Vision and Outlook for Lifecycle Excellence in the High-Tech Equipment Industry

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Vision and Outlook for Lifecycle Excellence in the High-Tech Equipment Industry

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Contents

1 Management summary

The high-tech equipment industry is undergoing significant socio-technological transformations that will impact system engineering practices across the entire product lifecycle. This document outlines a vision for lifecycle excellence of high-tech equipment, focusing on quality assurance, diagnostics, sustainability, and supply chain management.

Key transformational trends discussed in the document include the increasing role of AI, the growing scarcity of experts, and emphasis on sustainability. This works also highlights challenges such as the high cost of testing, the complexity of diagnostics, and the integration of sustainability into product attributes.

Key research directions discussed in the documents are:
- Quality assurance and control: focussing on the need for efficient testing of product lines, including change impact analysis and regression test selection.
- Intelligent diagnostics: emphasizing the importance of methods for root cause analysis and prognosis to reduce unscheduled downtime, and of methods for leveraging field learnings to enhance diagnostic knowledge.
- Environmental sustainability and circularity: integrating circularity and sustainability into systems engineering without compromising other system qualities.
- Supply chain management: developing methodologies for bi-directional information and data exchange between suppliers and buyers to improve diagnostics and overall system quality.
- Secure data handling: establishing frameworks for secure, resilient data pipelines, optimized sensor placement, and scalable storage.
- Combination of different aspects of the lifecycle: promoting the development of a holistic approach to engineering diverse system qualities across all phases of the lifecycle, to minimize risks and ensure overall equipment effectiveness.
- Human-centric design: embedding user-focused design principles throughout the system lifecycle to enhance usability, adaptability, and sustainability.

2 Introduction

Over the next five to ten years, significant societal and technological changes will influence how high-tech systems are engineered. This document examines how these trends will impact the engineering practices related to the lifecycle aspects of industrial high-tech systems. It also outlines relevant research directions for future-proofing the lifecycle of high-tech systems.

2.1 Background

This document is part of the work conducted by TNO-ESI on the topic of Engineering for Lifecycle Excellence (LCE), which refers to the comprehensive management and optimization of a system throughout its entire lifecycle. From the initial concept and design, via its usage and integration with other systems, through to decommissioning and disposal.

The work done on the topic of LCE relies on several knowledge areas, i.e. expertises, among which the most relevant ones are:
- Intelligent Diagnostics
- Testing of Systems and Software
- Systems Architecting Systematics, specifically with the topic of sustainability.

These expertises address one or multiple stages in the lifecycle of an industrial high-tech system and focus on maintaining and optimizing different qualities of the system. In previous work, ESI has conducted literature and state of practice studies, with accompanied visions on key technological challenges. Related to the scope of this document see [1] for diagnostics, [2] for testing and [3] for sustainability.

2.2 Objectives

This document aims to provide a framework for guiding future research and development efforts in ensuring lifecycle excellence within the high-tech industry.

To do this, the key objectives are:
- Analyse how socio-technological trends will affect one or more stages of a system's lifecycle within the high-tech sector.
- Provide research directions for both ESI and key leaders within the high-tech sector, focusing on ensuring the excellence of systems throughout their entire lifecycle, considering the identified trends and challenges.

2.3 Outline

The document is organized as follows. Section 3 gives an industry overview, both embracing the socio-technical trends influencing the high-tech landscape and offering insights into how these trends will impact the current way of working. Section 4 focuses on the lifecycle of high-tech systems, breaking down its various stages from system (re)design to decommissioning. It highlights the challenges and opportunities encountered at each stage and analyses the complexities involved in designing, maintaining, and optimizing high-tech systems throughout their lifespan. Section 5 focuses on the research directions for the lifecycle of the machines produced by this industry. It explores several key areas of innovation and development, including quality assurance and control, orchestrating the supply chain, intelligent diagnostics and circularity. Finally, Section 6 concludes with a summary of the findings and insights gathered from the analysis.

3 Industry overview

3.1 The high-tech industry

The high-tech industry is a key driver of global innovation and a pillar of the Dutch economy [4] [5]. It creates world-leading systems for a variety of markets, including the semiconductor industry, electron microscopy, production printing, and healthcare. Developing these systems demands expertise across multiple fields, from precision mechanics and optics to embedded systems and advanced software engineering. These systems are increasingly cyber-physical, combining mechanical components, analog and digital electronics with advanced control software.

The priorities of the high-tech industry manufacturers are continually evolving. While performance, functionality, and competitive total cost of ownership (TCO) remain essential, modern systems must also be highly adaptable. They need to meet individual customer requirements, integrate seamlessly with existing industrial processes, and be future proof. This adaptability is crucial throughout the entire lifecycle of these systems. Furthermore, unlike other industries that focus on mass production, the high-tech sector is unique in producing customizable complex systems in low volumes, often only hundreds per year. Digitalization facilitates the flexibility of high-tech systems but also introduces challenges in managing their complexity.

Another unique aspect of the high-tech sector is the crucial role of collaboration. Diverse companies, typically with disjoint markets, but similar methodology needs, synergy and engage in joint innovation, particularly in research and development, to share knowledge and tackle increasing complexity. Ref [4] highlights the importance of robust ecosystems and public-private partnerships, with a shared long-term vision, in supporting innovation and speeding up the development of next-generation systems.

In the next section, we outline the socio-technical trends and corresponding needs that are shaping the future of the high-tech industry.

3.2 Trends and needs

As a starting point, this document will consider the trends and needs identified in the vision document of ESI's Systems Architecting & Systems Engineering [6], with a special emphasis on their relevance for the lifecycle of high-tech systems.

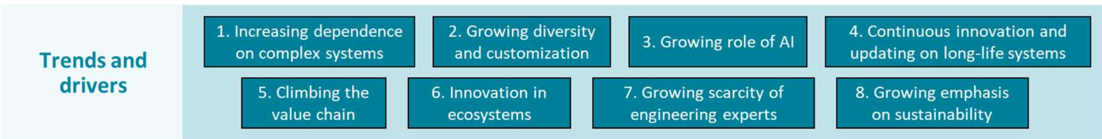

Figure 3.1 Trends and drivers as identified in [6]

3.2.1 Increasing dependence on complex systems

Society increasingly relies on high-tech systems. While the traditional focus on the system performance under ideal usage conditions remains important, a broader perspective is crucial to ensure the required dependability. Increasing dependability implies that maintenance strategies become more relevant, also in first stages of the lifecycle when diagnostics trade-off decisions are made, i.e. placement of diagnostic specific sensors or redundant components. Similarly, testing and validation are more relevant and needed to ensure systems that can not only meet functional requirements but also non-functional requirements like security, safety, and resilience, leading to more dependable systems.

3.2.2 Growing diversity and customization

The growing demand for diversity and customization in high-tech systems presents a significant challenge: how to efficiently develop and manage many system variants in a business conscious manner, i.e., keeping costs low? The industry must find ways to avoid treating each customized system as a unique entity requiring an ad-hoc design, implementation, integration, verification & validation, and maintenance strategy [7]. To address this trend, the sector must shift towards developing platforms and modular architectures that enable efficient creation of variants through configuration and parameterization, leveraging shared components and processes.

