Vaasan yliopisto
UNIVERSITY OF VAASA

Onni Rintala

Concept Development for Integrated Technology Product Portfolio Management System

Case Study in Marine Technology Company

School of Technology and Innovations
Master's Thesis in Technology
Industrial Systems Analytics

Vaasa 2025

UNIVERSITY OF VAASA
School of Technology and Innovations
Author: Onni Rintala
Title of the Thesis: Concept Development for Integrated Technology Product Portfolio Management System : Case Study in Marine Technology Company
Degree: Master of Science in Technology
Programme: Industrial Systems Analytics
Supervisor: Binod Timilsina
Instructor: Janne Klemola
Year: 2025 **Pages:** 110

ABSTRACT:
In the fields of technology products and industrial manufacturing, intelligent management of technology and product portfolios increases its relevance. Increasing portfolio complexity emerges from companies' pursuit to provide solutions for fragmenting market segments and individualizing customer needs in intensifying competitive landscape. Simultaneously, disruptive industry transformations such as energy transition are pushing companies to innovate and productize solutions in the middle of uncertainty. The importance of systemized technology product portfolio management through the entire product lifecycles has become obvious. However, this complex issue is poorly managed by companies. Also, a gap in academia exists in this increasingly critical topic.

This thesis explores the current status of management of technology portfolios, product portfolios and product lifecycles, the key needs and requirements for their systemized management and conceptualizes an architecture for integrated technology product portfolio management system. It adds to the body of knowledge in academia by integrating the technology and product portfolio management fields and creating a novel concept for systemized management of technology products across the entire portfolio and their lifecycles. Thesis research conducts a literature review and 3 focus group sessions to collect input, identify system requirements and develop a conceptual system architecture. Thesis research collaborated with an industrial manufacturing company in the business of marine technology to tackle the stated problem.

Thesis findings showed that there is a significant similarity between academia and case company in identified system requirements. The total number of 19 management methods from the fields of technology portfolio management, product portfolio management and product lifecycle management were studied, mapped and converted into system functionalities. In total 20 system requirements were found with the focus group inputs. These findings were linked in high-level design and conceptualization of integrated technology product portfolio management system. The developed concept supports decision-making of technology product portfolio management in industrial companies adding value, balance and alignment to their portfolios. Future research is suggested in areas of digital business industries, detailed design of suggested concept system and measurable impact of applied technology and product portfolio management systems.

KEYWORDS: technology portfolio management, product portfolio management, product lifecycle management, marine technology, system engineering

VAASAN YLIOPISTO
Tekniikan ja innovaatiojohtamisen akateeminen yksikkö
Kirjoittaja: Onni Rintala
Tutkielman otsikko: Concept Development for Integrated Technology Product Portfolio Management System : Case Study in Marine Technology Company
Tutkinto: Diplomi-insinööri
Ohjelma: Industrial Systems Analytics
Ohjaaja: Binod Timilsina
Edustaja: Janne Klemola
Vuosi: 2025 **Sivumäärä:** 110

TIIVISTELMÄ:
Teknologiatuotteiden ja teollisen valmistuksen aloilla teknologia- ja tuoteportfolioiden älykäs johtaminen lisää merkitystään. Portfolioiden monimutkaistuminen juontuu yritysten pyrkimyksestä tarjota ratkaisuja pirstaloituneille markkinasegmenteille ja yksilöityneille asiakastarpeille kiristyvässä kilpailuympäristössä. Samaan aikaan disruptiiviset teollisuuden muutokset, kuten energiamurros, ajavat yrityksiä innovoimaan ja tuotteistamaan ratkaisuja epävarmuuden keskellä. Systemaattisen teknologiatuoteportfolion johtamisen merkitys koko tuotteiden elinkaaren yli on tullut ilmeiseksi. Yrityksien kyvyt ja tavat johtaa tätä monimutkaista asiaa ovat kuitenkin puutteelliset. Myös akateemisessa tutkimuksessa on aukkoja tässä tärkeässä aiheessa.

Tämä diplomityö tarkastelee teknologiaportfolioiden, tuoteportfolioiden ja tuotteiden elinkaaren hallinnan nykytilaa, niiden systemaattisen hallinnan keskeisiä tarpeita ja vaatimuksia sekä konseptualisoi integroidun teknologiatuoteportfolion johtamisjärjestelmän arkkitehtuurin. Se täydentää akateemista tietämystä integroimalla teknologia- ja tuoteportfolioiden johtamisen alueet ja luo uuden konseptin teknologiatuotteiden systemaattiseen johtamiseen koko portfoliolle ja tuote-elinkaarille. Diplomityössä suoritettiin kirjallisuuskatsaus ja kolme fokusryhmäkeskustelua tiedon keräämiseksi, järjestelmävaatimusten tunnistamiseksi ja järjestelmäarkkitehtuurin konseptin kehittämiseksi. Diplomityö tehtiin tapaustutkimuksena yhteistyössä meriteknologian teollisuusyrityksen kanssa mainitun ongelman ratkaisemiseksi.

Diplomityön tulokset osoittivat, että akateemisen maailman ja tapausyrityksen välillä on merkittävä samankaltaisuus tunnistettujen järjestelmävaatimusten suhteen. Yhteensä 19 johtamismenetelmää teknologiaportfolion hallinnan, tuoteportfolion hallinnan ja tuotteen elinkaaren hallinnan aloilta tutkittiin, kartoitettiin ja johdettiin järjestelmän toiminnallisuuksiksi. Yhteensä 20 järjestelmävaatimusta löydettiin fokusryhmien kautta. Löydökset yhdistettiin integroidun teknologiatuoteportfolion johtamisjärjestelmän korkean tason suunnittelussa ja konseptoinnissa. Kehitetty konsepti tukee teknologiatuoteportfolion hallinnan päätöksentekoa teollisuusyrityksissä lisäämällä arvoa, tasapainoa ja yhdenmukaisuutta niiden portfolioihin. Tulevia tutkimuksia ehdotetaan digitaalisen liiketoiminnan alueilla, ehdotetun konseptijärjestelmän yksityiskohtaiseen suunnitteluun ja sovellettujen teknologia- ja tuoteportfolion johtamisjärjestelmien mitattavissa olevaan vaikutukseen.

AVAINSANAT: technology portfolio management, product portfolio management, product lifecycle management, marine technology, system engineering

Contents

Figures

Tables

Abbreviations

TPM = Technology portfolio management

PPM = Product portfolio management

NPD = New product development

PLM = Product lifecycle management

GHG = Greenhouse gas

AI = Artificial Intelligence

TRL = Technology readiness level

NASA = National Aeronautics and Space Administration

TRM = Technology roadmapping

MIT = Massachusetts Institute of Technology

ASTRA = Advanced Space Technology Roadmapping Architecture

ROA = Real options analysis

LP = Linear programming

NPV = Net present value

R&D = Research and development

DP = Dynamic programming

B2B = Business-to-business

PRM = Product roadmapping

KPI = Key performance indicator

BoL = Beginning-of-Life

MoL = Middle-of-Life

EoL = End-of-Life

OPM = Object-process methodology

UI = User interface

TMP = Technology-Market-Product

ESB = Enterprise Service Bus

1 Introduction

In the midst of intensifying global competition, rapidly changing market dynamics and global energy transition, conservative industrial sectors like marine industry are pushed to undergo a pivotal transformation. Pursuing sustainable competitiveness, companies are compelled to differentiate through technological innovations to create value for increasingly individualized customer expectations and fragmented market segments. This has led to the challenge of effective and efficient management of increasingly advanced technologies and complex product portfolios. The rise of Industry 4.0 reshapes the idea of customer lifecycle value with innovations in digitalization and aftermarket services while products' market lifecycles shorten forcing new product development to accelerate. At the same time, the regulatory and market pressure for more sustainable practices highlights the importance of managing the entire product lifecycles. Inspired by these challenges during exceptional time of industry transformations, this thesis investigates what kind of integrated technology product portfolio management system could serve as a valuable strategic management support for industrial manufacturing companies with technology-driven products aiming to maintain and improve their competitiveness in challenging business environments.

