to tailor them to their specific domain and organization. The list of standards is not exhaustive, and the reader must consider it as an initial overview.

From the INCOSE Systems Engineering Standards [24], we found the following standards.

- ISO/IEC/IEEE 15288: 2023 – Systems and software engineering -- System Life Cycle Processes.
- ISO/IEC TR 24748-2:2011 – Guide for Application of 15288 (version 15288:2008)
- ISO/IEC TR 24748-1:2010 – Guide for Life Cycle Management

These standards recognize that engineering projects progress through different stages or phases. These stages typically include conception, development, production, utilization, support, and retirement. The standards guide the processes relevant to each stage.

In addition, there are several relevant sustainability standards for various industries, including:

- ISO 14000 series [20]: Environmental Management Systems (EMS): ISO 14001 sets out the criteria for an environmental management system and guides organizations looking to enhance their environmental performance. It covers resource use, waste management, energy efficiency, and emissions reduction. SafetyCulture [25] provides a comprehensive introduction. ISO 14000 is often integrated with similar standards, such as the quality management system (QMS) standard, ISO 9001. They are related to each other in that both standards deal with establishing, implementing, monitoring, and improving processes, especially for companies involved in international trade. ISO 14001 focuses on environmental management, while ISO 9001 emphasizes quality assurance programs for managing businesses.
- ISO 50001: Energy Management Systems (EnMS): ISO 50001 specifies requirements for establishing, implementing, maintaining, and improving an energy management system. It helps organizations improve energy performance, reduce energy costs, and minimize greenhouse gas emissions.

Global Reporting Initiative (GRI) Standards: GRI supplies a framework for sustainability reporting, helping organizations measure and communicate their economic, environmental, and social impacts. The GRI Standards cover various topics, including governance, ethics, environmental impacts, human rights, labor practices, and product responsibility.

Carbon Disclosure Project (CDP): CDP is a global platform that enables companies, cities, states, and regions to measure, show, manage, and share environmental data. It focuses on carbon emissions, climate change risks, water usage, and deforestation.

LEED (Leadership in Energy and Environmental Design): LEED is a green building certification program that recognizes buildings and structures designed, constructed, operated, and maintained with sustainability in mind. It covers energy efficiency, water conservation, indoor environmental quality, and sustainable materials.

Forest Stewardship Council (FSC) Certification: FSC certification ensures that wood and wood-based products come from responsibly managed forests that provide environmental, social, and economic benefits. It promotes sustainable forest management practices, biodiversity conservation, and respect for indigenous rights.

Fairtrade Certification: Fairtrade certification ensures that products are sourced from producers who receive fair prices and wages, adhere to labor and environmental standards, and invest in community development projects. It covers various agricultural products, such as coffee, cocoa, tea, bananas, and sugar.

These standards and certifications are crucial in promoting sustainability, environmental stewardship, social responsibility, and ethical business practices across various industries. Organizations that adopt and adhere to these standards show their commitment to sustainability and contribute to a more sustainable future. These standards structure sustainably doing business and, therefore are related to the corporate level of an enterprise. At the product level and products a company needs to translate these standards toward the perception of Systems Architects and design teams.

Product Passports

The product passport is an important tool for making information available to actors along the entire value chain. Its availability should significantly enhance the end-to-end traceability of a product throughout its value chain.

The EU Digital Product Passports (DPP) [26] are comprehensive documents or digital records containing detailed information about a product, its materials, components, manufacturing processes, and environmental impacts. Product passports and sustainability are complementary concepts that promote transparency, accountability, and environmental responsibility in product design, manufacturing, and consumption, ultimately contributing to a more sustainable and fair economy.

By providing comprehensive information about a product's environmental and social impacts, product passports enable customers and OEMs to make more sustainable purchasing decisions, favoring products with lower environmental footprints and higher social responsibility.

For businesses, product passports can drive innovation and efficiency by highlighting areas for improvement in product design, manufacturing processes, and supply chain management.

From a regulatory perspective, product passports can inform policy decisions and regulations to promote sustainability, such as eco-labeling requirements, extended producer responsibility schemes, and standards for eco-design and product stewardship.

3.3 Conclusion

In this chapter, we assessed the question:

For the product development of the Dutch High-Tech industries, focusing on the Sustainability Domain. RQ1: What are the most relevant tools, regulations, and standards?