3.2.3 Growing role of AI

Artificial intelligence is already playing a significant role throughout the lifecycle of high-tech systems, and its influence is only set to grow. Engineers are currently using AI techniques to automate tasks, like optimize system performance and diagnostics through root cause analysis and prediction. Even in the early stages of the lifecycle, AI will play a crucial role, for example via requirements analysis and design space exploration and synthesis, leading to more efficient development and better-quality systems. This trend will only accelerate as AI technology advances and becomes further integrated into systems engineering processes.

3.2.4 Continuous innovation and updating on long-life systems

High-tech systems often operate for decades, and their lifespans are only getting longer. While these systems are constantly being updated, the market demands that they must remain dependable. This requires modular designs that are flexible enough and resilient to easily incorporate and manage innovative technologies [8]. Thorough testing is essential to guarantee that these updates do not negatively impact system quality. Strong lifecycle management, including long-term support and planning for obsolescence, is also critical.

3.2.5 Climbing the value chain

High-tech system manufacturers are transitioning from selling individual pieces of complex equipment to providing integrated solutions for entire production fabs and lines – a practice known as climbing the value chain. This shift expands the engineering scope across the full lifecycle. System design now necessitates modelling the entire fab, not just individual systems, to ensure compatibility and optimize workflow [9]. Engineers and the systems must be able to analyse data from the entire production line, to make informed decisions that maximize overall quality and throughput. Similarly, maintenance strategies evolve from optimizing individual system maintenance to optimizing maintenance at the fab level.

Furthermore, high-tech systems, are the integration of components from various companies, i.e., systems of systems, many of which operate as black boxes. This often leads to a lack of data sharing, necessitating run-time adaptability. Consequently, testing and maintenance are complicated, as the system's responses are not fully predictable during the design phase.

3.2.6 Innovation in ecosystems

The high-tech sector in general and the Dutch one in particular, benefit from a robust ecosystem of interconnected organizations. This collaborative environment reflects the industry’s shift towards integrated solutions, as seen in previous trends. This ecosystem supports the entire lifecycle, from fundamental research and development to the manufacturing and deployment of complex systems. Partnerships and knowledge sharing are crucial in these ecosystems, enabling companies to leverage collective expertise and resources across different organizations and along with full supply chains.

3.2.7 Growing scarcity of engineering experts

The growing scarcity of experienced engineers in the market, coupled with the retirement of experts within the companies, poses a challenge to the high-tech sector [5]. Such a loss of institutional knowledge not only slows innovation but impacts other aspects of the lifecycle of a system, to the point that selling systems might be hampered by a predicted lack of service support. The industry must democratize both system’s operation and research and development, by prioritizing structured knowledge capture and sharing within the organization, and by leveraging automation and AI to augment human reasoning.

3.2.8 Growing emphasis on sustainability

The high-tech industry is increasingly emphasizing sustainability and circularity (alongside performance and quality). While in the past sustainability and circularity were previously driven by cost-cutting, their importance is now further rising due to additional key drivers: regulatory requirements, customer demands for energy-efficient and sustainable machines, and the need to reduce dependency on critical raw materials. These aspects will become integral to product design, development, maintenance, recycling and disposal, ensuring compliance with future regulations and meeting evolving customer expectations. Integrating sustainability and circularity from the early development phases prepares businesses for long-term success in a competitive market.

4 Lifecycle of high-tech systems

4.1 Stages in the lifecycle

Multiple definitions of a system lifecycle and its stages, with corresponding models, exist within the field of systems engineering, see for example [10]. This subsection clarifies the lifecycles and their stages relevant for the topics in scope of this report: quality assurance and control (including testing), diagnostics and sustainability.

In the context of this document, the relevant lifecycles are as follows:

1. System (product, component) lifecycle from the standpoint of how it organizes engineering processes within an organization.
2. System (product, component) lifecycle with special emphasis on verification and validation (V&V).
3. Lifecycle of products, services and processes from the standpoint of their environmental impact.

These are briefly elaborated below.

System lifecycle as framework for organizing engineering (and organization) activity
According to the ISO 15288 standard [11] (p.11) the **life cycle** refers to the *"evolution of a system, product, service, project or other human-made entity from conception through retirement"*. A **life cycle model** is a *"framework of processes and activities concerned with the life cycle which can be organized into stages, acting as a common reference for communication and understanding".* Typical stages of this lifecycle are shown in Figure 4.1.

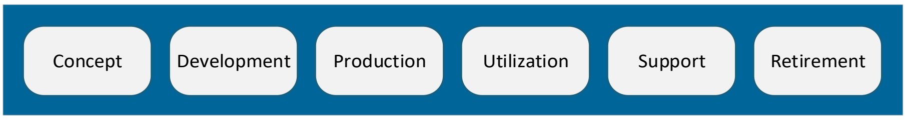

Figure 4.1: The evolution of product development (lifecycle according to ISO 15288 standard)

System lifecycle with special emphasis on verification and validation (V&V)
Different models describe system lifecycle stages and how they relate to each other. One of them is the Vee model (V-model). It shows the lifecycle stages, and it emphasizes within those stages the role of verification and validation (V&V). It associates each development stage with the corresponding test stage [12].

There are many variations of V-models, for a historical overview see [13]. For example, the V-model in Figure 4.2 positions software and hardware testing in the lifecycle, from unit tests towards integration and acceptance testing. The V-model in Figure 4.2 positions V&V in relation to conceptual and more detailed design.

The V-model presents development stages as a sequence, a useful simplification for positioning V&V in the system development stage. In reality, the development of high-tech systems, lifecycle processes are not strictly sequential; concurrency, iteration and recursion may be better represented with nested V-models [12].

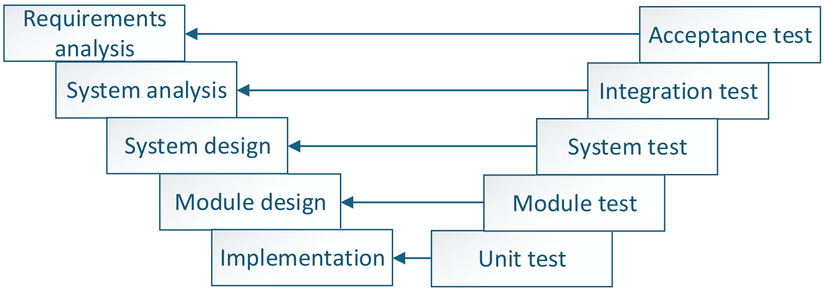

Figure 4.2: A Vee model placing unit, module, system and integration test in relation to development stages.

Lifecycle from the environmental impact standpoint
The environmental impact assessment, including CO2 footprint, of high-tech industrial systems throughout their lifecycle utilizes Life Cycle Assessment (LCA), an approach standardized by the ISO 14040:2006 standard [14].

