

Application of a Systematic Approach for Monitoring Between Foresight and PEP in the C2CBridge Project

Carsten Thümmel, Nils Ansbach, Andreas Siebe, Tobias Düser and Albert Albers

Institute of Product Engineering (IPEK)

Karlsruhe Institute of Technology (KIT)

Karlsruhe, Germany

carsten.thuemmel@kit.edu, nils.ansbach@student.kit.edu, andreas.siebe@kit.edu,
tobias.dueser@kit.edu, albert.albers@kit.edu

Abstract

In product engineering processes, foresight analyses are typically conducted only at early project stages, while their underlying assumptions remain largely unchallenged as development progresses. This can lead to late design changes and increased correction costs when environmental conditions, technologies, or market requirements evolve. To address this gap, this paper applies a systematic approach for continuous monitoring and validation of product properties throughout the product engineering process. The approach integrates strategic foresight, environmental scanning, and indicator-based monitoring into a continuous feedback loop that enables early identification of relevant deviations from expected developments. The approach is demonstrated using a case study from the project Country to City Bridge (C2CBridge), a research initiative focused on developing user-centered, intermodal mobility solutions. The application is deliberately limited to the vehicle concept to ensure methodological clarity. The results show that systematically linking trends, prognoses, indicators, and product characteristics allows the identification of sensitive product properties and key indicators that are critical for long-term product robustness. Furthermore, the case study reveals methodological refinement needs, particularly regarding evaluation schemes, normalization of assessment scales, and usability in practical application which is partially implemented. Overall, the findings indicate that continuous monitoring can significantly enhance decision-making robustness and adaptability in long-term product development under uncertainty.

Keywords

Foresight, methods, mobility, needs, product engineering.

1. Introduction

In a world that is changing faster than ever, market needs, demand, and product requirements become increasingly dynamic. This creates a challenge for companies to meet evolving market demands throughout lengthy product-development cycles while remaining competitive. (Albers et al., 2021) In the 19th century, Charles Darwin demonstrated that survival hinges not on strength or intelligence but on the capacity to adapt swiftly to change (Harris, 2009). Schumpeter's theory of "creative destruction" articulated that economic progress emerges from the continual replacement of outdated structures by novel ones, making innovation a pivotal driver of market success (Schumpeter, 1912). These foundational ideas resonate strongly in today's business environment, where rapid technological advances and volatile market conditions demand that firms constantly reinvent their products and services.

Product development faces a paradox: the design and engineering phases often span several years, while customer preferences, regulatory landscapes, and competitive pressures evolve continuously (Cooper & Kleinschmidt, 1993; Weissenberger-Eibl & Almeida, 2019). Early-stage foresight activities, such as scenario analysis, allow organizations to embed anticipated future requirements into the product-engineering process (PEP) and to align initial specifications

with long-term market expectations (Albers et al., 2013; Fink & Siebe, 2016). However, as the PEP progresses, the assumptions that underpinned those early decisions tend to lose relevance, creating a risk that subsequent design choices are based on increasingly outdated expectations (Siebe, 2018).

Recent literature acknowledges that strategic foresight has only been partially integrated into the PEP and that systematic monitoring of product properties remains underdeveloped (Albers, Dumitrescu, et al., 2018; Thümmel, Schwarz, et al., 2023; Weissenberger-Eibl, 2025). Without a mechanism to regularly validate and, if necessary, adjust the underlying assumptions, firms may overlook shifts in customer needs or regulatory requirements, leading to costly redesigns, delayed market entry, and erosion of competitive advantage (Marthaler, 2021; Thümmel, Kleinschrot, et al., 2023).

Addressing this deficiency, the present paper uses a framework that continuously assesses the validity of foresight-derived assumptions throughout the entire PEP. The framework was previously developed as part of the overarching research (Thümmel, Ebi, et al., 2025; Thümmel, Schmidt, et al., 2025) in which this paper also belongs. By coupling scenario-based anticipation with real-time monitoring of market signals, regulatory updates, and technical constraints, the framework enables decision makers to proactively recalibrate product specifications, thereby mitigating downstream redesign costs and preserving market relevance. Within this paper the framework will be evaluated through a case study demonstrating its applicability and identify potential for improvement.

2. State of Research

2.1 Product Engineering Process – From the Idea to Innovation

The product engineering process (PEP) is part of the product life cycle and encompasses all activities from strategic planning and product development to production system development and the start of production. It can be understood as an "interplay of different activities" (Albers & Gausemeier, 2012). Product development in the early phases is particularly critical, as decisions made there strongly influence subsequent stages and largely determine overall project success (Cooper & Kleinschmidt, 1993; Verganti, 1997). Product development is a continuous interplay between the system of objectives, the operating system, and the system of objects (Ropohl, 1975).

Building on this system triplet, Albers, Reiss, et al. (2016) developed the integrated Product engineering Model (iPeM), which structures the PEP into phases with core and support activities. Within iPeM, multiple product generations, the associated production systems, overarching strategies, and validation systems are represented on different levels (Albers, Reiss, et al., 2016). Products and systems are typically developed across generations based on reference systems. To describe this, Albers and Rapp (2022) introduced the descriptive model of System Generation Engineering (SGE). In this view, products are conceived as systems that are perceived and used as products, while several successive generations are developed in parallel but at different stages of maturity. Elements of the reference system are transferred into new system generations through mechanisms such as adoption, differentiation, and principle variation (Albers, Kürten, et al., 2022). The activities validation and verification are considered fundamental elements in the PEP (Albers, Behrendt, et al., 2016). These two activities are very important from the beginning of the development because the later changes must be made, the more expensive the development becomes and is therefore subject to losses. This is described by the "Rule of Ten" according to Ehrlenspiel et al. (2020).

Foresighted, systems-oriented development forms the basis for future innovation (Albers & Gausemeier, 2012). Innovation is often defined as the successful realization of a technical invention in the market as a product (Schumpeter, 1939). Albers, Heimicke, et al. (2018) extended this understanding with the concept of the product profile. A product profile models the situation of needs and the benefits for provider, customer, and user, thereby delineating a solution space for product design and enabling a systematic validation of benefits. This aligns with Patnaik and Becker (1999), who argue that development activities should initially focus on understanding needs rather than specifying solutions, in order to keep the solution space open and avoid premature fixation.