Many tools, frameworks, methods, and standards, coupled with a growing number of regulations, are readily accessible. Navigating through this vast array of resources constitutes a significant undertaking. Moreover, it's crucial to note that these tools are inherently generic and must be tailored to suit the specific needs of a particular industry or product. This customization process demands expertise from professionals who are well-versed in the tools' intricacies and the nuances of the products to which they're applied. We found two clusters of tools that serve the industry:

1. The reference and reasoning frameworks: The UN Sustainable Development Goals and ESG (Environmental, Social, Governance) and Green House Gas protocols supply domain definitions and a taxonomy. This taxonomy is used as a company’s reporting structure, required by regulating authorities. The action perspectives sketched by ‘circularity’ as presented by the Butterfly Model focus on the strategies to recycle at the highest possible value level, as described by the Value Hill. Circularity affects not only an individual company but the whole society, including all upstream and downstream activities and an acceptance to reuse existing materials and parts in new products, as well as life span extension, upgrades, and refurbishment. To be successful, all aspects must provide value as presented by the Circular Value Driver framework.
2. More practical tools for the industry are the LCAs and the ISO standards. There are two kinds of LCAs: the detailed LCA that will be done at the product is ready to be manufactured. The other is a more lightweight version, which supports the decision-making process and design space exploration during the Product Architecting phase. We found many suppliers of software tools as well as many datasets, making the right selection very complex. Other practical guides are the standards that address sustainability and system concerns. However, these standards are high-level and have to be made specific.

4 Results, insights, and observations

This chapter discusses the state of practice and the current standards, methodologies, and best practices that have gained general acceptance within a community of practitioners. It describes answers to the following question:

For the product development of the Dutch High-Tech industries, focusing on the Sustainability Domain, RQ2: What is the actual state of embedding sustainability aspects into the product development?

The outcomes of this assessment are divided into two groups. Chapter 4.1 addresses aspects that are relevant to the company while chapter 4.2 discusses product related aspects.

4.1 Company related.

This chapter discusses aspects that are relevant at the company level. They include organizational aspects, as well as legal and reporting, sharing knowledge, and making a business from more sustainable products.

TNO-ESI industrial partners' profile

In the past, most of our partners worked as independent enterprises but became integrated into larger corporations. In terms of sustainability, they must align with the corporate goals of these conglomerates. The organizational structure is illustrated in Figure 8, with complexity arising from the four layers. Sustainability reporting and goals are primarily set at the corporate level while our partners comprehend the implications for their products. This needs multiple levels of downward translation for setting objectives while reporting flows upward. This resembles a company's financial structure, where financial objectives are set as a downward stream and reporting as an upward stream.