In this process, illustrated in Figure 4.3, the lifecycle consists of the following stages: Raw material extraction, Material production, Production, Use and maintenance, Recycling and Disposal. In this lifecycle, the high-tech system itself is placed within a larger system, in which raw materials are transformed into materials, and these are transformed into the product. The input into this system is energy, water, land, and the outputs are waste and gases.

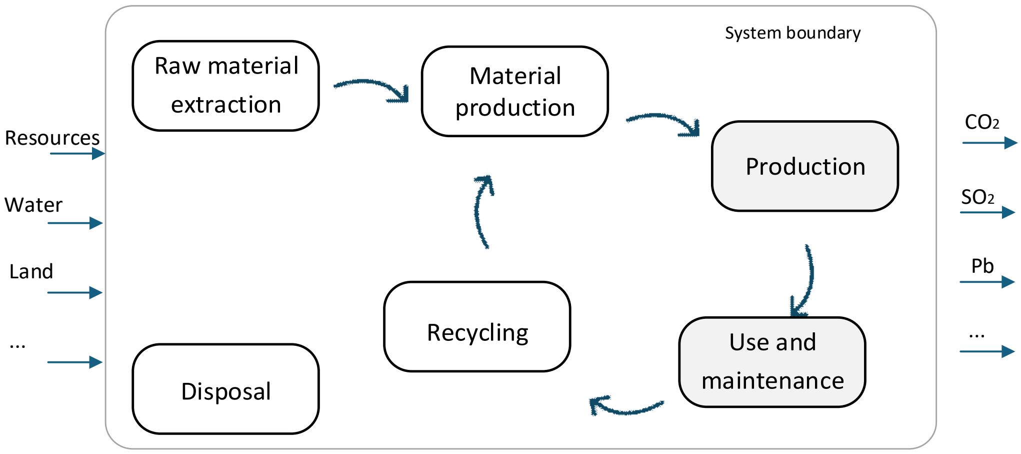

Figure 4.3: The product evolution, from raw materials to the final product. Life cycle stages according to the ISO 1440 standard

The environmental impact of a single product extends beyond the control of a single organization. While a company can manage aspects like manufacturing and transportation, other stages involve multiple stakeholders including suppliers, logistics providers, and waste management companies. For example, in Figure 4.3 the stages coloured in grey are typically in the sphere of influence of one high-tech industrial organization (production and maintenance).

4.2 Existing visions

Below we give a list of visions from systems engineering organizations, applied research, and strategic consulting illustrating the latest views driving lifecycle engineering in the industrial high-tech equipment sector.

- INCOSE Systems Engineering Vision 2035 [15] discusses a future where lifecycle integration is driven by fully model-based systems engineering (MBSE), digital threads,

AI-enhanced simulation, and continuous lifecycle validation across design, operation, and disposal phases, aligned with the ISO 15288 standard [11].
- TNO's High-Tech Industry Vision 2040 focuses on the European scene envisioning that high-tech sectors will realize 150% productivity gains through digitalization, circular design, and new value chain ecosystems [4]. TNO stresses lifecycle excellence as central to competitiveness, autonomy, and sustainability.
- Accenture Technology Vision for High Tech [16] highlights the role of AI, positioning it as an enabler for digital and autonomous product development and service innovation, i.e. AI for system engineering. It emphasizes trust-by-design, ethical engineering, and sustainability integrated throughout the asset lifecycle.
- Paulson & Partners [17] focuses on applied tools for lifecycle optimization in high-tech manufacturing: digital twin simulations, Internet of Things monitoring for operational insight, and product lifecycle management based integration linking upfront design to end-of-life performance.

Across these visions we identify the following common patterns:
- Model-based lifecycle integration: emphasis on MBSE, digital twins, and continuous digital threads linking design, manufacturing and operation.
- Predictive maintenance: real-time data analytics, and automated servicing models to support asset performance and lifespan extension.
- Embedded sustainability: lifecycle thinking is tied to circular economy principles, materials efficiency, reuse/remanufacturing and CO_2 reduction strategies.
- Value chains: from refurbishment and reuse to pay-per-use service systems, lifecycle excellence is viewed as a driver of resilient, resource-efficient new business models spanning the full value chain.
- Closed feedback loops for continuous improvement: real-world usage data informs next-generation design, enabling modularity, optimization, and iterative innovation.
- Human-centered design: systems are designed for transparency, ethical use, user collaboration and to ensure responsible lifecycle decisions.

4.3 Challenges and opportunities

This section addresses the major challenges and opportunities for the high-tech equipment sector in achieving lifecycle excellence across the stages discussed above.

Here and in the remainder of this document we define lifecycle excellence as follows:

> *Lifecycle excellence entails managing products from their inception to retirement so that they are easily upgradeable, long-lasting, available with minimal downtime, reliable, and easy to use and maintain. Servicing is best-in-class and customized to individual market segments (or individual customer) needs. Furthermore, lifecycle excellence means considering, managing, and minimizing the environmental impact of products.*

4.3.1 Related to quality assurance during development stages

The primary goal of a manufacturer of cyber-physical systems is to stay competitive by bringing product innovations faster to market, at lower cost and with promised quality. By maintaining consistency over time, a relationship of trust and reputation is cultivated with users. This trust can easily deteriorate due to a release containing defects in new features, or breaking existing functionality, or due to mismatched expectations of user needs. The

severity of such defects may pose either short-term business risks, or long-term existential risk for organizations. In traditional systems engineering processes, *testing* is a primary means to detect defects and assess quality of the engineered systems. The rigour and representativeness of testing activities to a large extend determine the perceived quality of the final product by their intended customers.
To effectively manage the qualification of complex systems in all their variants, configurations and operating environments, the testing process is typically divided into many phases, with increasing scope from unit, component, integration, system to acceptance testing, as shown in the right-hand part of Figure 4.2.

The key questions about "what to test" and "how to test" must be addressed in each phase, and almost always this requires the participation of several stakeholders from business and technical domains, to collaboratively specify/agree on requirements, identify (internal and external) risks, potential usage scenarios, combined with knowledge of past defects from the field. With these insights, test architects define suitable testing strategies and create plans to mitigate risks and reduce the chances of defect leakage to the field.

To systematically organize testing processes, methodologies such as Test-Driven Development (TDD), and Behaviour-Driven Development (BDD) are widely adopted by industry.
Test-driven Development (TDD), was introduced by Kent Beck in the late 1990s as part of Extreme Programming. It follows the Red-Green-Refactor cycle: developers first write a failing test (Red), then write just enough code to make the test pass (Green), and finally refactor the code for clarity and efficiency (Refactor). This cycle ensures that code is thoroughly tested and continuously improved. Behavior-driven development (BDD) evolved from TDD in the early 2000s, pioneered by Dan North, to make testing more accessible to non-developers. It focuses on the expected behavior of software from the user's perspective, using natural language constructs like Given-When-Then to describe scenarios. This makes it easier for developers, testers, and business stakeholders to collaborate and align on expectations of system behavior. While TDD is more technical and code-centric, BDD emphasizes shared understanding and communication, aligning development with business goals and user needs. However, both approaches have a focus only on automating the execution of test cases, so not on the other aspects that precede it, or succeed it, for instance specification analysis, risk assessment, impact analysis, test planning, test creation, or test analysis.