2.2 Strategic Foresight – Looking into the Future

Rapid technological progress, political change, and increasing societal uncertainty have intensified the need to better anticipate future developments (Schwarz, 2023). One of the main reasons for using strategic foresight in product development lies in the long iteration cycles and long development times of complex products, as well as the ambition to generate innovation (Gausemeier, 2019). While strategic foresight was initially treated as a separate process, it is increasingly being integrated directly into the PEP (Müller, 2008).

Strategic foresight originates from future management, whose purpose is to enable organizations to respond adaptively and quickly to anticipated changes (Westkämper, 2006, 2009). With increasing time horizon, three levels are distinguished: operational, tactical, and strategic. Depending on the time horizon addressed, different instruments of foresight are used: prognoses (short-term), trends (medium-term), and scenarios (long-term) (Siebe, 2018). Scenarios are intended to depict possible future developments. In contrast to trends, they are based on open and interconnected thinking and can be constructed with different focuses, for instance on the environment, customers, or technologies (Fink & Siebe, 2011, 2016).

The scenario technique according to Gausemeier et al. (1998) consists of five main steps. Starting from an analysis of a predefined scenario field—often described with a system model—factors that characterize the current situation are identified. From these, a manageable set of key factors is selected based on evaluation criteria. For each key factor, alternative future projections are formulated along two defined dimensions. Scenarios emerge from the plausible combination of one projection per key factor. They are positioned on a map of the future space and described in detail. Finally, measures can be derived via scenario transfer, linking foresight results to strategic decision-making and planning (Gausemeier, 2019; Gausemeier et al., 1998; Siebe, 2018).

Besides supporting the strategic orientation of companies, scenarios and other foresight instruments are increasingly used to derive product properties and characteristics for integration into the PEP. The objective is to anticipate future market requirements and customer needs by integrating elements of trend and future research (Weissenberger-Eibl & Almeida, 2019). Meyer-Schwickerath (2014) examined how scenario techniques and strategic early warning – derived from strategic foresight – can be linked to the PEP within the iPeM framework. He showed how foresight results can be embedded into the PEP via the system of objectives. Building on this, Albers, Dumitrescu, et al. (2018) pointed out the need for a methodological bridge between envisioned futures and technical subsystems. Albers, Marthaler, et al. (2022) developed an approach for deriving product profiles and properties of future product generations based on strategic foresight. These properties are assessed for their future relevance, among other methods using the Kano model. If certain properties consistently contribute to customer satisfaction across different scenarios, they are considered future-robust. The resulting properties form an important basis for defining the PEP's system of objectives (Marthaler, 2021; Meyer-Schwickerath, 2014).

Thümmel et al. (2022) distinguish between future-oriented and future-robust product development strategies. Kuebler, Schuster, et al. (2023) proposed another foresight-based approach that focuses on planning upgrades and updates for products. Product properties derived from scenarios are classified as either static or dynamic. Static properties are robust across multiple scenarios and can be designed with long-term stability in mind, while dynamic properties should be designed in an upgradable manner so that products can be adapted to different future developments. The combination of such properties enables the definition of product scenarios, which represent alternative product configurations analogous to environmental scenarios. In both future-robust and upgrade-oriented approaches, roadmaps can be generated to prioritize development activities and plan product evolution over time. (Albers et al., 2023; Kuebler, Schuster, et al., 2023; Kuebler, Thümmel, et al., 2023)

2.3 Monitoring in Strategic Foresight and Product Engineering

Monitoring is defined as the “targeted, continuous observation of specific sections and objects of a system to record information about activities and changes” (Sieg, 2007). It is a fundamental activity in companies and is already firmly established in various areas. Within the PEP, monitoring supports the assessment of the status of research, development, and production (Gruber et al., 2003; Gruber & Venter, 2006).

In strategic foresight, monitoring is an essential component of the process due to the high rate of change in the environment. It ensures that developments are observed continuously and that their implications can be reassessed. Monitoring is embedded in both scenario controlling and trend management and thus directly influences the evolution of key factors in scenarios (Fink & Siebe, 2016). In scenario controlling, the relevant areas of the future space defined by the scenarios are regularly examined to identify unforeseen environmental changes at an early stage. The first step is to determine whether and how these changes affect the initially assessed probabilities of the scenarios. Trend management deals with developments over time by continuously observing known trends and identifying new, unexpected trends. Such changes are documented and, if necessary, transferred into the existing scenarios in the form of new or adapted projections.

An analysis of various scenario development methods has identified influencing and key factors as central elements and therefore as promising starting points for monitoring. However, a subsequent examination of available monitoring methods revealed a lack of structured approaches for continuously integrating monitoring of future environmental developments into the PEP (Thümmel, Kleinschrot, et al., 2023). This indicates a need for methodological support. To address this gap, Albers et al. (2024) introduced a specific definition of monitoring in the context of the PEP. In this understanding, monitoring is classified as part of validation activities. It systematically searches for information on previously identified indicators that are relevant for the future environment. Through structured observation during product development, monitoring is intended to support cross-generational recognition of changes and to enable the initiation of appropriate actions. To evaluate product alignment and detect deviations, product profiles have been positioned within the future space using equivalent scenarios (Thümmel, Kiss, et al., 2024). Further, building on a developed descriptive model (Thümmel, Urbina Puch, et al., 2024) and a process model (Thümmel, Heller, et al., 2024), an approach for continuous monitoring of product properties between strategic foresight and the PEP was developed (Thümmel, Ebi, et al., 2025; Thümmel, Kuebler, et al., 2025; Thümmel, Schmidt, et al., 2025). The approach comprises three activities: Preparation, Metric and Monitoring Activity.

3. Methodology

3.1 Research Need and Research Goal

In the product engineering process (PEP), engagement with future developments is currently performed only sporadically. Typically, a foresight analysis is conducted at the project's initiation, and product parameters are derived and fixed based on its results. As the PEP progresses, the underlying assumptions are rarely re-examined in a systematic way, even though contextual conditions, requirements, and market demand evolve over time. Consequently, later development decisions may rely on outdated expectations, and necessary adjustments are often made late – resulting in high correction costs.