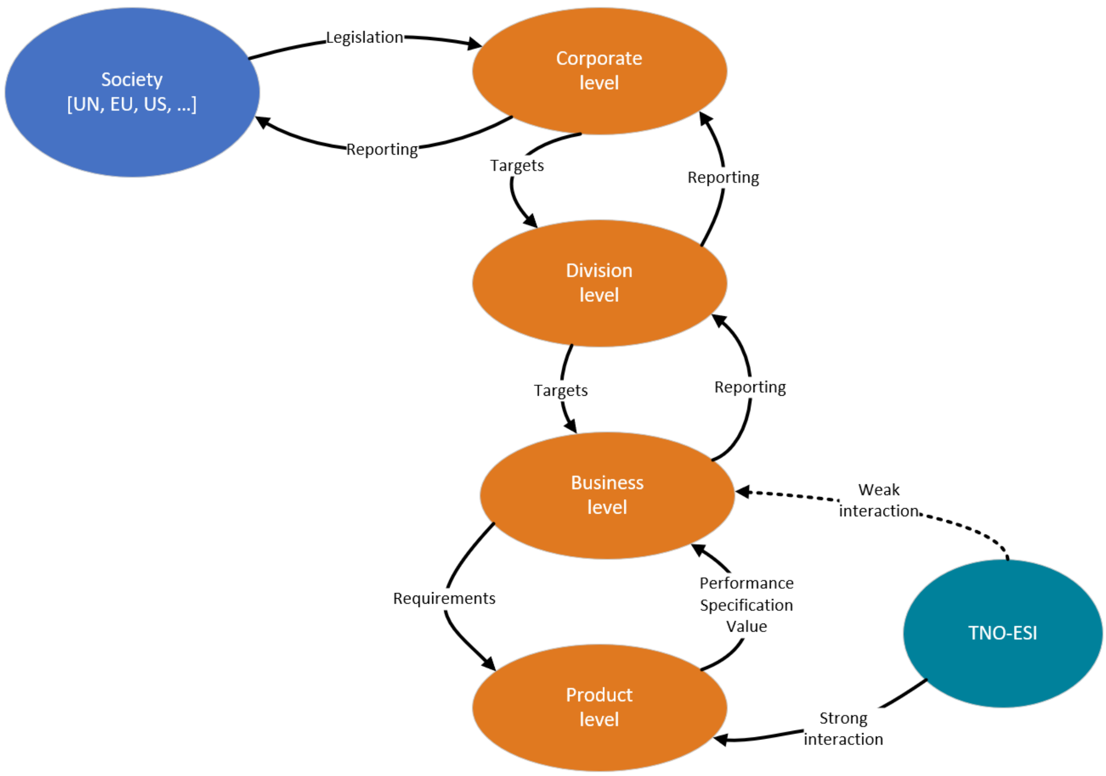

Figure 8 :The company's structure reveals a gap between the corporate level and the product level.

Many of the TNO-ESI industrial partners operate at levels below the division level, primarily at the product development level. Some participants are members of a dedicated sustainability team operating at the division level, but their responsibilities extended down to the product level as well. A CEC finding was the importance of involving and aligning all layers. That top-level commitment to sustainability must be set and stimulated through all (lower) levels of an organization.

All industry partners operate within the Dutch High-Tech industry, specializing in professional, often customized, or tailor-made solutions with extended life cycles spanning multiple decades. Upgrades, offering significant new features, further prolong the products' lifetimes. In certain instances, products undergo refurbishment for a second life after being decommissioned by the initial customer. When recycling is executed out of sight of OEMs that value is not recuperated by the OEM. Value capturing by the OEM is indeed the case for other strategies like refurbishment, repair, etc.

Corporate reporting

All companies provide publicly available reporting at the corporate level. We scanned the reports, and we counted the UN SDGs that were mentioned.

UN Sustainable Development Goals (SDG)		
1	No Poverty	1
2	Zero Hunger	
3	Good Health and Well-Being	2
4	Quality Education	2
5	Gender Equality	2
6	Clean Water and Sanitation	1
7	Affordable and Clean Energy	3
8	Decent Work and Economic Growth	3
9	Industry, Innovation and Infrastructure	3
10	Reduced Inequalities	1
11	Sustainable Cities and Commuties	1
12	Responsible Consumption and Production	4
13	Climate Action	4
14	Life Below Water	
15	Life on Land	1
16	Peace, Justice and Strong Institutions	3
17	Partnership for the Goals	2

Figure 9: Overview of partners' contribution to the UN Sustainable Development Goals at the corporate level, based on their public sustainability reporting.

Some companies use the ESG structure for their reporting rather than the UN SDGs. This makes it difficult to map their goals and we have to exclude them from the table. However, these reports have comparable sustainability objectives. From the table, we conclude that SDGs 12 and 13 were mentioned by most partners.

Green House Gas emissions

All companies have made reported goals for climate neutrality by 2050 of carbon emissions: The industrial partners already address Scope 1 and Scope 2 related issues. Many partners mentioned that the operation of their buildings and factories has full attention. However, for all partners, Scope 3 is the major concern. They have limited insight into their upstream supply chain since their subcontractors are not able to provide this information. Product passports and more legislation are seen as important means to address this subject.

Business Models

Sustainable business models are designed to operate in a way that minimizes negative environmental, social, and economic impacts while maximizing positive contributions to society.

The High-Tech industry consists of commercial companies that perform a profit-driven business. They need to bring the sustainability aspects (of their products) into their business models in such a way that it sustains and not decreases the existing business value. During the interviews, some partner representatives mentioned that their customers might not be ready to pay for more sustainable products. They expect that when (stricter) legislation and tax sustainability will become a factor this issue will be solved.

The complexity of sustainable business models has to do with trade-offs between sustainability aspects and existing business models. This applies not only at the moment of purchase but during the whole product life cycle. For example, when a company makes products more sustainable by extending their lifetime, this affects the business model based on new product sales in a negative way, while it supports the business model for selling repairs, spare parts, and product updates/upgrades. Another example is the reduction of energy consumption. Equipment transforms most of the consumed energy into heat. The cooling is often at the expense of the customer, because of air conditioning which is part of the building infrastructure. This is a customer's dilemma between product cost of ownership versus its revenues. There is a clear business advantage when more energy-efficient equipment reduces both the cost of consumed energy and the cost of cooling, allowing for a reduction in the building infrastructure and maintenance costs. To deal with this complexity, we conclude that a more explicit and holistic true cost calculation and value creation process is required.