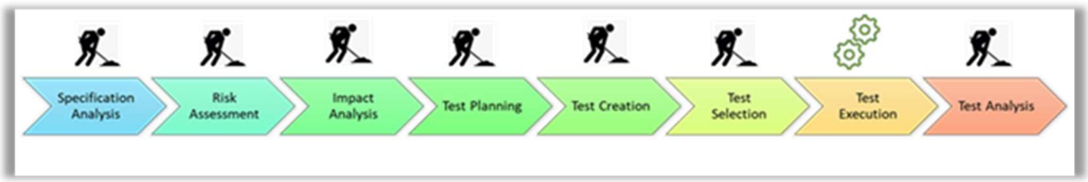

Figure 4.4 Current state of practice in testing relies too much on manual work

As a consequence, despite its rising popularity and adoption, there is growing recognition [18] [19] that BDD incurs significant costs, time without significant gains in preventing defect leakage to the field.

The key driving factors include:
- the *creation* of new test cases (for new functionality) and the *selection* from existing ones (after an update/upgrade) is still a *manual, repetitive, error-prone and intuition-driven* activity, *i.e. handcraft* in Figure 4.4*,*

- over-reliance on *key* domain experts to *qualitatively* determine *what* and *how* to test, means that there is no way to *quantitatively* make any kind of statements about coverage by test cases and the resulting system quality,
- the cost of maintaining test infra and test artefacts increases non-linearly over time.

Clearly the current approach to testing cyber-physical systems in industry is manual, time consuming, relies on hard-to-find experts, and, most importantly, is exploding in both costs and effort. Such approach is not expected to scale with ever-increasing complexity of products over their long lifetimes, while keeping up with rapid advances in technologies. With every upgrade and update to product-lines, testers have to deal with a combinatorial increase in variations of control flow, data and configurations (hardware and software), in order to mitigate the regression impact on existing functionality, while delivering new ones with promised quality. The current state of test automation solutions does not provide test architects with the guidance and means to analytically reason about such complexity, identify risks and mitigate them through high-quality test cases achieving the desired coverage.
So, there is an urgent need for innovations in testing methodologies addressing specification analysis, test planning, test creation, test execution analysis, as well as impact analysis and test selection for product-lines. Furthermore, we need the means to measure meaningful coverage and system quality metrics, which will enable stakeholders to quantitatively assess if the system is sufficiently tested and delivers on promised quality.

Beyond testing, also diagnostics introduces substantial quality assurance challenges during the development stages. A key challenge arises from the architectural trade-offs between system reliability and system diagnosability. Reliability strategies aim to maximize Mean Time Between Failures (MTBF) through redundancy or components with extended lifespans, often incurring in higher initial costs and complexity. Conversely, diagnosability focuses on minimizing Mean Time To Repair (MTTR), primarily by leveraging increased numbers of (diagnostic) sensors for precise fault isolation and faster system recovery.

4.3.2 Related to diagnostics during usage stages in product development stages

During operational usage, complex cyber-physical systems show a diverse spectrum of failure modes originating from various sources, including hardware, software, and the operational environment.

Current diagnostic methodologies during operational and maintenance stages, often adopt a ‘reductionist’ approach by developing isolated solutions for failures from a single source. However, the inherent complexity of high-tech systems necessitates a ‘system-reasoning’ approach, employing multi-domain diagnostic techniques capable of simultaneously addressing all potential failure sources, as the origin of a given fault is often unknown a priori. Furthermore, while component-level diagnostics, particularly for performance prediction, is valuable, the modular architecture of high-tech systems demands a scalable diagnostic strategy. This requires the selection of an appropriate abstraction level, enabling the detection and prediction of faults at both the component and system levels, potentially capturing emergent behaviours arising from interactions across different hierarchical levels. An additional challenge for diagnostics is related to the high-variability and customisability of high-tech systems, which is often referred to as the fact that each system is unique. This directly implies that each systems manifests failures in a slightly unique manner, making it cumbersome to deploy generic, i.e. for multiple systems, diagnostic methods. Resulting in the reliance on experienced service engineers with knowledge on several types of systems to solve diagnostic problems.

To address the complexities of high-tech system diagnostics described above, organizations have traditionally expanded their service organizations. In other words, they relied heavily on human expertise for root cause analysis. While this approach has historically been viable, both economically and in terms of personnel availability, the growing scarcity of engineering experts, as detailed in Section 3.2.7, makes this model unsustainable. Consequently, a critical challenge for the high-tech industry is the strategic transition towards a digitally augmented service paradigm. In this new paradigm, automated diagnostic systems and intelligent algorithms, will reduce the dependence on (manual) human reasoning for resolution of fault. This transition should benefit different diagnostic strategies, namely both reactive and predictive ones.

4.3.3 Related to sustainability and circularity

In practice, there is a growing emphasis on sustainability within the manufacturing industry. However, it has not yet fully been integrated as traditional qualities like performance, cost or safety. Currently, the focus is on factory and process energy savings and often sustainability is considered as a constraint rather than a core value. While there may be abundant data, the ability to make sense of the information contained in the data at the architecting level remains a significant challenge [20].

We identify the following challenges and opportunities. The first challenge focuses on adopting circular and lifecycle thinking across ecosystems of companies, the second addresses aligning sustainability with business models and architectures within a single organization, and the third emphasizes leveraging digital engineering as an enabler for both sustainability and circularity.

1. Sustainability and circularity go beyond the scope of one company. Often, a significant portion of a company’s carbon footprint originates from emissions within the supply chain and at the customer premises where machines are used [21] [22]. One effective strategy for reducing carbon emissions is to introduce circular practices, which requires coordination among suppliers, logistics providers, waste management companies among others. This requires tracking and monitoring emissions in the entire supply chain.

   Beyond acquiring and sharing necessary data, architecting methodologies need to adopt a lifecycle approach and a scope larger than that of one isolated product. This aligns with the INCOSE 2035 vision, which identifies sustainability as a global megatrend and foresees that “sustainability will become a key attribute of the enterprise culture and products” [15]. The challenges of circular systems engineering and the current lack of actionable insights, knowledge reuse and trade-off balancing is described here [23] and in our own work in high-tech industry [24].
   This requires systems-of-systems thinking and lifecycle management, across ecosystems of different not only products but organizations as well. Questions such as interoperability across organizations, governance mechanisms for shared lifecycle responsibilities need further research.

2. Reducing environmental impact while maintaining the business value. Despite the growing importance of sustainability, many customers in the high-tech equipment industry still prioritize costs and performance over environmental considerations. Tighter environmental

regulations are expected in the future, which will require companies to adopt more sustainable practices, but they are not there yet. This means that companies must find ways to integrate sustainable practices that also offer economic benefits to remain competitive.