To close this gap, Thümmel, Schmidt, et al. (2025) propose a systematic approach for continuous monitoring that repeatedly subjects the initial assumptions and derived parameters to a target-actual comparison throughout the entire PEP. Deviations are identified early and assessed by an interdisciplinary expert panel. Based on this evaluation, informed decisions can be taken to adjust requirements, target values, and design specifications as needed. The overall aim of the monitoring framework is to reduce development risks and to allocate time and resources more efficiently within the product engineering process. In this paper, the developed approach will be applied to a case study which should show its applicability. Furthermore, potential for improvement should be identified to enhance the framework.

3.2 Research Methodology

To reach the goal set, the following research question was derived: “What methodological adaptations and development potential can be derived from the experiences gained by applying the systematic approach for continuous monitoring to the project C2CBridge?”

Following the Design Research Methodology (DRM) by Blessing and Chakrabarti (2009), this research utilizes a case study as an application evaluation. By implementing the proposed approach within a live project, the study aims to assess its usability and applicability in a complex design environment. This descriptive approach provides empirical evidence on whether the proposed support effectively addresses the initial research criteria under real-world conditions. The main application was done by one person but in constant exchange with two experts from the project consortium. Especially to implement knowledge about the vehicle concept, its functions and properties this was crucial.

3.3 Research Environment

The case study in this paper was conducted in the project Country to City Bridge (C2CBridge). This collaborative initiative is part of the German Center for Future Mobility and receives funding from the German Federal Ministry for Digital and Transport. The overall aim of C2CBridge is to design user-focused public transportation solutions that serve as compelling alternatives to private vehicle usage for commuting between rural and urban regions.

This initiative explores a comprehensive mobility framework featuring autonomous, platoon-ready on-demand taxis of passenger car size, coupled with smart transfer hubs. To ensure active participation from citizens and stakeholders during the development phase, the project utilizes immersive visualization technologies. The proposed vehicle concept is not designed to supersede traditional public transit or solely address last-mile logistics. Instead, the project aims to

determine how distinct transportation modes can be seamlessly integrated and how transitions between them can be most effectively structured.

Primary research inquiries focus on pinpointing the specific types and levels of personalization required to facilitate a behavioral shift toward sustainable, intermodal, and multimodal travel. The project consortium is composed of diverse research institutions specializing in mobility, transportation, and product development. Within this cross-disciplinary partnership, both established strategies and novel methodologies are being implemented, optimized, and assessed. (C2CBridge Project Proposal, 2023; Thümmel, Kempf, et al., 2025).

4. Results

In this paper, the systematic approach for continuous monitoring and validation of product properties in the product engineering process, developed by Thümmel, Schmidt, et al. (2025), is used as a foundation. The included process model consists of three activities forming a dynamic monitoring framework. The *Preparation Activity* defines scope, sources, and an expert team. The *Metric Activity* combines foresight with environmental scanning for weak signals. Tipping points are set by linking indicators/indications to product properties and defining thresholds. The *Monitoring Activity* tracks deviations to update thresholds and triggers actions. The process model is visualized in Figure 1.

The approach bridges strategic foresight and operational monitoring by establishing a continuous loop that early-detects relevant environmental changes, translates them into quantifiable indicators, and derives corrective actions to keep products competitive throughout long development cycles.

It starts with a **Preparation Activity** where overarching goals are defined and both internal sources (product databases, KPIs, etc.) and external sources (industry reports, trend analyses, etc.) are selected. Also, a team is built as well as experts selected that will be consulted during the conduction of the approach.

In the subsequent **Metric Activity**, insights from foresight and environment analyses are converted into a hybrid set of indicators and indications. Scenario-based foresight identifies future-relevant drivers and maps them onto concrete product functions like resilience or adaptability, while systematic environment scanning gathers signals, e.g. from patents, conference papers and media. Quantitative thresholds are then derived from historical data, expert workshops or benchmarking and are continuously refined as new monitoring results or market developments arise.

During the **Monitoring Activity**, the defined metrics are applied continuously, with actual values routinely compared against the pre-set thresholds. When a deviation exceeds the limit, a decision-making must be made which could include actions in a technical (e.g., material changes), strategic (e.g., target-value adjustments) or communicative (e.g., stakeholder briefings) manner. Parallel supporting activities ensure comprehensive documentation in a central knowledge repository and structured communication among stakeholders (Figure 1).

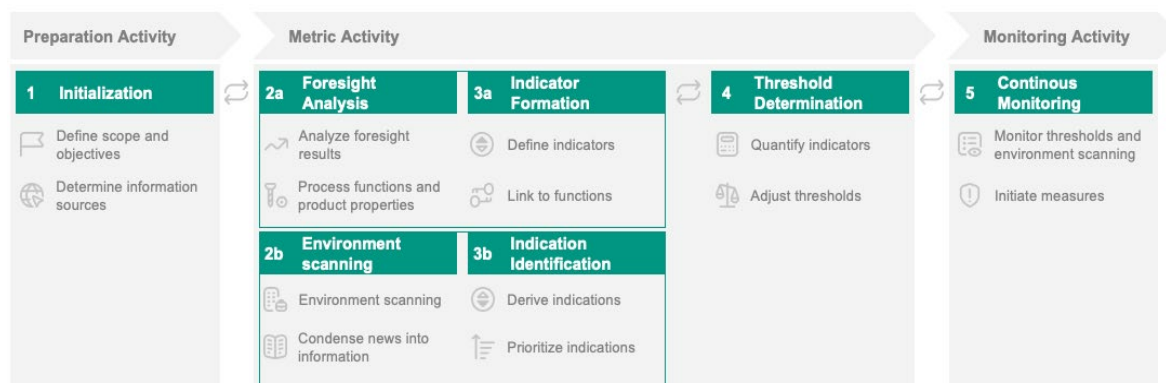


Figure 1. Process model of the approach for continuous monitoring of product properties against future development (Thümmel, Schmidt, et al., 2025)

4.1 Preparation Activity

Successful monitoring requires thorough preparation. During the initialization, all prerequisites on which the monitoring process is based are established. First, the scope and objectives are clearly defined and communicated to create a shared understanding within the team. In our application example, the overarching objective is to establish an early warning system for changes that may potentially influence the vehicle concept within the C2CBridge project. At the same time, clear boundaries are set, specifying what is included in the monitoring process and what is explicitly excluded. Within the C2CBridge project the focus is on the vehicle/shuttle. Analyzing the entire project would not be feasible due to its scope. The work was primarily conducted by a single individual, with appropriate support of several experts within the project provided at relevant stages.