Learning from each other

Partners also noted that all companies share similar concerns at the same stage in their sustainability journey. At a broader level of analysis, these issues seem uniform. However, partners expect divergences when delving into specifics, given variations in products, markets, and organizational structures among companies. The question arises as to whether common solutions can be applied widely or, if company-specific, tailored solutions are more appropriate, considering these factors.

Certain partners have already identified specific areas for collaboration. For instance, regarding the supply chain, partners have recognized common suppliers. They aim to prevent situations where a supplier must adhere to various processes and standards required by different Original Equipment Manufacturers (OEMs). It is anticipated that these suppliers also cater to other OEMs within the Dutch high-tech industry. The potential involvement of additional OEMs in this initiative could lead to the establishment of standardized procedures within the Dutch high-tech supply chain.

Regulating authorities

Regulating bodies worldwide are increasingly enforcing regulations on products and companies. There is a risk that legislation from different authorities may create ambiguity, be impossible to fulfill at the same time, or even create conflicting conditions. Companies are aware of this. However, since many regulations are currently not in place or are unclear, this is not a major concern. It is expected that this will appear first in already strongly regulated companies. Examples are in the medical, military, and mobility domains where safety regulations are already in place. For example, to reuse, the safety regulation of the US-based Food and Drugs Administration (FDA) may conflict with sustainability regulations of the EU.

4.2 Product related

This chapter discusses aspects that are relevant at the product level.

The energy footprint

All products developed and manufactured by the TNO-ESI industrial partners are electrically powered, with no direct use of fossil fuels. Some partners foresee that as electricity becomes more sustainable in the future, the energy consumption of their products will also become sustainable. However, all partners work on understanding and reducing the energy footprint of the product in use during their lifetime. We found three approaches.

- Equipment is designed to run at its full production ability. However, in cases where this capacity is not required, energy consumption can be reduced, for example, by slowing down mechanical transportation speeds or switching off computing capacity.
- After installation, field upgrades that increase the production throughput while keeping the power consumption at the same level, reduce the consumed amount of energy for a manufactured product. This makes the production more sustainable over time.

In the end, most of the energy consumed will result in heat that has to be extracted. This cooling is often at the customer's expense. So, energy reduction affects both the direct cost of energy and the extraction of the excessive heat generated. In addition, reducing electrical energy consumption supports the energy transition.

Partners have already integrated awareness of energy reduction into their daily product design and engineering practices. Designers and experts are adept at addressing these challenges and regard them as standard engineering practices.

Some partners mentioned that the metric of total consumed energy consumed by their equipment during its lifecycle is a questionable KPI. They argued that in the field of production equipment, a correct KPI is energy consumption to the produced output. This implies that when field upgrades increase the production throughput at the same level of electricity consumption, the equipment may be more sustainable.

SMART requirements

During the product definition phase, design teams need SMART (Specific, Measurable, Achievable, Relevant, Time-bound) product requirements, including those that address sustainability. However, partners currently face challenges in specifying these sustainability-related SMART requirements. Additionally, there is a lack of understanding about how these SMART Sustainability requirements align with higher-level sustainability objectives at the business, division, or corporate levels. This issue is intertwined with the organization's organizational structure, as depicted in Figure 8.

Life span extension

A topic mentioned by multiple partners is the life span extension and decommissioning of products at the end of their lives. Products have a very long lifetime, and it was mentioned that for many products, the decommissioning and end of life are not reached since the products are still in use. Many products have already a second or third life after decommissioning, extending their life for multiple decades. For some companies, almost all products ever built and delivered are still in use. They were designed and manufactured when sustainability and material recycling was not a topic. We conclude that decommissioning in the high-tech industry is not common practice. Hence, there is limited experience in how to deal with this very long lifetime, as well as the decommissioning and recycling of material. The topics of Design for Disassembly or Design for Circularity have many architectural points of view. We can extend these viewpoints with lifetime extension by repairing, refurbishing, and upgrading. This allows us to consider the sustainability subject from the Systems Engineering life cycle perspective. A good example to learn from is the military industry where equipment, designed and manufactured during the early days of the Cold War is still in use and continuously upgraded to deal with new threats and expected to be in service for even more decades. An example is the Boeing B52 Stratofortress [27] which was manufactured in the early 1950s and has a life extension up to 2050. For Europe, the Greek army considers options to upgrade their Leopard 1 main battle tanks, which originate from the early 1960s [28].