To address these challenges, systems engineering techniques to deal with uncertainties are needed, which look beyond performance, quality and cost and also incorporate long-term environmental impacts and multiple stakeholders. This requires SE capabilities for trade-off analysis beyond traditional methods, to perform technical and cost trade-off, under expanded scope of uncertainty. These new capabilities should support technical and cost trade-offs under an expanded scope of uncertainty and ensuring decisions balance environmental goals with cost and performance constraints.

3. Twin transition is a shift towards green and digital transition [25], in which digital technologies are envisioned as having a key role in enabling and accelerating environmental goals [26]. High-tech companies introducing digital engineering including MBSE [27] face both the challenge and an opportunity: to strengthen their sustainability ambitions while adopting and expanding these practices. Digital engineering tools and methods including Model Based System Engineering (MBSE) can enhance sustainability efforts, by for example being able to share, manage, monitor data across the supply chain. The challenge lies in undergoing both digital and circular/sustainable transitions simultaneously, ensuring they do not compete for resources, but rather complement and enhance each other.

In summary, to overcome the non-technical challenges, many external preconditions need to be met. For example, collaboration across supply chains and adjustments to business models. In the technical domain - to prepare for future needs, systems architectures and designs should (1) adopt a broader, holistic view incorporating lifecycle and ecosystem architecting approaches (2) align new business models and architectures and (3) leverage digital engineering as an enabler for the twin transition.

5 Research directions

The high-tech sector necessitates focused research across several key areas to develop methodologies for managing the inherent complexities of modern systems throughout their lifecycle. The sections below elaborate on these research directions.

5.1 Quality Assurance and Control

By improving efficiency and effectiveness of current testing process, significant reductions in time to market can be achieved, while ensuring that delivered products have acceptable quality. To achieve this, we identified four main research directions.

5.1.1 Systems Modelling and Verification

The current state of practice in industry still relies on an informal document-driven approach to capture requirements and design artefacts. Such natural language specifications of complex system functionality are typically incomplete, often outdated (over time), varies in quality based on the skills and domain knowledge of the author and risks multiple interpretations by the reader depending on their background. As system complexity is tackled by decomposing the whole into functionally meaningful parts, a trail of design and requirements documentation are created and manually linked to each other by engineers and designers. Such traceability is crucial to properly manage engineering processes, as well as to enable the assessment of impact due to updates or upgrades in the future. However, such static traceability between documents does not enable system architects to reason about the impact on the dynamics (behaviour) of systems and their many variants (configurations). Therefore, such analysis relies on key experts who have years of experience and knowledge about the overall system functionality, rationales for past design decisions, observed defects in the field and are aware of the implicit assumptions in the implementations, based on which they qualitatively (intuition-driven) assess the potential risks of a new release. Besides the inherent risk of such an analysis overlooking critical functional impact, a rapidly shrinking workforce leads to scarcity of such experts, which pose a critical risk to continuity at manufacturing companies.

Vision
From informal document-based requirements and design artefacts to formal model-based systems engineering and analysis to enable early feedback on design issues and missed requirements, as well enabling a shift-left of quality assurance activities to improve efficiency and effectiveness of the systems engineering process

Ambition
Make implicit knowledge possessed by key domain experts and scattered documentation, explicit in formal models of system requirements and design.
Lower the entry barrier to modelling by making them intuitive and domain-specific.
Ensure scalability of models through traceable abstractions and views.
Empower system architects and designers to assess the correctness of requirements and design specifications, as well as conformance between high-level and detailed specifications.
Prescribe sound design guidelines and patterns for systems modelling.

Goals

- Develop the means to formally capture requirements such that it is adoptable by engineers and architects in industry
- Formalize the semantics of industry standard modelling languages such as SysML and BPMN (suitable subset) to make them suitable for model checking, code generation, model-based testing, etc.
- Define behaviour preserving transformations between popular modelling languages such as Cocotec [28], ComMA [29], Dezyne [30], SysML [31]) and BPMN [32] to enable interoperability and reuse.
- Develop design guidelines and patterns to create sound system specifications
- Develop scalable model checking capabilities to check conformance of design specifications w.r.t. their requirements
- Develop provably correct transformations to synthesize software implementations and from system models
- Reduce the modelling effort by means of AI assistants

5.1.2 Efficient and Effective Testing of Product-Lines

Testing product lines presents several unique challenges due to the inherent complexity and variability of these systems. Unlike single-system testing, product lines involve a family of related products that share common features but also differ in specific configurations. This variability leads to a combinatorial explosion of possible product variants, making exhaustive testing practically infeasible. Testing methods in the high-tech equipment industry have not kept pace with ever-increasing complexity of their product offerings. As a result, the time and effort needed to deliver promised system quality is exploding, but often under-estimated. As more domain experts retire from the workforce, coupled with a scarcity of skilled engineers, it is becoming increasingly important to create break-through innovations to improve the efficiency and effectiveness of testing processes in industry. Ensuring consistency and correctness across all variants requires sophisticated techniques such as feature modelling, variability-aware testing, and automated test generation. Moreover, maintaining traceability between features and test cases, managing evolving requirements, and integrating testing into continuous development pipelines further complicate the process. These challenges demand a strategic balance between test coverage, efficiency, and scalability.

Vision

Testing product-lines presents a significant challenge due to the combinatorial explosion of hardware and software configurations, which makes exhaustive testing impractical. Our vision is to address this complexity by developing methodologies that effectively select representative configurations and relevant test cases, while minimizing any negative impact on product quality by incorporating knowledge from domain experts about potential risks from new developments and/or from past issues detected in the field by customers.

Ambition

Model-based testing is a promising technique that can help address the short-comings of current testing methods in industry. By capturing knowledge about the system (and its variants [33]) as formal models, model-based testing techniques [34] can automatically generate high quality test suites. Such test suites are typically infeasible to be created by handcrafting them due to limited time and resources. However, much research is still necessary to extend model-based testing methodologies to deal with variability aspects of product-lines, across the testing lifecycle, i.e., component, system and system-of-systems testing phases. To simplify adoption of new methodologies, particular attention must be paid towards ease of modelling aspects and the relation to industry standards, such as SysML and BPMN. For MBT, more research into scalable and effective data generation techniques is urgently needed.

Goals

- Support variability modelling of product-lines by extending industry standard modelling and test specification languages
- Formal semantics and language extensions to industry standard modelling languages to make them suitable for MBT applications
- Develop state-of-the-art test generation techniques for product-lines, with particular attention to effective test data generation [35] [36] and variability handling techniques.
- What are effective strategies to specify and use test purposes capturing identified product risks and testing requirements to steer test generation to produce test cases that cover them.
- Develop MBT methodologies to improve the shortcomings of existing test automation frameworks/tools.