Building on this, the information base is established. Appropriate data and information sources are identified and documented to ensure transparent and traceable information acquisition. In addition, communication is defined. In our application example, this included the specification of communication interfaces with the PEP and project management, for instance through expert workshops. Finally, documentation standards are defined. In this application context, documentation is carried out using Microsoft Excel to enable efficient updating and evaluation.

4.2 Metric Activity

4.2.1 Foresight Analysis

In the foresight analysis, existing future scenarios are considered. Those were created earlier and represent possible developments within the mobility context (Thümmel, Kempf, et al., 2025). The eight scenarios range from autonomous to non-autonomous mobility concepts and from strong public transport usage to a dominance of private individual transport. These scenarios were developed based on key factors that were elaborated in expert workshops. Besides scenarios, also trends and prognoses are considered. It became evident that a clear distinction between prognoses and trends is meaningful. Prognoses are derived from internal data and project-specific developments, whereas trends describe external market and technological developments. For example, the trend “City OS” represents a general development within the industry, while the prognoses “Connected Intelligence” emerged from internal projections, in which vehicle–cloud integration was predicted to become a standard feature in 90% of new vehicles. For the C2CBridge project, relevant trends were identified in an initial step. For this purpose, the Trendmanager (Trendone) was used, complemented by AI-supported tools such as ChatGPT (OpenAI) and Gemini (Google). Prior to use, all information was reviewed for accuracy by an expert panel. For prompt formulation, an established schema was applied, which is also recommended by the platforms themselves. First, a role to be assumed by the AI is defined. Subsequently, the task and objective are described, and the context is specified. This is followed by requirements regarding the output format, and, if necessary, additional dos and don’ts. This structured approach improves transparency and increases the likelihood of targeted and consistent results. Within the Trendmanager, trends are categorized into micro, macro, and megatrends, hierarchically structured, and grouped into clusters. For the present analysis, macro trends were primarily considered, as they describe concrete developments while remaining sufficiently general for the application context. An example is the trend “Connected Mobility,” which aggregates various solution approaches to meeting mobility needs. To ensure structure and traceability, a short description and the corresponding source were documented for each trend; when AI tools were used, the search term or prompt, the model applied, and the date were additionally recorded.

In the next step, the trends were evaluated according to their relevance and probability. The evaluation was based on the assessment scheme (see Figure 2). For the application example, minor adjustments were made to the wording of the evaluation criteria in comparison to the existing scheme of the existing approach (Thümmel, Schmidt, et al., 2025). On the probability dimension, the criteria “time horizon” and “scope and impact” were revised. For the time horizon, criteria 1 and 2 were adapted to short-term (1) and medium-term (2), as distinguishing developments occurring earlier or later than four years proved difficult, whereas an assessment in terms of short- or medium-term is more intuitive. For the same reason, the scale for scope and impact was adjusted to: negligible (0), weak (1), moderate (2), and strong (3). Regarding relevance, the criterion related to the degree of control was also modified; the new order is free development (0), medium to high (1), low (2), and no control (3). A high score (i.e., no room for action) is considered critical, which necessitated reversing the order of the scale.

Probability (P): Driven by Foresight			Relevance (R): Driven by Product Development		
PO Probability of Occurrence	TH Time Horizon	SI Scope & Impact	OR Opportunities & Risks	IE Implementation Effort	SA Scope for Action
0 Unlikely	0 Someday, maybe	0 Someday, maybe	0 Does not concern us or none	0 No resources required or none	0 None available
1 Doubtful	1 > 4 years	1 > 4 years	1 Low	1 Low	1 Limited
2 Possible or very likely	2 < 4 years	2 < 4 years	2 Medium to high	2 Medium to high	2 Medium to high
3 Almost certain	3 Present	3 Present	3 Very high	3 Very high	3 Free development
How likely is it that the key factor will change in the future?	Within what time frame is the change expected to occur?	How strongly will the factor influence the market or the product?	How important is it to react to this factor in the short term?	How much effort is required to consider or react to the key factor?	How much flexibility do I have in development, and how much has already been determined?

Figure 2. General evaluation framework using the example of assessing key factors in foresight results. Adapted from Thümmel, Schmidt, et al. (2025).

Furthermore, it became apparent that the preselection of topic-specific trends resulted in both probability and relevance being assigned very high values. These evaluations serve internal prioritization purposes and should not be interpreted as statistical truth. To achieve better differentiation between values and to use a more generally applicable scale, both dimensions were normalized to a range of 0–1. Additional weighting of individual factors enabled further fine-tuning of the evaluation criteria. In the final step, the normalized values are assigned to predefined action areas (I–VI), see Figure 3. For this purpose, the quantified mean value μ and the standard deviation σ are used to define the boundaries according to $G = \mu \pm b$, with $b = \sigma * k$, where k represents the sensitivity factor. The sensitivity factor allows for manual fine adjustment of the boundaries within tolerable ranges to ensure a balanced distribution across the categories. This is necessary because the categories serve as a basis for further evaluations, and a monopolized distribution would not be appropriate. For improved usability, the categories are additionally highlighted in the used Excel sheets using color coding.