This thesis research is conducted as a commissioned work for a Finnish marine technology and manufacturing company. Technological leadership is vital for the companies' competitiveness that are highly exposed to energy transition highlighting the criticality of success and right timing in technology productization, commercialization and product management. The research utilizes a case study approach for the empirical research part and to validate the research for further implementation. The company has identified a need and value for enhancing their strategic portfolio management practices to utilize synergies across product families and align technology development programs.

In this first chapter of the thesis, the research background is covered setting the field and context for the thesis. After background information, the research purpose, the identified gap in literature and the research objectives in addition to academic and practical values of the thesis are described in detail. Then, the research questions are stated and followed with definitions of the main theories, limitations of the thesis and research scope. Ending the introduction chapter, the overall thesis structure is described.

1.1 Background

As a market becomes more populated by companies competing with each other, the market matures and the decision-making power in selling-buying transactions starts to shift to buyers. This transition has been apparent in many manufacturing industries where historically there has been little competition. The market shift from a conventional seller's to uprising buyer's market pushes companies to their limits in competition and differentiation up to the level where potential sales revenues may cause such additional costs that vanish the expected profit margins (Schuh et al, 2018a). Due to the increasing competition, volatile market conditions and heterogeneous customer expectations as well as shortening innovation cycles, product portfolios tend to expand excessively converting the efforts of companies into strategically disadvantageous (Riesener et al, 2019). Product tailoring, widely adopted by business strategists to provide higher value for the customer, as a downside often increases the expenses from product development, complexity of supply chain and widening portfolios (Schuh et al, 2018b).

In industries that have based on delivering projects with high-technology products, portfolio complexity and advancement inevitably increase due to evolving customer requirements and fragmented customer segments. Thus, technology and product portfolio management are critical activities in these technology-driven manufacturing industries where technology leadership is essential, product development requires significant resource allocation, and manufacturing processes are complex. Stated by Dickinson et al (2001), even with the best technology, companies are more likely to fail to achieve their potential success without proper execution, timing and strategic alignment which could be assessed through effective portfolio management. The primary objectives of portfolio management, value maximization, portfolio balance and strategic fit, (Dickinson et al, 2001) highlight the importance of integrating portfolio management practices of technology and product management activities for higher strategic alignment and portfolio streamlining. These objectives are inherently integral for sustainable competitiveness and business success as value maximization means maximizing the financial value of the portfolio short- and long-term, portfolio balance refers to balancing risk levels, resources, projects and products, and strategic fit is about aligning portfolio items with the corporate and business strategies (Lahtinen, 2021).

Realization of a holistic energy transition challenges decision-makers in building new and converting current energy infrastructure to support sustainable energy supply (Large and Cummins, 2021). According to Saxena (2024), marine logistics, that transports over 80% of global merchandise trade volume, as an individual contributor accounts for approximately 2.8 % of global greenhouse gas (GHG) emissions. Referring to Ramsay et al. (2023), in 2015 Paris agreement it was agreed that minimum 50% of marine logistics' Well-to-Wake emissions are to be reduced by the year 2050. They stated that due to the fact that 99.5% of current global fleet (excluding non-propelled, non-merchant and inland waterway vessels) is powered by fossil-fueled combustion engines, transition from fossil to alternative low or zero carbon fuels, such as liquid natural gas, methanol, ammonia and hydrogen, is the most promising and possibly the only route to achieving the target emission reductions. The fuel transition is a major disruption for the marine industry as in order to achieve the emission objectives, the transition should happen over the same time span as is a lifetime of single vessel. Simultaneously, the catalogue and future availability predictions of alternative fuels keep changing which creates uncertainty for the companies on what technologies to invest in. As technical maturity, energy supply infrastructure and vessel tank capacities challenge rapid development of the fuel transition, approximately 12% of newbuild ships are equipped with alternative fuel capable fuel systems (Ramsay et al., 2023). From a financial point of view, alternative fuels are currently reliant on carbon tax prices and green electricity costs as even the most cost-efficient alternative fuels come into consideration only after carbon tax prices go beyond 100 €/ton of CO_2 (Harahap et al., 2023).

Policymakers in international organizations, especially in Europe, have set a number of targets and incentives for industries to push the energy transition forward. Launched in 2005 as the world's first carbon market, the EU Emissions Trading System requires polluters in all EU member states and the European Free Trade Association countries in various industries, including maritime transport, to pay a market determined price for the GHG emissions that exceed the emission cap set in EU emission targets (European Commission, 2025a). In the European Commission's FuelEU Maritime Regulation fully applied since January 2025, alternative fuels and clean energy technologies are promoted to achieve the target of 80% GHG Well-to-Wake emissions reduction by 2025 (European Commission, 2025b). The carbon intensity reduction milestones of this regulation are demonstrated in Figure 1. The International Maritime Organization consisting of 176 members with its Net-Zero Framework has been the first in the world as an entire industry to set binding limits for emissions and pricing for GHG in order to reduce the amount of GHG emissions from international shipping into net-zero by 2050 (International Maritime Organization, 2025).

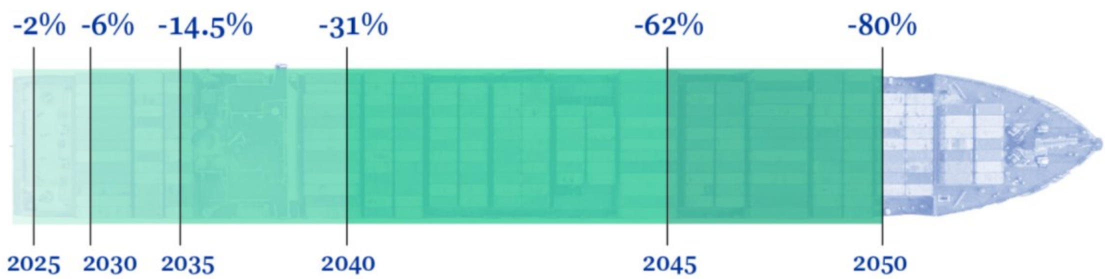

Figure 1. The targets for annual average carbon intensity reduction in maritime transportation from 2025 to 2050 (European Commission, 2025b)

1.2 Research purpose, gap, objectives and value

In today's rapidly advancing technology landscape, companies must manage increasingly complex portfolios of technologies and products. Effective technology portfolio management and product portfolio management are critical for aligning innovation with market demand, building and maintaining competitive offering and planning long-lasting product lifecycles sustainably. However, technology-driven manufacturing companies tend to manage technology portfolios, product portfolios, and product lifecycles distinctively, resulting in fragmented decision-making, inefficiencies and lack of strategic alignment. A solution to this problem is explored and constructed in this thesis.

In recent academic literature, the popularity of the thesis's keywords in the context of manufacturing is limited while the keywords as themselves have a long history. Product lifecycle management as an academic concept has been trending since the 1990s while portfolio management theories date back to the 1950s and advanced mechanical marine engines have been manufactured since the 19^{th} century. Using results from searching the keywords of the thesis and adding the word "manufacturing" for the higher context accuracy, Table 1 on the state of existing literature was generated. The articles were searched from four databases that are among the most popular research databases online: JSTOR, EBSCO, Directory of Open Access Journals (DOAJ) and Science Direct.

Table 1. Number of articles from years 2020 to 2025 found on the keywords with additional search term "manufacturing" for context in selected databases

Database	**Keyword**			
	Technology portfolio management	Product portfolio management	Product lifecycle management	Marine engine technology
JSTOR	642	550	154	209
EBSCO	0	2	9	0
DOAJ	5	8	43	5
Science Direct	5	61	1254	4
Total	**652**	**621**	**1460**	**218**

Figure 2 concludes the numbers from Table 1 to depict the distribution of articles between the fields of study. The context of manufacturing has a high impact on the distribution and existence of recent academic literature as the rise of Industry 4.0 technologies have advanced the capabilities for product lifecycle management while recent portfolio management interest is more focused on information technology related industries.