Architecting for Sustainability

Nearly every partner emphasized the significance of System Architecting for Sustainability as a pivotal focus area for ESI. Muller [29] defines System Architecting as "*System Architecting is a means to create systems efficient and effective, by supplying overview, by guarding consistency and integrity, and by balancing*" The System Architecting phase emerges as a critical juncture for integrating novel considerations, such as sustainability, into the exploration of product design spaces to understand how demands for sustainability can be reached within existing business and with common business models. Consequently, System Architects must be equipped with the awareness and training necessary to effectively address this evolving subject matter.

The CANVAS project [30] proposes a first method of how System Architects can incorporate sustainability principles into their existing reasoning domain (Figure 10). They must integrate customer, business, technology, and sustainability aspects into a set of architectural concepts in such a way that it brings some kind of business value.

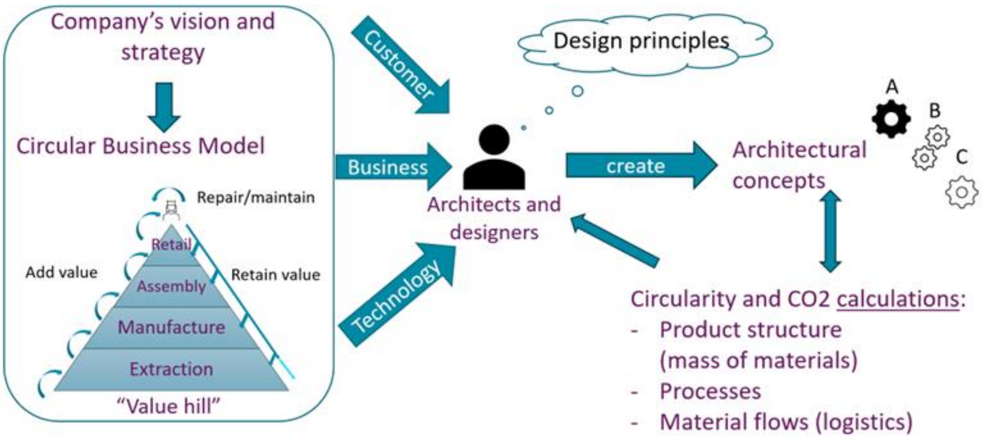

Figure 10: The System Architect is in the center of the Sustainability. Source [31]

The CAFCR [32] (Customer, Application, Functional, Conceptual, Realization) reasoning framework is a multi-view method for (embedded) System Architecting at the product level, which can include sustainability aspects as well. It is a proven and well-known approach which can be combined with the A3 architecting method [33]. Muller already made steps by integrating sustainability into System Architecting [34]

To address sustainability-related concerns, other well-known reasoning frameworks may be applicable as well. For example, BAPO (Business, Architecture, Process, Organization) [35] provides a structured approach to business transformation, emphasizing the interconnectedness of various organizational elements and the importance of aligning them with strategic goals. By addressing business, architecture, process, and organization in an integrated manner, BAPO aims to drive sustainable growth and competitiveness for businesses.

Now, sustainability is often not integrated into the initial stages of product design; rather, we observed that it tends to be addressed later in the development cycle. There's a recognized need to transition towards Sustainability by Design, similar to the concept of Security by Design, which encompasses architecting processes. Drawing parallels, it could be helpful to draw lessons from Safety Critical Systems where legislation has been a primary driver for implementation, for example in the medical, automotive, and aerospace application domains.

Life Cycle Assessments

Almost all partners are dealing with Life Cycle Assessments of the material footprint of their products. We found that LCAs are done at the engineering phase on the ready product. LCAs heavily depend on databases with data on the use of various materials. Currently, different sets of data exist in the world. Partners found that they got different outcomes from their analysis when using different data sets. According to [36], we must narrow LCAs down to a specific context or scenario or align with a specific method.