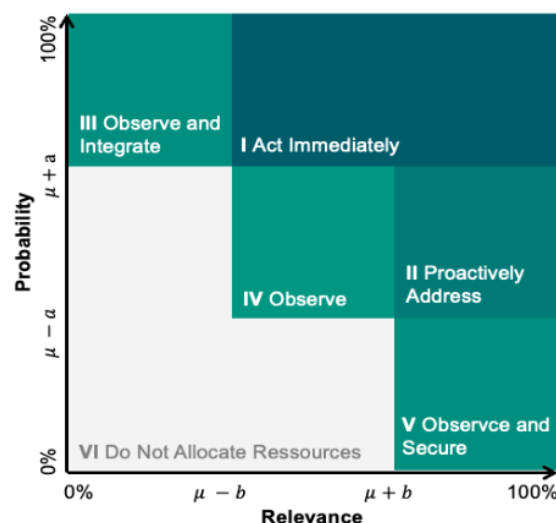


Figure 3. Portfolio Diagram with Sections (Thümmel, Schmidt, et al., 2025)

Finally, the product to be developed is subjected to an in-depth analysis. The objective of this step is to systematically identify and structure the relevant product characteristics as well as product and sub-functions to comprehensively describe the product and its functional interrelationships. Both technical and user-related aspects are considered. The analysis focuses on function-relevant features, interactions between individual product components, requirements for

system architecture, and aspects of user-friendly and practical design. This work was carried out in an expert workshop with two specialists from the vehicle domain within C2CBridge. The interdisciplinary exchange enabled the integration of different perspectives and ensured a comprehensive understanding of the product. In total, 34 product characteristics and functions were discussed and subsequently evaluated regarding their relevance. This includes e.g. the SAE-level of autonomous driving, the range or the interior cleaning detection.

4.2.2 Indicator Formation

The indicators are developed by an expert panel and formulated according to the SMART principle to ensure a clear and consistent definition. As a result, the indicators are described in a specific, measurable, achievable, relevant, and time-bound manner, which enhances shared understanding within the team and facilitates subsequent evaluations. In addition, a brief description and a clearly defined measurement method are documented for each indicator to ensure unambiguous and traceable data collection. Examples are advances in sensor technology, development of battery technologies, and digitalization of fleet management.

In the subsequent step, an indicator-evaluation matrix is created in which the indicators are mapped against the previously defined product characteristics and functions. The objective is to assess the strength and nature of the impact of each indicator on a given product characteristic, thereby determining the indicator's relevance with respect to the product. Based on the defined evaluation system, key indicators can be identified, while particularly sensitive product characteristics and functions become visible. The results form the basis for subsequent prioritization within the monitoring process.

4.2.3 Environment Scanning & Indication Identification

In the next step, the environmental analysis is conducted, in which the environment is systematically “scanned” to identify relevant current developments at an early stage. As an established tool, the Trendmanager is used for this purpose, as it provides a structured aggregation of cross-sectoral and up-to-date developments. Within the scanning process, news and information are first collected and documented. Based on this raw information, indications are subsequently derived, which serve as condensed signals of potentially relevant changes for the monitoring process. Relevant information is researched and consolidated from news. In practice, it has proven particularly important to formulate indications in a measurable and unambiguous manner. Therefore, the information is re-formulated according to the well-established SMART principle from project management, ensuring that they are specific, measurable, achievable, relevant, and time-bound. This formulation facilitates clear differentiation between individual indications while simultaneously enhancing comprehensibility and traceability. An example of an indication is: “LiDAR sensors available for under USD 500 in series production by 2027.”

The derived indications are then assessed using the same selection and evaluation process that was previously applied to trends and prognoses. To ensure the traceability of the indications' relevance and timeliness over time, each indication is additionally assigned a date. This makes the “age” of an indication transparent, allowing for re-evaluation after a defined period or for outdated or no longer relevant indications to be deliberately removed from the monitoring system.

4.2.4 Threshold Determination

In the next step, an indicator–indication evaluation matrix is created, in which the previously defined indicators are systematically mapped against the identified indications. The objective is to assess the extent and manner in which individual indicators are represented, influenced, or confirmed by indications, thereby determining the relevance of the indicators in the context of the observed environmental developments. Based on the defined evaluation system, key indicators with particularly high explanatory power in relation to relevant indications can be identified. At the same time, indications that exhibit increased sensitivity to changes in individual indicators become visible.

In the subsequent step, potential thresholds are defined by analyzing the expected temporal development of the indicators and identifying possible points of deviation. For this purpose, historical values are used to define an expected range based on the derived mean in combination with the standard deviation, within which the next value is forecasted. If subsequent updates yield values outside this expected range, this indicates a deviation from the anticipated trajectory of the threshold. Such a deviation may potentially have implications for the overall product. In this case, it must be assessed whether appropriate courses of action need to be derived and initiated.

Within the C2CBridge project, the average curb weight of passenger cars was considered as an illustrative indicator. A significant deviation from the expected trajectory may have direct implications for product design. For example, a substantial increase in vehicle weight could require the use of lighter sensors, whereas a decrease in weight might allow for the integration of additional sensor technology. Methodologically, a slight upward trend in average vehicle curb weight over recent years was identified based on historical data. Accordingly, an expected range was defined within which future development should occur. Deviations from this range are interpreted as potential tipping points and may provide indications of a possible need for adaptation in the product concept.

4.3 Monitoring Activity

In the last step, a continuous monitoring of the previously identified indicators and indications is carried out. The primary focus is on threshold definitions, which are continuously reviewed and updated. In this process, it is assessed whether the initially assumed developments and time horizons are occurring as expected or whether relevant deviations can be identified. An overview page within the Excel document used serves as guidance. It enables a simple, transparent, and effective application of continuous monitoring. This ensures that even untrained stakeholders can gain quick and intuitive access to the monitoring process.

The environmental analysis is continuously updated by integrating new and relevant information and news based on scanning. Existing indications are re-evaluated or additional indications are derived. The updated indications are subsequently incorporated into the evaluation matrix, with particular attention given to changes in the classification or category of the indications. In the case of significant changes, it must always be assessed whether appropriate courses of action need to be derived. If changes to the product occur during the product engineering process, the underlying indicators as well as the defined product characteristics must also be reviewed and, if necessary, adjusted.

5. Conclusion and Outlook

This paper applied the systematic approach for continuous monitoring and validation of product properties in the product engineering process (PEP) to the C2CBridge project to assess its practical applicability and identify potential for methodological refinement. The case study demonstrates that the approach effectively closes a relevant gap in current PEP practice by enabling a structured and continuous reassessment of initially assumed future developments and derived product properties.

The results show that the combination of foresight analysis, environmental scanning, and indicator-based threshold monitoring provides a robust framework for early detection of relevant environmental changes. By systematically linking trends, prognoses, indicators, and product characteristics, the approach supports transparent decision-making and allows potential deviations to be identified at an early stage. In the C2CBridge application, this enabled the identification of sensitive product properties and key indicators that are particularly relevant for the vehicle concept, thereby improving risk awareness and supporting proactive adaptation measures.