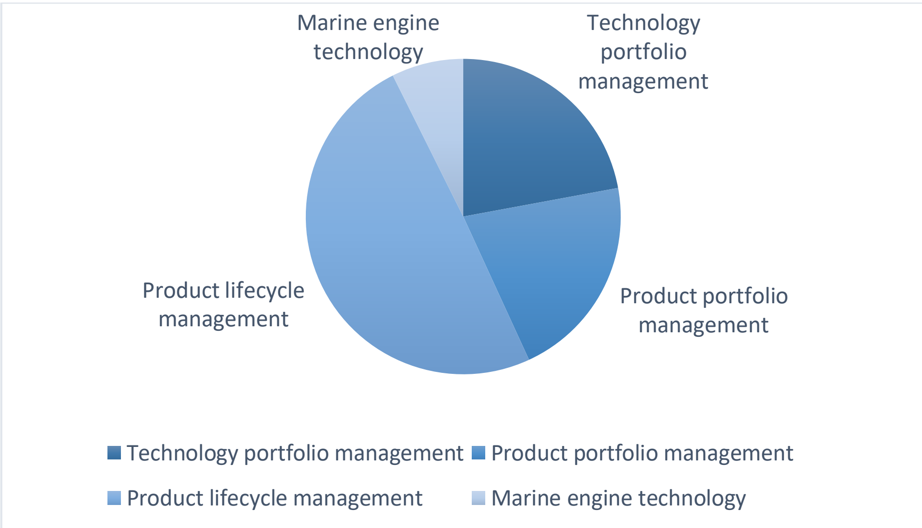

Figure 2. Total distribution of articles from years 2020 to 2025 found on the keywords with additional search term "manufacturing" in selected databases

Despite the long history and numerous academic research of all three main management theories of the thesis, in conducted research gap analysis of systematic literature reviews it was found that notable research gaps exist within the fields (see Table 2). Identified research gaps support the premise of an increasing need for an integration of these fields, especially in the context of physical technology products, industrial manufacturing organizations and complex portfolios. This research gap analysis provided a clear indication for a strong academic interest for this thesis in addition to industry interest by unveiling the limitations in current state of research.

Figure 3 illustrates the positioning of thesis in literature addressing the identified research gap. Despite the clear strategic interdependence of these fields, a lack of an integrated approach aligning technology portfolio, product portfolio and product lifecycle management was identified. This thesis research intends to bridge the gap in integration of these fields in technology-driven manufacturing industries by proposing a novel integrated framework and validating it through feedback and verification by a case company specialized in marine technology.

Table 2. Research gap analysis

Research area	Literature review	Identified gaps
Technology portfolio management	Kumar et al. (2008); Killen et al. (2007); Srivannaboon and Munkongsujarit (2016)	Limited research and empirical evidence on physical technology products, manufacturing industries, technology lifecycle perspective and integration of project portfolio management and technology management.
Product portfolio management	Hannila et al. (2020); Schmidt and Mantwill (2024); Doorasamy (2015)	Limited research on less mature companies, impact of emerging technologies such as digitalization and automation on product portfolio management, product portfolio management strategies in complex fields with high product variance and success of different product portfolio management practices in use.
Product lifecycle management	Seegrün et al. (2023); Corallo et al. (2022); Marcos De Oliveira et al. (2021)	Limited research on sustainability-focused application of Industry 4.0 technology in product lifecycle management, application of product lifecycle management in industrial organizations and on comprehensive and validated simultaneous evaluation models of technological readiness, economic viability, and sustainability impact.

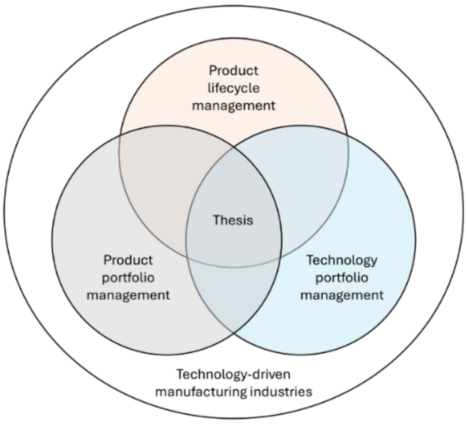

Figure 3. Thesis positioning in literature

In order to solve the stated research problem and close the identified research gap, three research objectives have been set for the thesis. These research objectives support the execution of this research and provide a comprehensive foundation for the proposed framework and its further iteration. The research objectives are the following:

RO1: To explore the current state of best practices, most adopted frameworks and most common concepts in technology portfolio management, product portfolio management and product lifecycle management in technology-driven manufacturing industries

RO2: To investigate the gap between the integration of current state frameworks and the key needs and requirements of product, portfolio and strategy management professionals for a holistic technology product portfolio management system.

RO3: To develop a concept of an integrated technology product portfolio management system for technology-driven manufacturing industries like marine technology

Thesis contributes to the academia's body of knowledge in technology portfolio, product portfolio and product lifecycle management by bridging the disciplines, synthesizing current concepts and closing gaps in existing frameworks. This thesis offers practical value to technology-driven manufacturing companies by identifying and evaluating the most effective frameworks and methods for managing complex technology and product portfolios in addition to proposed management system concept. By proposing a concept for an integrated technology product portfolio management system, the research supports improved strategic alignment, lifecycle planning, and execution efficiency and aims to provide higher competitiveness, enhanced business sustainability and better cost-efficiency for the applicable and applying companies.

1.3 Research questions

The case company showed interest in enhancing offering portfolio management effectiveness and efficiency to support its competitiveness and technological leadership within its industry. This thesis aims to explore questions that would provide understanding and set a runway for supporting this objective. The thesis is built around three research questions derived from the research objectives supporting the actual concept development. The research questions investigate the current state of frameworks, the key needs and requirements of the system and overview of a suitable concept for technology product portfolio management system. The research questions are the following:

RQ1: What is the current state of frameworks, methods and concepts in technology portfolio management, product portfolio management and product lifecycle management?

RQ2: What are the key needs and requirements from technology product portfolio management system?

RQ3: What could a suitable conceptual system architecture of integrated technology product portfolio management system look like?

1.4 Definitions, limitations and scope

This thesis explores three management theories, technology portfolio management, product portfolio management and product lifecycle management, and integrates them into a holistic framework. The research is limited to including only recent literature and industry expert feedback and validation. The scope of the thesis is focused from theory perspective on management decision-making and activities excluding creation and further planning of portfolios and product lifecycles, and from an industry perspective, it is focused on technology-driven manufacturing industries.

Technology portfolio management is the collection of technologies in development and in use of the organization. It is defined by Yu (2007) as a part of technology management decision-making process consisting of two main activities. Referencing Yu, the first activity of technology portfolio management is to monitor and track the progress and evolvement of the technology portfolio affected by corresponding relationships and development of technologies and business environment. The second activity is to re-integrate the technology portfolio with organizational strategy for continuous optimality in resource allocation and change responsiveness (Yu, 2007). According to Yu, the key objective of technology portfolio management is to maintain the best resource allocation to different technological alternatives for development and application of the technologies.

Product portfolio management is a management process established for continuous and simultaneous evaluation and prioritization of new and existing products and product options as a whole product offering portfolio (Paletta, 2019). It is supposed to take all synergies and interdependencies into consideration in order to support decision-making in resource allocation, new product introduction, product development and possible phase-outs (Paletta, 2019). Referencing Cheng et al (2022), product portfolio management decisions on company’s product offering are based on the prevalent market conditions and dedicated business strategy aiming for the highest possible profitability. Mustonen et al. (2020) state that decisions on developing, selling, delivering, maintaining and removing of products are defined by product portfolio management. As an important distinction from project portfolio management that considers one-time delivery projects, product portfolio management takes a stand on products that are or are planned to be produced and delivered repeatedly over a longer time period.