Currently, Life Cycle Assessments (LCAs) are conducted based on the engineered Bill of Material (BOM) breakdown structure. Consequently, engineers can perform these assessments only when the product is nearing readiness for production, typically in the final phase of product development. These LCAs are conducted at the part level, rendering them highly detailed and necessitating a significant amount of effort.

Many partners have highlighted the necessity for a lightweight or rapid-scan LCA that supports the architectural phase of product development. As discussed in Chapter 3.1, the concept of such LCA is already known. The main issue is how to translate this generic lightweight LCA method into a method that fits a partner's specific organization and its needs.

4.3 Conclusion

In this chapter, we assessed the question:

For the product development of the Dutch High-Tech industries, focusing on the Sustainability Domain RQ2: What is the actual state of embedding sustainability aspects into product development?

All industrial partners are actively engaged in exploring methods to integrate sustainability into their product development processes. However, we found a significant gap between the sustainability strategies outlined at the corporate level and their implementation at the various product levels. While all companies have set up sustainability objectives and provide reports, as required by regulations, the translation of these corporate goals into actionable insights for architects and designers remains unclear. Currently, there is a lack of SMART (Specific, Measurable, Achievable, Relevant, Time-bound) sustainability requirements. However, there is a notable exception: all companies are actively pursuing energy reduction initiatives throughout the entire lifespan of their products in service.

Despite these efforts, aspects such as circular economy principles and supply chain sustainability are still ambiguous and require further investigation. Transitioning towards circularity needs the involvement of the entire supply chain, which underscores the importance of implementing product passports to track sustainability metrics. While this infrastructure is not yet set up, efforts are underway to develop and implement it.

At the product level, organizations tend to concentrate on specific details, such as the mechanics of conducting Life Cycle Assessments (LCA), rather than grasping the broader concept of sustainability in its entirety. This narrow focus often revolves around practical design intricacies, but there's a growing recognition of the need to transition to company-wide and aligned sustainability goals. Crafting a compelling business case that supports environmental sustainability into products stays challenging, as individuals gravitate towards familiar approaches and solutions. However, navigating sustainability effectively requires a willingness to confront uncertainties and adapt to unknown variables.

Compared to other industries, e.g., petrochemical, steel making, transportation, agricultural, and consumer products markets, we found that many partner representatives believe that their products are already rather sustainable. They mentioned the following reasons:

- Most products have a very long life cycle of over 25 years, with continuous upgrades. Some products have a second lifetime at another customer after decommissioning and refurbishing. Regarding circularity, they acknowledged that due to this long lifetime, they have little experience with decommissioning and recycling of materials.

- All equipment is powered by electricity, they do not directly use fossil fuels. So, they expect that in the future, when the energy transition brings more sustainable electricity, customers can operate their equipment more sustainably as well.
- Our partners are integrated into larger global corporations. They argued that the individual contribution of a partner's product to the corporate sustainability goals could be low, compared to other corporate activities. The corporations prioritize the low-hanging fruit in other divisions or business units.

5 ESI involvement

This chapter addresses the question:

For the product development of the Dutch High-Tech industries, focusing on the Sustainability Domain. RQ3: What are the topics where TNO-ESI can provide leadership?

Chapter 5.1 addresses the topics where TNO-ESI can actively provide value from the partner's perspective while chapter 5.2 goes into the TNO-ESI internal structure and way of working.

5.1 Cooperation with partners

The companies of the High-Tech industry have acknowledged a need for cooperation on the topic of environmental sustainability. This is where TNO-ESI can bring leadership, in synergy with industry partners, TNO expertise, academics, and new partners that play already a role in the sustainability transition.

Systems Engineering and System Architecting are at the center of this transformation towards more sustainable business. To be successful in the future, the partners expect to include sustainability-related principles in their product definitions. These principles relate to the CAFCR-reasoning framework, which supports integration as well as balancing, of (sustainability-related) system qualities at the product level. A more holistic picture provides the BAPO framework. Next to System Architecting, partners mentioned three important subjects. They fit into the System Architecting umbrella as well. They are:

- Quick Scan LCAs serve a distinct purpose as they contribute to decision-making during the design phase, which occurs early in the product development process. They are integral to tasks such as Design Space Exploration, dilemma resolution, and trade-off analysis.
- SMART requirements on sustainability. There is a lack of understanding about how these SMART Sustainability requirements align with higher-level sustainability objectives at the business, division, or corporate levels.
- Lifespan extension. Products already have a considerably long lifespan, but implementing architecting principles focused on decoupling, adopting a more modular approach, designing for flexibility, and reducing dependencies on specific technology choices could further extend the lifespan of products. These principles enable more frequent field upgrades to adapt to new demands from customers.