At the same time, the case study revealed several areas for further development. Methodological adaptations were required, particularly regarding the evaluation schemes for relevance and probability. Normalization of scales and sensitivity-based categorization proved necessary to ensure meaningful differentiation and practical usability in a project-specific context. In addition, the effort required for data preparation, evaluation, and documentation highlights the importance of tool support and standardized templates to facilitate efficient application, especially in larger or more complex projects.

Looking ahead, future research should focus on validating the approach across additional case studies with different product types, development durations, and organizational settings to assess its generalizability. Further work could also explore a stronger integration of digital tools, such as automated data collection, dashboard-based visualization, and advanced analytics, to reduce manual effort and improve scalability. Moreover, the integration of continuous monitoring results into existing decision-making and governance structures within the PEP represents an important area for further investigation.

Overall, the findings indicate that systematic continuous monitoring represents a valuable extension to established product development practices. When appropriately adapted to the project context, the approach has the potential to

significantly enhance robustness, flexibility, and future readiness of products developed under uncertain and dynamic conditions.

Acknowledgement

This paper was created in the “Country to City Bridge” project of the „German Center for Future Mobility“, which is funded by the German Federal Ministry for Digital and Transport.

References

- Albers, A., Behrendt, M., Klingler, S., & Matros, K., Verifikation und Validierung im Produktentstehungsprozess. In U. Lindemann (Ed.), *Handbuch Produktentwicklung*, pp. 541–569, Carl Hanser Verlag, <https://doi.org/10.3139/9783446445819.019>, 2016.
- Albers, A., Dumitrescu, R., Gausemeier, J., Lindow, K., Riedel, O., & Stark, R., *Strategie Advanced Systems Engineering: Leitinitiative zur Zukunft des Engineering- und Innovationsstandorts Deutschland*. <https://www.advanced-systems-engineering.de>, 2021.
- Albers, A., Dumitrescu, R., Marthaler, F., Albers, A. A., Kühfuss, D., Strauch, M., Siebe, A., & Bursac, N., PGE-Produktgenerationsentwicklung und Zukunftsvorausschau: Eine systematische Betrachtung zur Ermittlung der Zusammenhänge, *14. Symposium für Vorausschau und Technologieplanung*, 2018.
- Albers, A., Düser, T., Kuebler, M., Schwarz, S. E., Lickefett, M. S., Pfaff, F., & Thümmel, C., Upgradeable Mechatronic Systems – Definition and Model of Upgrades in the Context of the Model of SGE - System Generation Engineering, *Fisita World Congress 2023*, 2023.
- Albers, A., & Gausemeier, J., Von der fachdisziplinorientierten Produktentwicklung zur Vorausschauenden und Systemorientierten Produktentstehung, *Smart Engineering*, pp. 17–29, Springer, Berlin, Heidelberg, https://doi.org/10.1007/978-3-642-29372-6_3, 2012.
- Albers, A., Heimicke, J., Walter, B., Basedow, G. N., Reiss, N., Heitger, N., Ott, S., & Bursac, N., Product Profiles: Modelling customer benefits as a foundation to bring inventions to innovations, *Procedia CIRP*, pp. 253–258, <https://doi.org/10.1016/j.procir.2018.02.044>, 2018.
- Albers, A., Kürten, C., Rapp, S., Birk, C., Hünemeyer, S., & Kempf, C., *SGE – Systemgenerationsentwicklung: Analyse und Zusammenhänge von Entwicklungspfaden in der Produktentstehung*, 2022.
- Albers, A., Marthaler, F., Schlegel, M., Thümmel, C., Kübler, M., & Siebe, A., Eine Systematik zur zukunftsorientierten Produktentwicklung: Generationsübergreifende Ableitung von Produktprofilen zukünftiger Produktgenerationen durch strategische Vorausschau, *KIT Scientific Working Papers*, no. 186, Karlsruher Institut für Technologie (KIT), <https://doi.org/10.5445/IR/1000153864>, 2022.
- Albers, A., Meyer-Schwickerath, B., & Siebe, A., Vorausschau im Kontext des Produktentstehungsprozesses mittelständischer Unternehmen: Ein Ansatz auf Basis des integrierten Produktentstehungs-Modells (iPeM), *Symposium für Vorausschau und Technologieplanung*, pp. 55–73, 2013.
- Albers, A., & Rapp, S., Model of SGE: System Generation Engineering as Basis for Structured Planning and Management of Development, *Design Methodology for Future Products* (Ed. D. Krause), pp. 27–46, Springer International Publishing, 2022.
- Albers, A., Reiss, N., Bursac, N., & Richter, T., iPeM – Integrated Product Engineering Model in Context of Product Generation Engineering, *Procedia CIRP*, pp. 100–105, <https://doi.org/10.1016/j.procir.2016.04.168>, 2016.
- Albers, A., Thümmel, C., Schmidt, J., Schwarz, S. E., Schlegel, M., Siebe, A., & Düser, T., Understanding and definition of scanning and monitoring of the future space in the context of the product engineering process, *18th International Design Conference*, Design Society, Dubrovnik, Croatia, 2024.
- Blessing, L. T. M. and Chakrabarti, A., *DRM, a design research methodology*, Dordrecht, Heidelberg, Springer, 2009.
- C2CBridge Project Proposal, *Vorhabenbeschreibung: Verbundvorhaben C2CBridge 1 - Country to City Bridge - Analyse und funktionale Lösungskonzepte*, 2023.
- Cooper, R., & Kleinschmidt, E., Screening new Products for Potential Winners, *Long Range Planning*, pp. 74–81, [https://doi.org/10.1016/0024-6301\(93\)90208-W](https://doi.org/10.1016/0024-6301(93)90208-W), 1993.
- Ehrlenspiel, K., Kiewert, A., Mörtl, M., & Lindemann, U., *Kostengünstig Entwickeln und Konstruieren: Kostenmanagement bei der integrierten Produktentwicklung*, Springer Vieweg, 2020.
- Fink, A., & Siebe, A., *Handbuch Zukunftsmanagement: Werkzeuge der strategischen Planung und Früherkennung*, Campus Verlag, 2011.
- Fink, A., & Siebe, A., *Szenario-Management: Von strategischem Vorausdenken zu zukunftsrobusten Entscheidungen*, Campus Verlag, 2016.