Product lifecycle management is described as a business management activity for products and product portfolios managing the whole product lifecycle and collection of product lifecycles in different stages from idea to growth, maturity and disposal (Stark, 2011). According to Udroiu and Bere (2018), product lifecycle management includes management of the various phases of product lifecycle: ideation, conception, design, validation, prototyping, manufacturing, use, maintenance and disposal. Product lifecycle management has traditionally been associated with manufacturing businesses (Saaksvuori & Immonen, 2008) which makes it highly relevant for the purposes of this thesis. In the context of this thesis, product lifecycle management considers market and product maturity in addition to product data management. This note is important as these terms are often mixed. Product lifecycle management has a wider and holistic scope in managing and controlling product lifecycle while product data management has a central role in managing product data efficiently through digital tools (Saaksvuori & Immonen, 2008).

The information sources used for the literature review included peer-reviewed academic journals, textbooks and white papers related to research topic. The thesis excludes unofficial publications such as social media posts in order to ensure the validity of the information. The information used dated no further back than in the year 2000. No older publications were used in order to ensure the relevance and timeliness of the information. The range of expert insights for validation of the proposed framework is limited to the comments from the case company’s key personnel in product, portfolio and strategy management. The case company approach in marine technology as a part of technology-driven manufacturing industries may limit the possibility of the research results’ generalization as the validation judgement of the proposed framework is limited to include only the case company.

In the scope of the thesis is to cover and integrate technology portfolio, product portfolio and product lifecycle management frameworks and concepts applicable for technology-driven manufacturing industries. The focus is set on portfolio management activities. The thesis includes holistic concept development for a technology product portfolio management system on a high level. Included in the thesis scope is the integration of expert comments from the case company’s aforementioned departments into the proposed high-level concept as adjustments while the scope excludes detailed design and implementation of a full software system for the case company.

1.5 Thesis structure

The thesis structure consists of five chapters following the standards of academic writing. At the beginning of the thesis are abstract in English and in Finnish languages, the table of contents and abbreviations. Chapter 1 consists of introduction to the research presenting an outlook of the thesis by going through the research background, purpose, key objectives, questions, limitations, definitions and scope. Chapter 2 explores the main theories and defines the main concepts essential for the thesis establishing a solid foundation for the following chapters. The third chapter explains the research methods and data used for the research purposes. The analysis and results are presented in chapter 4 consisting of the concept development of integrated technology product portfolio management system. The final chapter concludes the thesis with a summary of the work and findings in addition to critical analysis discussion of managerial implications, research limitations and suggestions for future research. At the very end, the references and appendices are listed.

2 Literature review

Industrial manufacturing covers many traditional industries such as automotive, marine and mining providing a vast basis of literature for the purposes of this thesis. The fields of technology portfolio management (TPM) and product portfolio management (PPM) are established in academic literature, but in recent literature they are relatively underexplored. Research on TPM and PPM has predominantly focused on new product development (NPD) projects and innovation strategy rather than the context of entire product lifecycle. On the other hand, product lifecycle management (PLM) is an emerging field of research being highly related to recent digital transformation and the paradigm of Industry 4.0.

The following sections of literature review cover the latest existing literature in TPM, PPM and PLM. The literature review of this thesis focuses on technology-driven and industrial manufacturing industries in order to provide a holistic basis for the theory integration into an applicable framework for the case company. The current states of TPM and PPM in industrial manufacturing industries are reviewed in sub-chapters 1 and 2. These are followed with a concise literature review of product lifecycle management in sub-chapter 3.

2.1 Current state of technology portfolio management

Technology portfolio management (TPM) as a term has limited amount of recent research available with the definition aligned with the thesis. Recent research has focused more on information technology portfolio management (ITPM) related to the pool of IT tools, assets and software in companies rather than product technologies the businesses are built around. Another defining difference between these two portfolio management activities is that ITPM is more focused on managing operational expenses while TPM focuses on business-critical capital investments for technology development.

A higher level of competitiveness can be maintained with TPM through improved adaptability to market changes, new business opportunities and technological disruptions (Surina et al., 2019). Golzari Nezhad and Mehrabanfar (2014) found that as a result of effectively utilizing TPM in strategic management, Boeing, a well-known aerospace equipment manufacturer, was able to balance and maximize the value of their technology portfolio. According to Yu (2006), TPM aims to find the most competitive edge -promising technologies within budget and with available capabilities while allocating resources and considering the profitability of the investments. These key observations showcase the potential of TPM in industrial technology companies.

Oliver Yu (2006) comprehensively illustrated the general scope and relationships of technology portfolio planning and management (see Figure 4). Due to the extensiveness of the scope, decision making in TPM is complex and multi-disciplinary. The scope can vary from including corporate strategies and global development in ecology, politics and societies to managing individual technology development projects on a detailed level (Yu, 2006). The three innermost circles in Figure 4 consider internal company matters while the two outermost circles extend to an external environment making it a practitioners' decision to what extent and which aspects to include.

Figure 4. General scope of technology portfolio management (Yu, 2006, p. 2)

The impacts of development in relevant areas of economics, politics, environment and international relationships could be assessed and formulated into the management systems to support decision making of technology investments (Yu, 2006). This process requires identifying, quantifying and weighing key factors that could have an effect on the competitiveness or feasibility of the technology invested in and developed in order to monitor and forecast the factors and their relationships. Yu pointed out that this aforementioned assessment of subjective factors into quantified values, while often complex and multidimensional, is a cornerstone for all management decisions. He noted the possibility of agent problems in strategic management decisions if one stakeholder looks for growth opportunities and revenue maximization and other looks for stability and cost minimization. This notion highlights the importance of strategic alignment throughout the organization and its integration into management systems, including TPM systems.

Yu (2006) described the process of technology portfolio planning and management through a 6-phase loop underlining the required continuity of interest in changing environments (see Figure 5). While Yu separated planning and management into different entities, they are tightly bound as management activities such as monitoring changes in values and attitudes require their initial definition done in planning phase. Referencing Yu, different analytical models such as time series analysis, saturation and seasonal fluctuation models can be used and combined to monitor and forecast changes and relationships. Due to complex and dynamic relationships between the aspects presented in Figure 4, a level of uncertainty exists with the analytical modelling as straightforward engineering formulas are often not applicable or lack proper validation and precision (Yu, 2006). Yu noted that the applicability of deterministic approaches depends on definition and formulation of relationships. He then presented three approaches to form value relationship: aggregated values, linear value functions and procedures for subdivisible alternatives. For understanding payoffs, resource allocation and alternative selection, Yu listed tools such as benefit-cost ratio, multi-factor evaluation, analytic hierarchy process, linear and dynamic programming, branch-bound approach and generalized LaOrange multiplier method.