Most partners responded that they want some way of continuation, preferably in the form of a Special Interest Group (SIG). The main subjects should *be Architecting for Environmental Sustainability* including *how to bridge the gap towards the corporate sustainability objectives.* To meet expectations, most partners mentioned explicitly that the SIG should present new valuable knowledge, helping the partners to make steps in their sustainability journey. They see an important role for TNO-ESI to ease and feed the higher levels of abstraction in SIG sessions.

5.2 Extend to TNO-ESI expertise

The core of TNO-ESI is the (applied) research programs, where expertise provides value to the program lines. The research program is translated into projects, based on cooperation with selected industry and academic partners in the context of "Industry as Lab". The principle is depicted by Figure 11.

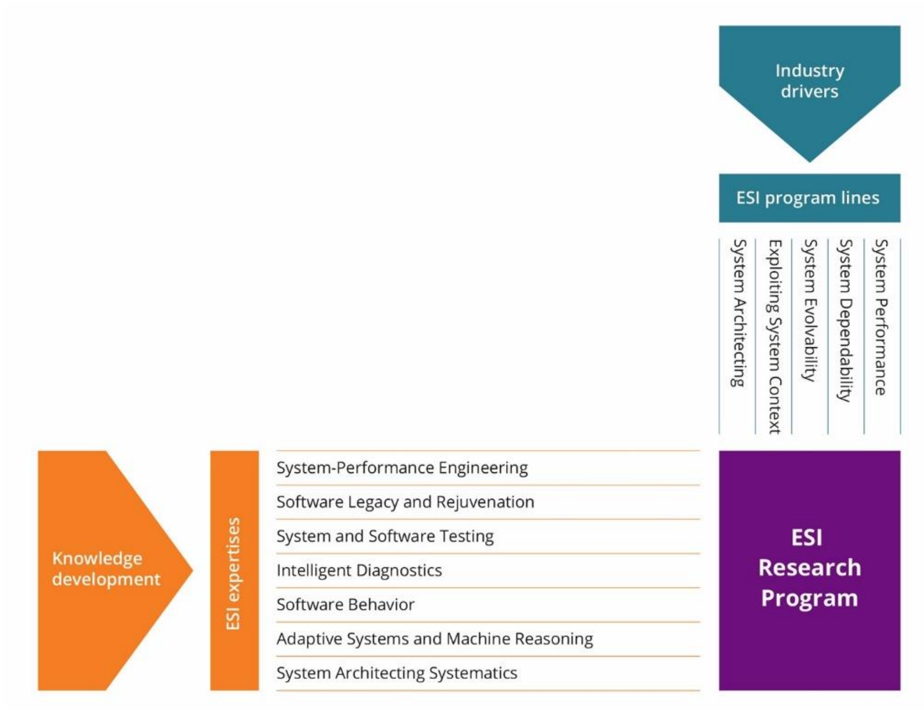

Figure 11: Sustainability aspects merge into the expertise and program lines

TNO-ESI must integrate sustainability concerns into the existing expertise or establish new expertise areas. In the table below we present ideas on how expertise areas can contribute to sustainability.

TNO-ESI expertise	Sustainability related questions
System Architecting Systematics	How to integrate sustainability into System Architecting and Systems Engineering? How to create business value and support innovation?
System Performance Engineering	How to keep the performance of the system at spec or even increase the system performance, which contributes to the life span extension without increasing energy consumption?
Intelligent Diagnostics	How can diagnostics drive System Life span extension as well as energy reduction by supporting Field Service Engineers, finding faulty parts, and reducing the need to travel to systems? How to reduce waste by reducing the consumption of spare parts?
Software Behavior	How can scheduling, predicting, and calibration algorithms influence aspects such as energy consumption during production and standby mode in a more sustainable way?
Software Legacy	How to extend the life span of the installed base by keeping the software stack understandable and upgradable for the next decades when the original designers have retired?

Testing	How to ensure that systems are correctly designed from a sustainability perspective, even with field upgrades, while the original systems are not available anymore for testing?