5.1.3 Change Impact Analysis and Regression Test Selection

Evolution is a constant challenge of brown-field systems development (i.e., iterations of an existing product(s) to create new ones). The current state of testing tools available to industry lacks any kind of automated reasoning to determine what to test whenever there is a change to the system or its specifications. In standard industry practice, experts based on their deep domain knowledge and gut-feelings take a risk-based approach to qualitatively answer this question. As a result, there is no way to quantitatively assess the effectiveness of the testing processes and the quality of the tested product. To improve efficiency and effectiveness of testing processes following a change (due to an update or upgrade), we need automated techniques to select the relevant configuration sets and test cases based on analysis of changes to system requirements, design, or software.

Vision

Typically, a retest-all strategy after a change to specification or products does not scale at the system level due to the amount of time and resources needed. As industry slowly shifts away from a document-based approach to a model-based approach, opportunities are opening to apply state-of-the-art techniques for change impact analysis of specifications and based on that select relevant tests and configuration sets to run them on. Our vision is to provide answers to the crucial question: how to provide guarantees that this selection covers for all the changes?

Ambition

Develop theoretically grounded [37] [38] and sound algorithms for selecting regression test configuration sets with guarantees on covering impact of specification changes.

Goals

- Develop novel automated techniques for change impact analysis of requirements and design specifications, and classification of change sets.
- Develop automated regression test-configuration selection based on impact analysis
- Account for product risks identified by domain experts (e.g., FMEA etc.) as part of modelling, for instance using test purposes.
- Develop techniques to exploit usage profiles from the field to better focus testing efforts based on how customer’s use the system.
- Define a classification of specification coverage metrics and provide the means to compute them and relate them to domain-specific risks and priorities.

5.1.4 Establishing the Test Pyramid

Testing complex systems can be managed effectively by conducting the process in phases. Testing in the early phases, such as unit and component (integration) testing, focus on verification of system design, while later testing phases, e.g. system and acceptance testing, consider validation of user requirements. In practice, most companies strive for a test pyramid approach, i.e., more testing at lower levels and less on higher levels to keep withing limited cost and time budgets. However, there is a lack of a systematic methodology to achieve the test pyramid without compromising on quality. To address this gap, we need formal techniques to help automatically optimize testing effort across the test lifecycle by exploiting what has been tested in the prior phases.

Vision
Testing typically happens in phases across the product development lifecycle, e.g. unit, component, integration, system, acceptance, and SoS. It is a common situation in practice that prior testing efforts (coverage/issues found) are not considered in the later phases of testing to optimize on what to test. The fundamental question we want to answer here is whether testing can truly be compositional. In other words, if we test parts of the system with very high specification coverage, can we skip certain tests when we test the combination of the parts, without compromising on product quality?

Ambition
Develop theoretically grounded methodologies to enable refinement of high-level specifications into low-level ones, to enable semantic traceability between them i.e., based on conformance checking [39] of behaviour between the linked engineering artefacts, instead of relying on manually added static links based on the intuition and knowledge of an engineer. Based on such traceability, we want to optimize [40] the volume of tests across the phases with guarantees that no product functionality went untested, i.e., without compromising test coverage and product risks.

Goals
- Develop novel techniques for refinement of requirements and design specifications to automatically establish semantic traceability between high level specifications and their low-level detailed ones.
- Develop novel techniques for compositional MBT which will enable leveraging the test coverage achieved in earlier phases of testing (unit and component phases) to focus more on the gaps during later phases of testing (system and acceptance phases).
- Develop a classification of coverage metrics and the relation to product quality

5.1.5 AI-assisted Testing

While model-based testing (MBT) methodologies have demonstrated their potential to enhance the effectiveness of software testing processes, their broader adoption remains limited due to several persistent challenges. These include the substantial modelling effort required, the lack of specialized competencies among test engineers, and the inherent complexity of real-world systems—particularly stemming from the combinatorial nature of the solution space. Recent advancements in artificial intelligence (AI), especially in large language models (LLMs), offer promising avenues to address these limitations. Widely adopted applications such as conversational agents, automated text generation, and code synthesis illustrate the potential of LLMs to bridge the semantic gap between natural language specifications and formal model-based representations. Furthermore, their capacity to identify patterns in large-scale datasets can be harnessed to optimize and automate key testing activities, including test planning, specification authoring, implementation, and maintenance.

Vision
Investigate whether and how AI-based solutions can be used to improve efficiency and effectiveness of testing cyber-physical systems(-of-systems) in industry.

Ambition
Several recent studies expose serious limitations about the correctness and trustworthiness of LLM-based solutions to code generation and test generation tasks. To alleviate these limitations, there is rising interest by the research community to combine [41] the strengths of AI-based solutions (semantic parsers) and formal methods (symbolic reasoning). We want to leverage [42] the capabilities of LLMs to address the limitations [43] of classical model-based testing techniques (modelling effort and dealing with the combinatorial explosion of solution space) using latest prompt engineering techniques [44], such as Zero-shot and Few-shot learning, Chain-of-Thought, and Self-Consistency.

Goals
We want to find out whether and how AI-based solutions can be used to augment symbolic approaches to improve
- the efficiency of the model creation process from natural language specifications
- the risk assessment and test planning process by analysing usage profiles from the field and defect databases.
- the efficiency and effectiveness of the test creation process
- the prioritization and selection of regression testing process.
- the efficiency of the root-cause analysis process due to test failures.

5.2 Intelligent diagnostics

We see three main research directions related to intelligent diagnostic, connected to the usage and maintenance stages of the system lifecycle. For a broader view on this topic, we refer the reader to [1].

5.2.1 Enabling root cause analysis of performance issues at system-level

Vision
Diagnosing performance issues in high-tech industrial systems presents a significant challenge. Methodologies exist for diagnosing hard-down system failures, i.e. when the system stops working, and the challenge is applying them at large scale, i.e. systems with many components. However, a similar, broadly applicable approach is lacking for performance issues. These issues, characterized by sub-optimal operation, e.g., reduced throughput or product quality, rather than complete failure, are often more difficult to resolve due to the numerous potential contributing and balancing factors. Digital assistance is envisioned as the key to rapidly identifying the root causes of these performance degradations.

Ambition
Building on established expertise in diagnosing hard-down system failures, a research effort should be undertaken to focus specifically on performance diagnostics. Collaborating with

industry partners who face their own specific diagnostic challenges in this area, this research effort should aim to develop a broadly applicable methodology for performance diagnostics. This approach will leverage both design knowledge and real-world operational experience, from service engineers and subject matter experts, to effectively address performance issues.

Goal
Develop or extend a methodology that supports reasoning for performance issues to reduce the time spent by the high-tech industry on diagnosing complex performance issues.

5.2.2 Reducing unscheduled system downtime through prognosis

Vision
Preventing the system from unexpectedly stopping or reducing performance is the final goal for the high-tech industry. Unscheduled system downs should be avoided and replaced by scheduled maintenance actions, to maximize the overall system's effectiveness.