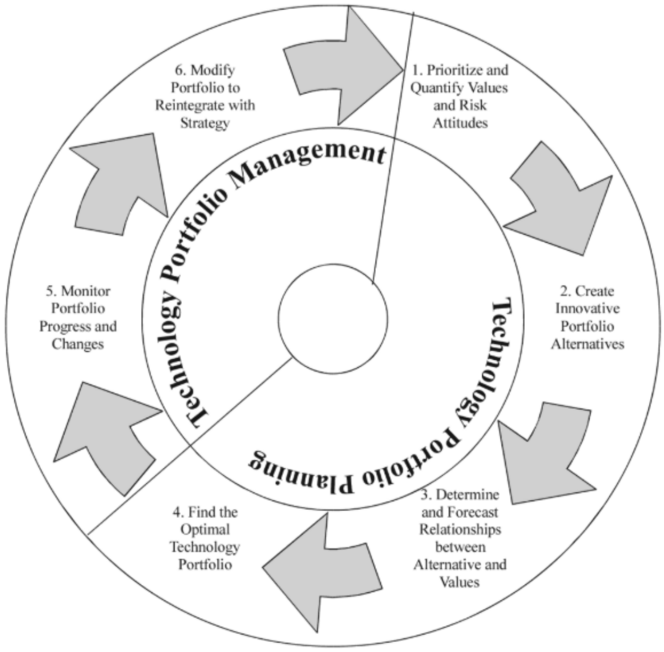

Figure 5. Decision-making process framework of technology portfolio planning and management (Yu, 2006, p. 4)

The main responsibilities included in management of technology portfolios are to monitor the progress and changes of the portfolio, modify and reintegrate the portfolio with strategy and optimize resource allocation (Yu, 2006). Continuous tracking of the portfolio and its match with strategy, value relationship forecasts and available alternatives is a key activity as modern business environments are increasingly dynamic and exposed to major regulatory and geopolitical changes, especially in technology-focused and -pioneering companies. For timely monitoring of technology portfolio, a classical method of project evaluation and review is often used as a technology project management technique while a more novel and rapidly advancing artificial intelligence-based approach can be used for early trend and risk identification (Yu, 2006). As stated by Yu, the portfolio is able to maintain its competitiveness with optimal resource reallocations as responses to changes in strategy and environment. For re-integration decisions, management teams can conduct scenario analyses and use quantitative methods to assess and evaluate the strengths and weaknesses of the portfolio (Yu, 2006).

2.1.1 General tools for technology portfolio management

Dickinson et al. (2001) noted that there is extensive variation with quantitative and qualitative TPM tools, metrics and methods. They divided them into three main groups: mathematical programming, classical and mapping. Available metrics influence the use of different models: with quantitative metrics mathematical models are used and with qualitative metrics charts and graphics can be utilized (Dickinson et al., 2001). Due to the nature of multi-disciplinarity of TPM, decision-makers quickly suffer from information overload and difficulty to balance between different metrics and methods even though those exact tools are supposed to help them (Dickinson et al, 2001).

Mathematical models can be used to optimize portfolio value. However, they might lack credibility due to lack of practical validation, overreliance on single uncertain value (projection of financial value) and overlooking strategic alignment (Dickinson et al., 2001). According to Dickinson et al., non-financial values, such as probabilities of technical and commercial success, reward, and strategy fit and leverage, can be considered in classical methods such as checklists, scoring and sorting models. On the other hand, scoring and sorting methods are criticized on subjective metrics, overreliance on financial data and inabilities to rank, balance and optimize portfolio (Dickinson et al., 2001). Referring to Dickinson et al., mapping tools visualize the portfolio using bubble diagrams, graphs and charts typically on two-axis illustrating the trade-off between for example risk and revenue or required effort and attractiveness. Dickinson et al. noted that while commonly used technology roadmaps display technology projects on horizontal time scale, they encounter problems with prioritization, balancing and financial value maximization.

Artificial intelligence (AI) has been widely studied and utilized by finance researchers in investment portfolio management which can be considered analogical to TPM. For example, Kumari (2024) studied the application of machine learning techniques such as natural language processing, sentiment analysis and reinforcement learning in dynamic portfolio management using large dataset analysis and pattern identification for real-time market trend predictions. Faheem et al. (2022) included also supporting vector machines and random forests in his comparison between the effectiveness of different AI models in portfolio optimization for analyzing multi-variate data and stated their usefulness in dynamic business environment. Uddin et al. (2025) experienced high performance of neural networks and machine learning techniques in their study to identify long-term relationships in financial data and predict financial risks. In similar tasks such as real-time trend recognition, portfolio optimization and big data analysis, machine learning techniques and neural networks could be advantageous also when practicing TPM. Despite the recent advancements in the field of generative AI and its promising potential in scenario analysis workshops, its application in TPM has still remained as an academically unexplored area.

2.1.2 Technology readiness levels

An important aspect in TPM is to keep track of the portfolio's technology maturity and ensure that the technology development pipeline is adequate. A method for standardized technology maturity assessment and comparison, technology readiness levels (TRLs), was developed and formalized by USAs National Aeronautics and Space Administration (NASA) for their space technology applications during the late 20th century (Hobbs et al., 2023). Following NASA, the US Department of Defense adopted the use of TRLs in technology development maturity assessment (Nilchiani et al., 2025) along with other high technology industries making it eventually a well-known and a widely adopted practice. Hobbs et al. explained that the assessment metrics scales from 1 (least mature) to 9 (most mature) providing information on the technology's development lifecycle status ranging from concept to deployment. As a counterweight for subjective evaluation methods, TRL assessment is based on qualifications, certifications and application proven evidence (Hobbs et al., 2023).

Nilchiani et al. (2025) noted that TRL method does not extend further to the technology lifecycle, highlighted a critical need for this and proposed a new TRL measure that would assess the aging of technology. This measure is especially relevant in industries that are undergoing rapid technological development or transition due to changes in regulation, economics or environment and which products have complex systems, for example energy and aerospace technology industries. In the article by Nilchiani et al., using a heavy military airplane model from Boeing as a case study, an extended TRL scale was introduced to support management decision making of sub-systems from their deployment (TRL 9) to obsolescence (eTRL 14). The sufficiency demonstrated in Figure 6 can be defined as the intersection between system requirements, performance and environment meaning that the highest level of sufficiency is achieved when the system is relevant in its environment and all system requirements are met in the operational context with pre-defined performance (Nilchiani et al., 2025).

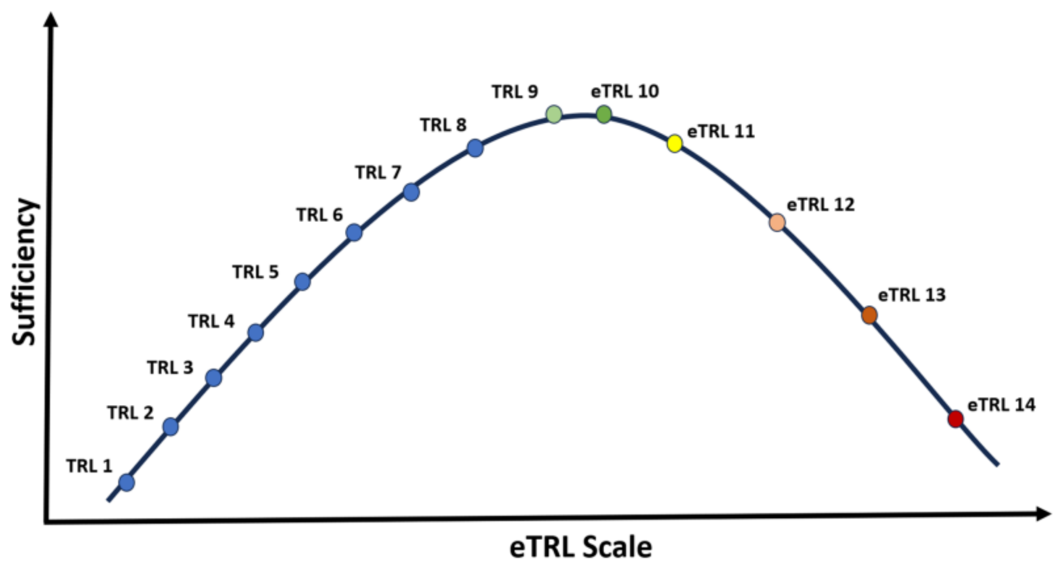

Figure 6. Natural technology lifecycle of a system (Nilchiani et al., 2025, p. 4)

Table 3. Descriptions of technology readiness levels on extended scale (adapted from Hirshorn et al., 2017; Nilchiani et al., 2025)