At TNO-ESI, we are currently establishing new research focusing on the integration of sustainability and systems engineering and systems architecture processes, starting with early architecting and design. The program focuses on topics such as the definition of sustainability-related indicators and their relations to corporate targets, trade-off analysis between the triad sustainability – cost – performance, impact of different sustainability-related business models on the architecting decisions (e.g., refurbishing vs recycling), architecting for lifetime extensions, etc.

To support the program, a project together with Canon [30] focuses on developing a methodology for early architecting for environmental sustainability and circularity. Furthermore, together with an international consortium of eight countries, an ITEA project was submitted aiming at combining model-based engineering practices with design for sustainability impact assessment. In addition, we are exploring the option of submitting a proposal for Chips Joint Undertaking [37].

5.3 Conclusion

Environmental sustainability fits well into the current TNO-ESI way of working with the ecosystem of industrial and academic partners. The existing expertise areas can include sustainability aspects in their research roadmaps and act as a starting point. Industry partners mentioned explicitly that they expect the Systems Architecting expertise to take the lead in integrating sustainability-related qualities into the System Architects' toolbox. Projects based on the industry as a lab concept that addresses specific questions at partners are a proven way of drilling into specific concerns. In addition, networking activities, which bring partners together in an informal setting, address the broader picture. The SASG (System Architecting Study Group) already includes sustainability-related topics on its agenda. A SIG with a focus on the sustainability aspects is the next step. However, at TNO-ESI, sustainability is not an explicit field of expertise, so we foresee a challenge in the organizational details to keep this networking activity at a sufficient quality level of shared knowledge.

6 Conclusion

The TNO-ESI sustainability study, in close cooperation with its industrial and academic partners, assessed the status and practices of integrating sustainability into the Dutch High-tech industry.

Sustainability is a complex domain where all aspects, like frameworks, legislation, reporting, quantifying, and standards, are tightly interconnected. The most important challenge for our industry is creating business value. To succeed, each step towards a more sustainable business must bring value. For such a successful sustainability track within organizations, stakeholders, business goals, architecting, and design must be fully aligned. At the product creation and development level, systems architects are central to driving sustainability into the product definition. This relates to issues about the interaction between the definition of the System of Interest and its context, the balancing of trade-offs, and understanding the dilemmas.

There is a discussion about how much an industry should do on sustainability. We found that some partners argue that working on sustainability is not immediately relevant until legislation is enforced, while others mention that not preparing for sustainability might affect their industry's role as a societal innovation leader.

There is an agreement that integration of sustainability into the design process of high-tech systems is one of the top priorities of the Dutch industry in general and TNO-ESI partners in particular. Where reporting on the environmental impact is a well-adopted discipline in most companies, designing for sustainability, especially starting in the early design phases, is still in its incipient phases. With this in mind, TNO-ESI is creating a sustainability program focusing on this aspect. Building on the ongoing project with Canon Production Printing, extending it through an ITEA-submitted proposal, and exploring other possibilities to finance it, such as Chips Joint Undertaking, TNO-ESI is ready to support its ecosystem by integrating sustainability in the system development process from early architecting.

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8 Glossary

ESG	Environmental, Social, Governance
CSRD	Corporate Sustainability Reporting Directive
LCA	Life Cycle Assessment; also, Quick Scan LCA.
GHG	Green House Gas emissions
SMART	Specific, Measurable, Agreed, Realistic, Time-bound
NFRD	Non-Financial Reporting Directive
CSR	Corporate Social Responsibility
CSP	Corporate Sustainability and Politics
SDG	Sustainable Development Goals
OEM	Original Equipment Manufacturer
EVR	Eco-cost Value Ratio
ESC	Environmental, Sustainability, and Circularity
PACE	Platform for Accelerating the Circular Economy
EMAS	European Union's Eco-Management and Audit Scheme
EMS	Environmental Management System
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
FTLCA	Fast Track LCA
GRI	Global Reporting Initiative
EnMS	Energy Management Systems
CDP	Carbon Disclosure Project
LEED	Leadership in Energy and Environmental Design
FSC	Forest Stewardship Council
FC	Fairtrade Certification
EGD	European Green Deal
DPP	Digital Product Passports
CAFCR	Customer, Application, Functional, Conceptual, Realization
BAPO	Business, Architecture, Process, Organization
FDA	Food and Drugs Administration
TCA	True Cost Accounting
CEC	Capital Equipment Coalition
SASG	System Architecting Study Group
GEF	Global Environment Facility
WEF	World Economic Forum