Ambition
While most predictive maintenance approaches rely on the availability of historical or simulated data at component level, it is more challenging to predict upcoming maintenance actions at system level. Our ambition is to develop a methodology to effectively assess what many component-level performance predictions mean for the whole system's performance prediction. Currently, this process is cumbersome, so methods need to be developed to bridge the gap from component-level health prognosis to system-level effects.

Goals
To meet the demands of the Dutch high-tech industry, our goal is to develop new methods to:
- forecast the future health state at the system level.
- assess the resulting implications of these forecasts for the system to meet its performance requirements.
- use these forecasts to proactively schedule necessary maintenance or propose effective mitigating actions.

5.2.3 Field learnings and causal discovery: increase the impact of knowledge

Vision
For any successful diagnostic and maintenance strategy, many sources of information are required, e.g. knowledge about the system's design, physics laws of different domains, and learnings from the field. All these sources should strengthen each other to bring intelligent diagnostics to the next level.

Ambition
In industry, closing the feedback loop from systems in the field to the design is challenging. For instance, even structured sharing of diagnostic learnings within a service organization is not trivial. Our ambition is to develop a framework to compile a central knowledge base for diagnostics, including relevant information on the system from all disciplines and field learning. This framework will enable structured data sharing and collaborative learning. Furthermore, our ambition is to use techniques such as causal discovery and rule-based reasoning on the knowledge base to learn about undiscovered (failure) mechanisms.

Goal
The goal is to develop methodologies that allow to infer new diagnostic knowledge from the existing base, while ensuring all knowledge (existing and new) adheres to the central architecture, e.g. ontology, designed to unify this information.

5.3 Environmental Sustainability and Circularity

This research direction addresses trends 5,6 and 7 described in Section 3.2.

Vision
The high-tech equipment industry is an integral part of a thriving circular economic ecosystem, including suppliers, logistics providers, recycling facilities, and other stakeholders. As such, large companies (high-tech equipment makers) and SMEs implement circular strategies that maintain or increase business value. (System) engineers design and architect products and services with lifecycle considerations and the broader business ecosystem in mind, ensuring sustainability and circularity are embedded into every aspect of their operations.

Ambition
Advance and specialize Systems Architecting and Systems Engineering methodologies to help R&D's introduce circularity and sustainability without compromising on other qualities. Develop necessary frameworks and methodologies that guide R&D's in communication with their business on the product roadmaps, guide architects and domain experts in what methods and techniques to use when, when designing for sustainability.

Goals: To meet the demands of high-tech industry we aim to address the following.

- There is a step needed from product scope towards an enterprise and even larger, a business ecosystem scope. How to design a product, how to design a manufacturing and logistics system, how to architect an ecosystem that provides eco-value, and at the same time gets profit and business value. We aim to develop systems-of-systems architecting approaches and lifecycle-based methodologies that enable interoperability, governance, and shared responsibilities across circular ecosystems of organizations and products.
- Among a broad umbrella on systems engineering approaches, and standards, architects and engineers need guidance for introducing or maturing sustainability and circularity as a system quality. The guidance is needed to support in decisions what techniques and methods to use when; in different stages of the project life cycle, and when aligning with different stakeholders.
- Circularity and sustainability are not isolated qualities, neither the most important ones. Therefore, methods are needed to combine them with other non-functional aspects, such as maintainability and availability (related to diagnostics and testing). The systems engineering community recognizes the need to advance methods for so-called loss-driven qualities. Yet, this work is relatively new and not mature yet. For example, a work towards combining loss-driven quality is an area where we can contribute. Figure 3.1 illustrates possible relationships between sustainability, circularity, and system availability.
- Frameworks and guidelines are needed for using digital engineering tools (MBSE, digital twins) to monitor, share, and manage lifecycle data, ensuring digital and green transitions complement each other.

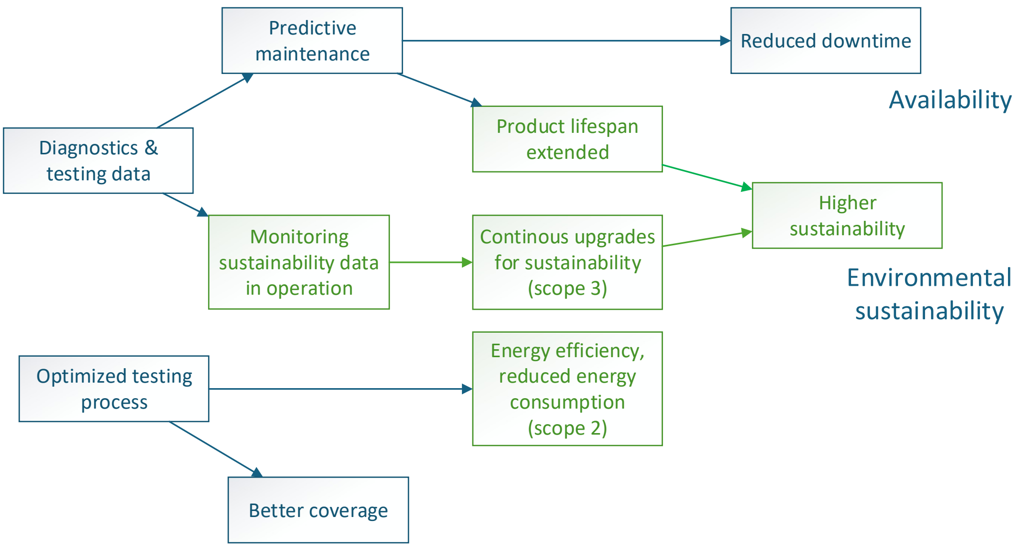

Figure 5.1: How better testing and diagnostics also help better sustainability (this picture does not show negative influence of emissions when AI is used to improve testing, diagnostics and design for sustainability)

5.4 Orchestrating the supply chain

Vision

High-tech systems rely on a complex supply chain of specialised components and materials sourced from a global network of suppliers. The dependability of a system then depends not only on itself but on also on the supply chain on which it relies. This applies not only during system operation but also for its timely installation. The supply chain also extends from the system itself to system-of-systems level. For example, in a fab where the quality of the production depends on the overall supply chains of all its systems. Ensuring and orchestrating the optimal operation of all these chains is a great challenge. In our vision, the bi-directional transfer of data and information, for example simulation or analysis models, across different entities throughout these networks of supply chains is of crucial importance.

Ambition

Typically, systems components acquired from a supplier are either standard components or built according to the buyer's requirements. In the former case, there is minimal information transfer between the supplier and the buyer. In the latter case, there is information transfer from the buyer to the supplier, in the form of requirements. Our ambition is to close and strengthen the loop in two ways: to transfer information and models from the supplier to the buyer and to transfer operational data from the buyer to the supplier. This should be primarily for the component being built based on requirements, but ideally also for standard components. This will unlock the potential to improve diagnostics and overall system quality by enlarging the optimization space of key aspects of a system, for example the definition of field replaceable units, and by pushing diagnostics further up in the chain.

Goal

Develop a methodology that allows the transfer of information, models and operational data across the supply chain of high-tech systems, back and forth between suppliers and buyers.