Technology readiness level	Description
TRL 1	Basic principles observation and reporting
TRL 2	Technology concept and application formulation
TRL 3	Experimental critical function or proof-of-concept
TRL 4	Laboratory environment component validation
TRL 5	Relevant environment component validation
TRL 6	Relevant environment system prototype demonstration
TRL 7	Operational environment system prototype demonstration
TRL 8	System completion and qualification in test and demonstration
TRL 9	Fully functional and successful operation proven system meeting all requirements.
TRL 10	Proven technology demonstration in extended operations
TRL 11	Acceptable system performance without modifications as not meeting non-critical functions causing minimal risk to overall system
TRL 12	Acceptable system performance with modification while critical function does not satisfy the target requirement causing acceptable risk to overall system
TRL 13	Unacceptable system performance as critical functions not meeting requirements causing unacceptable risk to overall system
TRL 14	Unacceptable system performance as critical functions not meeting requirements resulting in a cascade of critical system failures and unacceptable risk to larger system

TRLs can be used not just for tracking the development and maturity of technology, but they can also be used as setpoints to re-evaluate additional investments for, continuing without changes or freezing the technology development. This way, TRLs are a useful tool to incorporate in technology portfolio tracking and modification. Nakamura et al. (2013) highlighted this fact when stating that large investments and evaluation of technological and social factors are required each time when proceeding to the next TRL development phase. They noted that it is important to have a well-populated portfolio of technologies in TRLs 1-3 available for future in case an opportunity window opens. As the opportunity windows are not uniform, depend on the business environment and require capabilities varying between companies, it is essential to be prepared to act before the opportunity window closes (Nakamura et al., 2013). To have further details about each level of TRL, Li et al. (2017) developed a calculation formula of a multi-dimensional TRL assessment system for complex technologies taking into account seven dimensions ranging from requirements and verifications to risk and safety. They claimed that through their assessment method such new technology risks as performance shortcomings and schedule delays could be mitigated.

2.1.3 Technology roadmapping

One of the most adopted TPM concepts to balance market pull and technology push in technology-intensive industries is technology roadmapping (TRM) (Phaal and Muller, 2009). Phaal et al. (2024) defined roadmaps as “structured visual chronology of strategic intent” and mentioned that roadmaps are a way to organize available data, extract information and structure knowledge coherently. Small to large sized enterprises utilize TRM as a method to align their strategies and technologies in dynamic environments (de Alcantara & Martens, 2019). According to Zhang et al (2013), TRM is a powerful tool for managing technology development status, forecasting and assessment. Albright and Kappel (2003) stated that TRM can help in identifying key technologies, common needs and opportunities and focusing strategic development efforts for higher probability of success. Referring to Oliveira and Rozenfeld (2010), TRM has achieved effective outcomes by considering relationships between market, product and technology (see Figure 7). Thus, it is widely used for strategic, product and program planning as well as technological capability and resource planning (Oliveira and Rozenfeld, 2010). Technology roadmap architecture is built on two aspects: horizontal timeline and hierarchical layers of (1) market trends and drivers, (2) product-systems and (3) resources and technologies (Phaal and Muller, 2009). McDowall and Eames (2006) described TRM as crucial management tool for future technologies by visualizing future markets, policies and technologies. Vatananan and Gerdsri (2012) identified critical challenge of maintaining an active technology roadmap highlighting the importance of utilizing information system integrations for automated and real-time TPM tracking.

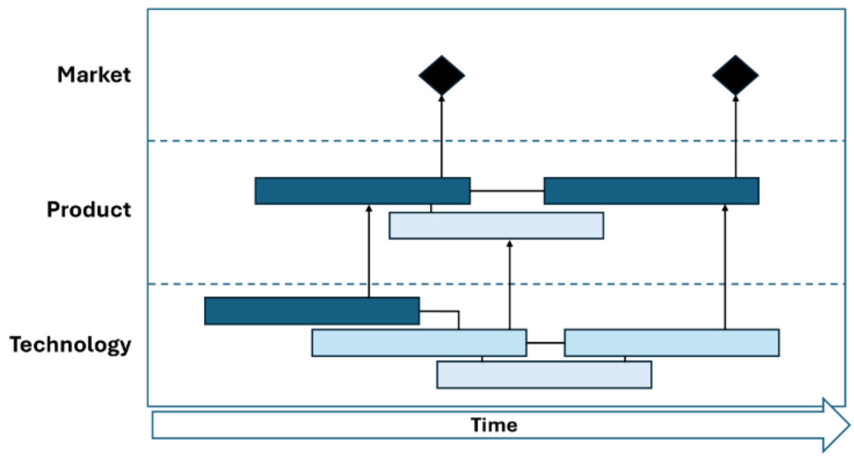

Figure 7. Illustration of a generic technology roadmap (adapted from Oliveira and Rozenfeld, 2010, p. 2)

Oliveira and Rozenfeld (2010) integrated activities from conventional TRM and project portfolio management into a systematic method (see Figure 8) to support the fuzzy front-end activities of TRM development in evaluation, selection and prioritization. They concluded the development phase of TRM into technology and market assessment, opportunity identification and analysis, idea screening and concept generation and evaluation. The procedure introduced by Oliveira and Rozenfeld included TRM originating analyses of strategy, market, product and technology and project portfolio management originating evaluations of financial side, probability of success and strategic alignment in addition to methods of project prioritization, relationship analysis and selection. While the work of Oliveira and Rozenfeld was focused more on planning rather than management of technology portfolio, it is useful to incorporate the multidimensionality of their method also in the context of TPM, especially in terms of interrelationship analysis, success probability evaluation, strategic alignment evaluation and resource management.

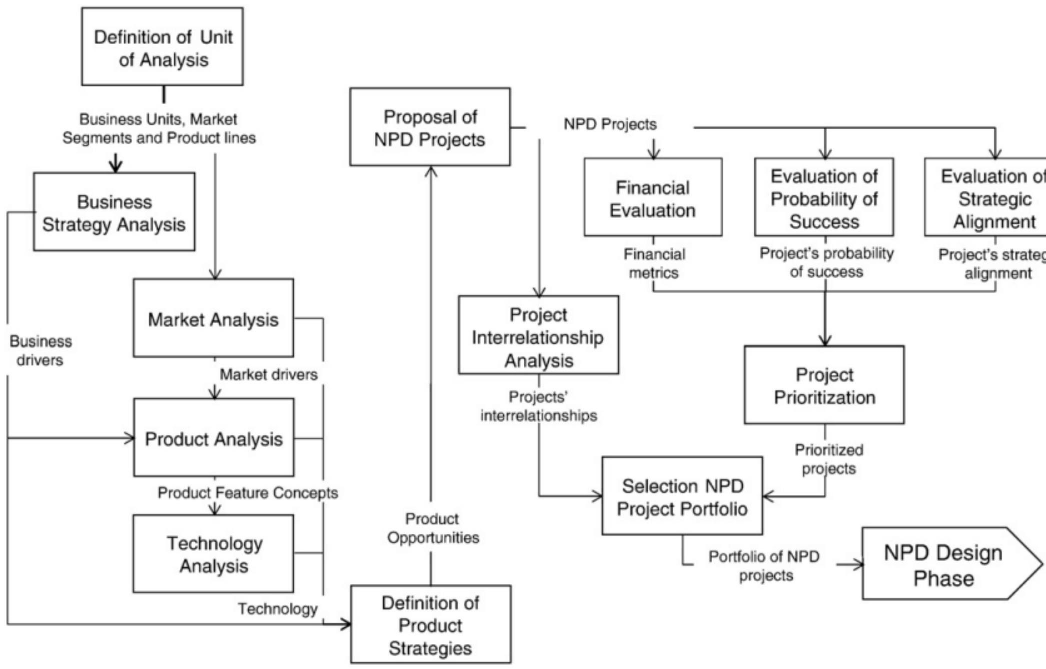

Figure 8. Overview of developing integrated technology project portfolio (Oliveira & Rozenfeld, 2010)

During early 2020s, NASA developed in co-operation with Massachusetts Institute of Technology (MIT) a TPM methodology called Advanced Space Technology Roadmapping Architecture (ASTRA) for technology valuation and portfolio construction of NASAs entire technology portfolio integrating models and simulations with renowned Markowitz portfolio theory (Bowie, 2021). According to Bowie, the ASTRA method workflow consisted of valuating technology investment portfolio, optimizing the portfolio and selecting the best technologies. The workflow and optimization were guided by mapping current and desired states and identification of synergy opportunities and optimal timing (Bowie, 2021). The key ASTRA authors, MIT professors de Weck and

Hastings (2021), described the working process with inputs, steps and outputs in a simple manner. The inputs used in ASTRA project were NASAs strategic goals in terms of missions and technologies, existing technology portfolio, subject matter experts and internal and external data sources (de Weck and Hastings, 2021). The four working steps they described included (1) defining current technology state-of-the-art and benchmarks, (2) mission and technology sensitivity analysis and target setting, (3) scenario analyses and technology valuation, and (4) final technology portfolio valuation, optimization and selection. As output from their work process, NASA received technology roadmaps, scenario-based technology valuations and technology investment efficient frontier (see Figure 9). TRL-risk adaptation was utilized in Markowitz portfolio construction approach (de Weck and Hastings, 2021).