- Gausemeier, J., Voraussetzungen für die Integration von Strategischer Vorausschau in der Entwicklung, 15. *Symposium für Vorausschau und Technologieplanung*, Universität Paderborn, Heinz Nixdorf Institut, 2019.
- Gausemeier, J., Fink, A., Schlake, O., & Siebe, A., *Szenario Prozesse: Ein Konzept zur dynamischen Entwicklung von Unternehmensstrategien*, ZWF, 1998.
- Gruber, M., Kolpatzik, B. W., Schönhut, J., & Venter, C., Die Rolle des Corporate Foresight im Innovationsprozess: Ziele, Ausgestaltung und Erfahrungen am Beispiel der Siemens AG, *Zeitschrift Führung + Organisation*, 2003.
- Gruber, M., & Venter, C., Die Kunst, die Zukunft zu erfinden – Theoretische Erkenntnisse und empirische Befunde zum Einsatz des Corporate Foresight in deutschen Großunternehmen, *Schmalenbachs Zeitschrift für Betriebswirtschaftliche Forschung*, pp. 958–984, <https://doi.org/10.1007/BF03371688>, 2006.
- Harris, E., Review: On the Origin of Species by Charles Darwin, *New Scientist*, [https://doi.org/10.1016/S0262-4079\(09\)60380-8](https://doi.org/10.1016/S0262-4079(09)60380-8), 2009.
- Kuebler, M., Schuster, W., Schwarz, S. E., Braumandl, A., Siebe, A., & Albers, A., Upgradeable Mechatronic Systems – An Approach to determine changing Product Properties using Foresight, *Procedia CIRP*, pp. 78–83, <https://doi.org/10.1016/j.procir.2023.03.084>, 2023.
- Kuebler, M., Thümmel, C., Spekker, M. W., Siebe, A., & Albers, A., Weiterentwicklung und Evaluation einer Systematik zur Bestimmung sich ändernder Produkteigenschaften, 17. *Symposium für Vorausschau und Technologieplanung*, Heinz Nixdorf Institut, Berlin, 2023.
- Marthaler, F., *Future-Oriented Product Development – a Systematic Approach to Deriving Cross-Generational Systems of Objectives of Future Product Generations Through Strategic Foresight*, Dissertation, Karlsruher Institute of Technologie (KIT), Karlsruhe, <https://doi.org/10.5445/IR/1000134977>, 2021.
- Meyer-Schwickerath, B., *Vorausschau im Produktentstehungsprozess – Das integrierte Produktentstehungs-Modell (iPeM) als Bezugsrahmen für Vorausschau am Beispiel von Szenariotechnik und strategischer Frühaufklärung*, Dissertation, Karlsruher Institute of Technology (KIT), Karlsruhe, <https://doi.org/10.5445/IR/1000044947>, 2014.
- Müller, A., *Strategic Foresight: Prozesse strategischer Trend- und Zukunftsforschung in Unternehmen*, Dissertation, Universität St. Gallen, Hochschule für Wirtschafts-, Rechts- und Sozialwissenschaften (HSG), Zürich, 2008.
- Patnaik, D., & Becker, R., Needfinding: The Why and How of Uncovering People's Needs, *Design Management Journal*, pp. 37–43, <https://doi.org/10.1111/j.1948-7169.1999.tb00250.x>, 1999.
- Ropohl, G. (Ed.), *Systemtechnik: Grundlagen und Anwendung*, Hanser, 1975.
- Schumpeter, J. A., *Theorie der wirtschaftlichen Entwicklung*, Duncker & Humblot, 1912.
- Schumpeter, J. A., *Business cycles: A theoretical, historical, and statistical analysis of the capitalist process*, McGraw-Hill, 1939.
- Schwarz, J. O., *Strategic Foresight: An Introductory Guide to Practice*, Routledge, <https://doi.org/10.4324/9781003302735>, 2023.
- Siebe, A. (Ed.), *Die Zukunft vorausdenken und gestalten: Stärkung der Strategiekompetenz im Spitzencluster it's OWL*, Springer Vieweg, <https://doi.org/10.1007/978-3-662-56264-2>, 2018.
- Sieg, O. C., *Ein Beitrag zur integrativen Unterstützung des Produktentwicklungscontrollings*, Dissertation, Ruhr-Universität Bochum, Bochum, 2007.
- Thümmel, C., Ebi, S., Schlegel, M., Siebe, A., Düser, T., & Albers, A., An Approach for Continuous Monitoring of Product properties Between Strategic Foresight and the Product Engineering Process, 25th *International Conference on Engineering Design (ICED25)*, Design Society, Dallas, Texas, 2025.
- Thümmel, C., Heller, T., Siebe, A., & Albers, A., An Approach for continuous Integration of Foresight Information into the Product Engineering Process, *Norddesign Conference*, Design Society, Reykjavik, Iceland, 2024.
- Thümmel, C., Kempf, C., Spekker, M. W., Schwarz, S. E., Düser, T., & Albers, A., Case Study: Systematic Approach to Derive Needs Based on Future Scenarios and Personas in the Project C2CBridge, 8th *European Conference on Industrial Engineering and Operations Management*, IEOM Society International, Paris, France, 2025.
- Thümmel, C., Kiss, D., Schwarz, S. E., Siebe, A., & Albers, A., Verortung von Produktprofilen im zukünftigen Umfeld durch Abgleich von Szenarien, *EEE 2024 - Entwerfen, Entwickeln, Erleben: Menschen, Technik und Methoden in Produktentwicklung und Design*, Technische Universität Dresden, Dresden, 2024.
- Thümmel, C., Kleinschrot, M., Schwarz, S. E., Siebe, A., & Albers, A., Analysis of the Integration of Monitoring Approaches Using Strategic Foresight in the Product Engineering Process, 2nd *Australian Conference on Industrial Engineering and Operations Management*, IEOM Society International, Melbourne, Australia, 2023.
- Thümmel, C., Kuebler, M., Siebe, A., Düser, T., & Albers, A., Anwendung einer Systematik für Monitoring zur Bedarfsvalidierung zwischen Vorausschau und Produktentwicklung im Projekt SofDCar, 19. *Symposium für Vorausschau und Technologieplanung*, pp. 93–112, Heinz Nixdorf Institut, Universität Paderborn, 2025.