5.5 Handling data securely during the full lifecycle

Vision
Data collected from complex high-tech systems is the cornerstone for continuous innovation and optimization of system productivity. Our vision is to fully operationalize the potential embedded within this data through a framework that spans the entire system lifecycle. This requires establishing a continuous, data feedback loop that transforms raw data into actionable insights for future designs and enables predictive maintenance in existing systems. Realizing this vision necessitates the development of data handling architectures where data integrity and confidentiality are security primitives central to the entire framework [45].

Ambition
Our ambition is to develop a unified framework that prioritizes data handling, by considering it from the concept stage of a system's lifecycle, rather than treating it as an afterthought. Such a framework should have data security and its business value as its core, and should be designed to facilitate compliance with evolving data regulations, e.g. GDPR [46], and industry-specific standards like ISO 27001 [47].

Goals
The development of methodology that allows the full exploitation of business-critical information hidden in data coming from high-tech system by covering the following aspects:
- Secure and resilient data pipelines
- Optimised sensor placement
- Scalable and flexible data storages

5.6 Combining different aspects

Vision
High-tech industrial systems must adhere to a diverse set of qualities, including functional suitability, reliability, maintainability, and security ISO 25010 [48]. While some of these qualities remain relatively stable over time and across various systems, others are inherently fluid, evolving rapidly with emerging technologies and shifting business demands. Security and sustainability, for instance, are dynamic qualities requiring continuous adaptation. Each quality presents unique challenges and necessitates specialized expertise to ensure effective implementation. Furthermore, the relative importance of these qualities varies significantly across the system lifecycle. During the initial design and development stages, the focus is often heavily weighted towards functional suitability, ensuring that the system meets its core requirements. As the system transitions into utilization and support, the priority shifts towards performance efficiency and maintainability, to achieve overall equipment effectiveness. In this context our vision is to enhance quality engineering for high-tech systems by transitioning from (lifecycle) stage-specific expertises to a more holistic lifecycle-wide approach.

Ambition
Our approach will focus on two key strategies: first, extending expertise focusing on a single quality to cover multiple lifecycle stages; and second, developing expertise in addressing multiple quality attributes within a single lifecycle stage. See Figure 5.2 for a visual representation. The overarching goal is to minimize risks associated with single-stage optimizations, thereby safeguarding overall equipment effectiveness throughout the lifecycle. This strategy aims to prevent costly retrofits, operational inefficiencies, and security

vulnerabilities. To achieve this, we can leverage existing tooling and modelling paradigms, mirroring the approach of unified modelling in intelligent diagnostics for maintainability, as discussed in [1].

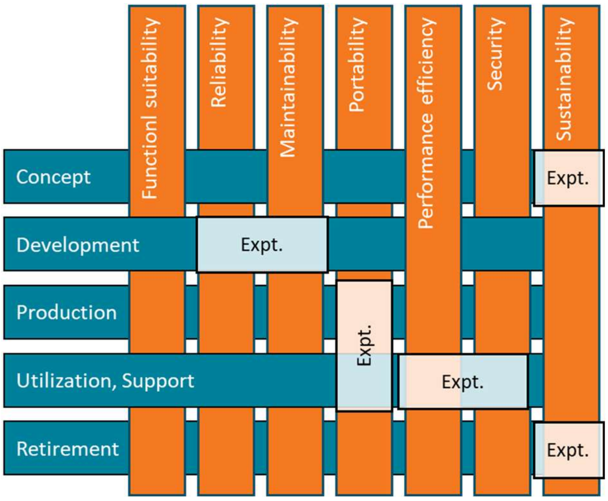

Figure 5.2 Addressing different qualities of a system across its lifecycle via expertises (expt.)

Goals
Develop methodologies to support engineering of system qualities across multiple phases of the lifecycle, by:

- implementing cross-training to ensure experts can address multiple quality attributes within a system's operating lifecycle.
- developing frameworks to prevent single quality optimizations.

5.7 Human-Centric design

Vision
Achieving the resilience and sustainability goals of Industry 5.0 presents a significant opportunity to evolve high-tech system design [49]. Currently, systems often fall short of their full operational potential because their initial architecture does not fully integrate the long-term needs and operational context of human users. Our vision is to close this gap by introducing a human-centric design approach. Prioritizing and optimizing human-system interactions across every phase of the product lifecycle. By embedding advanced technologies like AI, our vision is to cultivate a symbiotic relationship between the digital system and its human operators. This strategic focus guarantees superior operational dependability and ultimately delivers significantly extended system longevity.

Ambition
One of the challenges of human-centric design is creating intuitive systems that meet both the users' needs and business objectives, increasing user satisfaction and adoption rates and therefore leading to longer lifecycles. One of the ways to address the need to balance these sometimes-conflicting viewpoints is to develop cross-functional collaborations (designers, marketeers, engineers and business analysts) and to develop metrics and key performance indicators (KPIs) that can measure the alignment of user needs with business objectives.

Goals

Investigate how business models can be designed to prioritize user needs while achieving business goals, more specifically:

- identify best practices for advancing collaboration and aligning diverse perspectives.
- create a framework for evaluating the success of human-centric design initiatives with metrics such as user satisfaction, task success rates, and business outcomes like revenue and market share.

6 Conclusions

To effectively address evolving sociotechnical trends, as described in Section 3.2 of this report, the high-tech sector must strategically adapt its approach to engineering systems across their complete lifecycle. This report identifies seven key directions for this necessary adaptation, which are detailed in Section 4. The overarching strategic directions necessitate a fundamental shift in perspective, as summarised below:

Extended lifecycle scope: the conventional concept of a product lifecycle, focused on a singular product or product family, must be broadened to incorporate the entirety of the supply chain and the encompassing ecosystem within which the product(s) operate. This expanded view is crucial for realizing operational excellence via the deployment of intelligent diagnostics throughout the supply chain. Furthermore, it will provide the requisite framework for defining and achieving circularity principles, and meeting increasingly critical sustainability targets.

Enhanced automated testing: to ensure quality assurance, testing methodologies must transition towards a decreased dependence on manual labour and embrace comprehensive automation. Artificial intelligence (AI) will be pivotal in this evolution, enabling AI-assisted testing methods and addressing the emergent challenges associated with testing systems that integrate embedded AI functionalities.

Strategic data utilization and robust data architectures: data will function as a fundamental element for informed decision-making and the realization of the aforementioned strategic directions. Consequently, the development of robust and well-defined data architectures is paramount. The design of these next-generation architectures must integrate new considerations, with a specific emphasis on ensuring comprehensive security measures to safeguard sensitive information and maintain system integrity.

Shift to human-centric design: the lifecycle of future high-technology systems must explicitly consider and prioritize their interactions with human users at each phase of development and deployment. This human-centric approach aims to cultivate a more intuitive and effective integration of technology into human activities, ultimately enabling a symbiotic relationship between digital system and human operators and ultimately ensuring operational excellence.

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