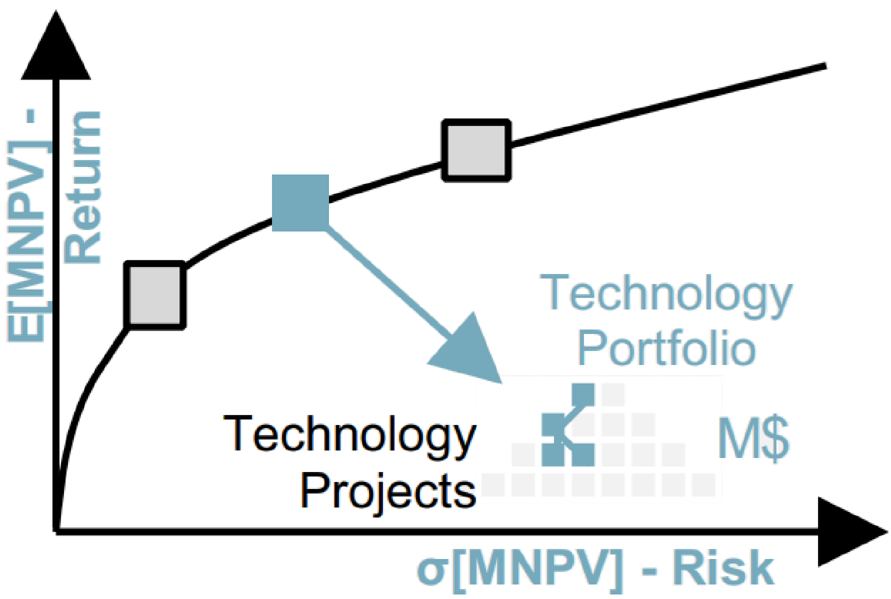

Figure 9. ASTRA technology investment efficient frontier graph (de Weck and Hastings, 2021)

Markowitz's portfolio theory applied in ASTRA is a foundational finance theory in investment portfolio optimization by maximizing profitability with a given risk level or minimizing risk level with a given profitability level. It provides an efficient frontier of portfolios to support investment decision-making. The calculation formulas for expected return and variance (risk) with n number of assets are demonstrated below. As de Weck and Hastings (2021) did, financial assets in Markowitz's theory can be interpreted analogously into technologies for the use of TPM calculations. Expected returns can be interpreted as profit predictions from NPV calculations. Risk can be interpreted as the probability of technical and market success and the volatility of profit predictions between different scenarios.

Formula of expected return in Markowitz's portfolio theory:

$$E(R_p) = \sum_{i=1}^{n} w_i \cdot E(R_i)$$

where:

- $E(R_p)$ = expected return of portfolio
- n = number of assets
- w_i = weight of asset i in portfolio
- $E(R_i)$ = expected return of asset i

Formula of variance (risk) in Markowitz's portfolio theory:

$${\sigma_p}^2 = \sum_{i=i}^{n} \sum_{j=1}^{n} w_i w_j \cdot Cov(R_i, R_j)$$

where:

- ${\sigma_p}^2$ = variance of portfolio return
- n = number of assets
- w_i = weight of asset i in portfolio
- w_j = weight of asset j in portfolio
- $Cov(R_i, R_j)$ = covariance between returns of assets i and j

Phaal et al. (2024) noted that in complex sociotechnical systems, strategically planned and dynamic systems-based architecture and visuality of roadmaps reduce information asymmetry. An advantage of roadmapping in comparison to other widely adopted strategy tools like SWOT is its time dimension in addition to the more commonly considered dimensions of trends, drivers, needs, functionality, performance, resources and enablers (Phaal et al., 2024). While TRMs provide clear advantages, they can get excessively complex in large corporations hindering their clarity for management decisions. Also, in case they lack real-time system integrations, it is probable that they cause significant amount of manual update work and lack in information quality and coherence.

Liu et al. (2024) acknowledged the weaknesses of traditional TRM stating its poor performance in complex systems with interaction between underlying technologies. They criticized the current TRM approach for its tendency to oversimplify the effect of dynamic interdependencies of the technologies by compressing them into linear silos. As data availability and big data analysis methods have improved, text information mining using machine learning and intelligent analysis has gained interest among researchers (Liu et al., 2024). Applying text information mining, Liu et al. successfully organized a case study in the field of nanorobot technology for technology roadmap interrelation analysis in order to demonstrate a solution to this problem. On the other hand, they solely focused on technology perspective and did not incorporate market dynamics dropping out one of the key elements of TRM.

2.1.4 Utility theory analysis

Utility theory is a well-known theory in decision-making research dominating the field of economic analysis for the last 50 years of 20th century (Moscati, 2016). Over time, utility theory has advanced to a variety of risk-considering decision-making theories such as game theory, prospect theory and theory of asymmetric information (Moscati, 2016). According to Hara et al. (2019), four axiomatic hypotheses are set for the utility theory:

independence, transitivity, continuity and completeness. Moscati explained that utility theory is based on calculating expected utility values for different decisions or scenarios and selecting the one with the highest utility value. This can be utilized by companies to prioritize technologies by their utility value financially and strategically based on for example technologies' market expectation, strategic fit and probability of success. The expected utility of a decision is calculated as a sum of utilities from outcome alternatives weighted by their probability of occurrence (Moscati, 2016). This is demonstrated as a formula below.

$$EU = \sum_{i=1}^{n} p_i \cdot u(x_i)$$

where:

- EU = Expected utility
- n = number of possible outcomes
- p_i = probability of outcome i
- x_i = outcome i
- $u(x_i)$ = utility function of outcome

Utility analysis is one of the key concepts and favorite methods in TPM used for project selection, resource allocation and risk management (Liang, 2013; Wirthlin et al., 2008). As an application example, Al-Harty (2007) applied utility theory in energy industry to model an efficient frontier for optimized project portfolio by incorporating net present values and risk policies. Stewart and Mohamed (2002) demonstrated the application of utility theory in information technology project portfolio management. They provided a framework that incorporated utility function based on a set of intangible and tangible criteria for evaluating business value and risk levels. Wicht and Szajnfarber (2014) mentioned utility theory as one common scoring method used for TPM in space agencies. Despite its commonality in practice, utility theory can be criticized for example for its use with technology project portfolios with finite resources that often conflict with the hypotheses: especially independence hypothesis as resources are in common use and thus the projects are not entirely independent.