- Thümmel, C., Schlegel, M., Kübler, M., Schwarz, S. E., Siebe, A., & Albers, A., Foresight in Product Development - A Review on Existing Understandings and Approaches, *1st Australian Conference on Industrial Engineering and Operations Management*, IEOM Society International, <https://doi.org/10.46254/AU01.20220086>, 2022.
- Thümmel, C., Schmidt, T. A., Siebe, A., & Albers, A., A Systematic Approach for Continuous Monitoring and Validation of Product Properties in the Product Engineering Process, *31st Conference on Engineering, Technology, and Innovation ICE 2025*, <https://doi.org/10.1109/ICE/ITMC65658.2025.11106569>, 2025.
- Thümmel, C., Schwarz, S. E., Ritzer, K., Kuebler, M., Siebe, A., & Albers, A., Identification of Fields of Action for the Integration and Validation of Future-Oriented Customer-Relevant Product Characteristics During the Product Engineering Process, *6th European Conference on Industrial Engineering and Operations Management*, IEOM Society International, Lisbon, Portugal, 2023.
- Thümmel, C., Urbina Puch, C. R., Ebi, S., Schwarz, S. E., Schmitz, M., Siebe, A., & Albers, A., Beschreibungsmodell für die kontinuierliche Integration von strategischer Vorausschau in den Produktentstehungsprozess, *18. Symposium für Vorausschau und Technologieplanung*, Heinz Nixdorf Institut, Berlin, 2024.
- Verganti, R., Leveraging on systemic learning to manage the early phases of product innovation projects, *R & D Management*, pp. 377–392, 1997.
- Weissenberger-Eibl, M. A. (Ed.), *Zukunftsgestalter Deutschlands: Pioniergeschichten aus Wirtschaft, Wissenschaft, Politik und Zivilgesellschaft*, Springer Gabler Berlin, Heidelberg, 2025.
- Weissenberger-Eibl, M. A., & Almeida, A., Prerequisites for the integration of strategic foresight with product development, *15. Symposium für Vorausschau und Technologieplanung*, Berlin, pp. 257–273, HNI, 2019.
- Westkämper, E., Einführung in die Organisation der Produktion. Springer-Lehrbuch. Springer, 2006.
- Westkämper, E., *Wandlungsfähige Produktionsunternehmen: Das Stuttgarter Unternehmensmodell*, Springer Berlin Heidelberg, <https://doi.org/10.1007/978-3-540-68890-7>, 2009.

Biographies

Carsten Thümmel graduated with a bachelor's degree in Mechanical Engineering in 2018 and received a master's degree in 2021 from the Karlsruhe Institute of Technology. He is a doctoral researcher and team leader in the research group Design Methods and Design Management at the IPEK – Institute of Product Engineering of the Karlsruhe Institute of Technology. His research interests include foresight, product planning and monitoring for innovation management and product development in combination with strategic foresight.

Nils Ansbach is a student of Mechanical Engineering at the Karlsruhe Institute of Technology (KIT) and has been working as a student research assistant at the IPEK – Institute of Product Engineering since July 2024. His academic focus includes intelligent systems, with particular interest in product engineering, mechatronic systems and products as well as Data Science. Through his work, he is gaining practical research experience in product engineering and system-oriented development.

Andreas Siebe is an Honorary Professor at the Institute of Product Engineering of the Karlsruhe Institute of Technology. His main lecture he is teaching is “Strategic product development – identification of potentials of innovative products”. He studied industrial engineering at the University of Paderborn and finished his Ph.D. at the Heinz Nixdorf Institute of Paderborn at the department of mechanical engineering. After this period, he was one of the founders and over a long time (20 years) member of the executive board of a consulting company dealing with the development of scenarios. He has vast experience in strategic consulting of industrial and service companies as well as public organizations. His main emphases are scenario planning, foresighted product development and the implementation of future customer needs into product development processes. Additionally, he is a lecturer for Future and Scenario Management at the University of Paderborn and for Strategic Management at the college of economics in Paderborn. He has published several books and (scientific) publications in international referred journals. Also, he is a popular speaker on events and conferences. His research interests include the combination of future methods with methods of product development, especially in the early phases.

Tobias Düser has been a full professor for product engineering and head of IPEK – Institute of Product Engineering at the Karlsruhe Institute of Technology (KIT) since October 2022. After his studies at the Karlsruhe Institute of Technology and subsequent doctorate at IPEK - Institute of Product Engineering, Tobias Düser held various positions within the AVL Group in the field of innovative development and validation methods. In particular, he worked on novel automation and simulation solutions for test benches. Among other things, he was involved in the development of a new business area, the product portfolio and partner network in the area of Advanced Driver Assistant Systems as well as for Automated Driving. He was a member of the global ADAS/AD leadership circle and also intensively

involved in global strategy development. From 2015, he was responsible for the Advanced Solution Lab at AVL and head of the Karlsruhe branch office. In 2020, he additionally assumed global responsibility for ADAS/AD Virtual Testing Solutions. Tobias Düser and his team worked on virtual and XiL-based validation methods for the validation and testing of Advanced Driver Assistant systems as well as for Automated Driving. Furthermore, he participates in various working groups such as IAMTS or UNECE.

Albert Albers has been a full professor for product development and head of IPEK – Institute of Product Engineering at the Karlsruhe Institute of Technology (KIT) since 1996. He received his doctorate in 1987 under Prof. Palandan of the University of Hannover. Before his appointment to Karlsruhe, Prof. Albers worked for LuK GmbH & Co. OHG, most recently as head of development and deputy member of the management board. He is a founding and former board member of the scientific society for product development WiGeP, a member of the German Academy of Science and Engineering (acatech), and a member of the Advisory Board of the Design Society. Since 2008, he has been President of the Allgemeiner Fakultätentag (AFT e. V.). In addition, Prof. Albers engages in the VDI and serves on the advisory boards of several companies. In 2016, he and the IPEK team were awarded the Honorary Award of the Schaeffler FAG Foundation for excellent achievements and competencies in science, research and teaching in the technical-scientific field.