2.1.5 Real options analysis

Wu and Buyya (2015) described real options analysis (ROA) as a derivative theory from financial options theory which takes into account real assets during investment estimation. Unlike the traditional investment evaluation approach which often bases merely on static data-based net present value (NPV) set once in the beginning, ROA provides more dynamism for the evaluation over the investment lifetime and, as a major advantage for TPM, takes into account the strategic value of the investment in addition to financial value (Wu and Buyya, 2015). This is especially important in technology investments in comparison to financial investments as they lack liquidability and can often be irreversible. According to Wu and Buyya, ROA is applicable in scenarios when more flexibility is required in case of new information about future value, strategic changes, or significant amount of uncertainty is involved. Wu and Buyya argued that the traditional NPV approach is inaccurate in considering the holistic end-to-end investment lifetime value and presented a concept of expanded NPV. Their calculation formula for the expanded NPV is presented below.

$$eNPV = NPV + real\ options\ value$$

Hunt et al (2008) stated that ROA has not been widely applied in technology management and demonstrated a case study of its application to TPM. They claimed that as a concept ROA is especially valuable and applicable to real investments such as new technology investments under uncertainty. The additional dynamism in risk management of technology development stands as a major advantage of ROA in TPM. On the other hand, Hunt et al noted that the non-existence of efficient market for real options such as new technology projects, lack of reliable data and disagreement on the technology's total value stand as a major challenge for the real option valuation.

Conduction of sensitivity analysis with the datasets is therefore a useful reliability-test method to acquire further understanding for decision making (Hunt et al, 2008). Also, Monte Carlo simulations can be used as an extension to sensitivity analysis for more advanced insights under uncertain and complex environments.

Wu and Ong (2008) developed a practical framework for technology investment management using real options valuation as a part of their work. They combined a quadripartite matrix and efficient frontier into a unified framework (see Figure 10). The framework provides a tool which managers can use to prioritize technology projects that are within their risk level and identify the best profit-risk ratio projects (Wu and Ong, 2008). They argued on behalf of real options analysis, especially with technologies that are characterized by dynamic business environment, potential for radical changes in expectations and long development and implementation time horizons.

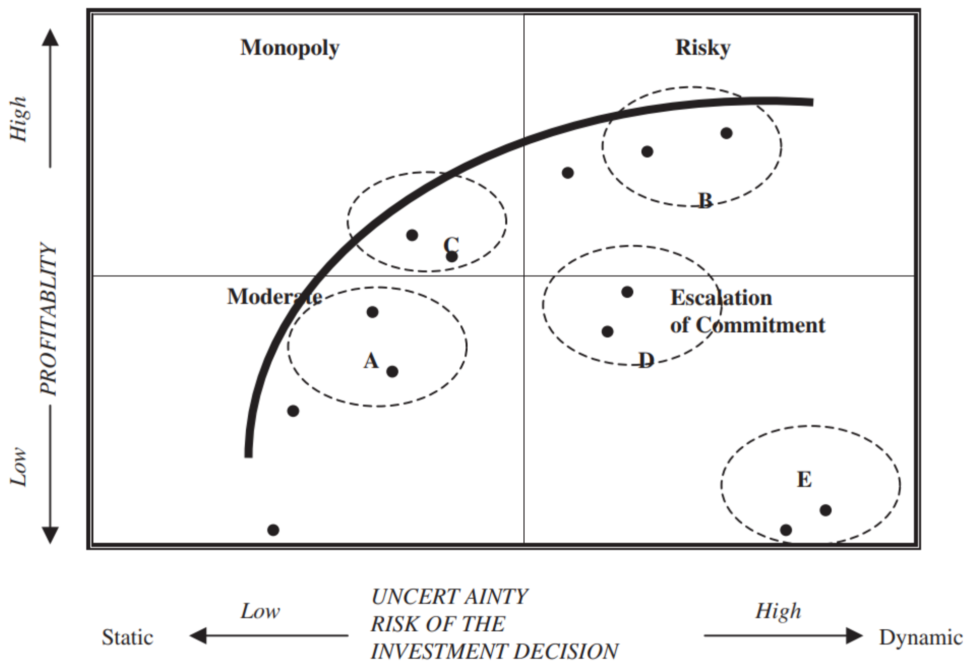

Figure 10. Technology investment management framework (Wu and Ong, 2008, p. 127)

Hilli et al. (2007) utilized ROA in product-technology portfolio management to evaluate technology investments and maximize portfolio value in capital intensive process industry. In their multi-phase ROA process, they applied multiple techniques such as scenario tree, dynamic programming for optimization, Monte Carlo simulation, sensitivity analysis and exponential utility valuation to successfully carry out the real option valuation.

In case a sufficient level of efficiency in real option market could be achieved or stated, it can be argued that the Black-Scholes model for financial options pricing could be applied to ROA. A certain level of efficiency would be required to estimate the value of technology frequently enough to be able to define the volatility of the value incorporated in Black-Scholes model. Although, Diepold et al. (2009) stated that while Black-Scholes options pricing model from finance theory has been used for real options valuation in IT sector, it is restricted by its assumptions and underestimates the associated risks and therefore lacks in applicability. The formula of Black-Scholes model for real options calculation (European style options) in the context of TPM is demonstrated below.

$$C = S_0 N(d_1) - Ke^{-rt} N(d_2)$$

where:

- C = value for real option
- S_0 = current estimated value of technology
- K = investment cost
- r = risk-free interest rate
- t = decision-making time window
- N(d) = cumulative standard normal distribution
- d_1 = 1st intermediate variable as risk-adjusted metric = $\frac{\ln\left(\frac{S_0}{K}\right)+(r+\sigma^2/2)t}{\sigma\sqrt{t}}$
- d_2 = 2nd intermediate variable as risk-adjusted metric = $d_1 - \sigma\sqrt{t}$
- σ = volatility of the technology value

As technology lifecycles shorten and innovation speed increases, technology companies need to put high stakes on risky research and development (R&D) investments in spite of the uncertainty of information in business environments (Wang and Hwang, 2007). According to, Wang and Hwang, ROA approach is better suited for technology investment valuation than basic NPV and discounted cash flow analyses as they tend to overestimate successes and underestimate failures while ROA acts the same way as capital market options having several stages for decision-making providing more dynamism and accurate valuation. For example, technology investments can be re-evaluated and adjusted based on technical success rate enabling options for dropping development projects, selling them or increasing the investment sum (Wang and Hwang, 2007). In their paper, Wang and Hwang developed a model that can be used to analyze technology investment trade-offs in uncertain environment using a fuzzy approach. Their model arguably improves the ability to create more accurate R&D project valuations.

2.1.6 Linear and dynamic programming

Linear programming (LP) is a common, long-used operations research technique with different types of models that use varying numerical parameters (Aliev et al., 2015). LP can be used as a simple mathematical method for optimizing a function with linear constraints to linear objectives, such as using time, budget and human resources as constraints and maximum NPV as an objective. Yu (2006) drew the connection with LP and TPM by listing a set of algorithmic approaches to support the management decision-making process. These approaches included benefit-cost ratio, multiple rating evaluation, analytic hierarchy process, branch-and-bound, generalized LaGrange methodology and different value functions. These LP methods can provide practical support in linear and well-defined decision-making problems such as independent minor R&D project selection. Litvinchev et al. (2012) studied this exact application of LP in technology project selection except that they included synergies between projects. However, LP methods are exposed to oversimplification in more complex problems and dynamic applications.

Dynamic programming (DP), a multi-stage optimization method, was included in Yu's (2006) tools for TPM. It is based on Bellman's principle of optimality in which the final result is found by dividing the original problem into smaller sub-problems and arranging the solutions into a sequence of decisions (Zaccone et al., 2018). For this reason, it is more suitable for complex problems with various alternative routes for an optimal solution. As an example of application, Baker and Solak (2014) developed a framework for energy technology R&D portfolio management by utilizing multi-model DP approach. As another application example of DP in TPM, Hilli et al. (2007) utilized DP in their study on real options analysis of product-technology portfolio. Loch and Kavadias (2002) developed a multi-factor dynamic model of resource allocation to tackle the complexity issue of NPD project portfolio

While useful for complex problem solving, the application of DP may be limited by high computational capacity requirement especially with very complex problems. As noted by Iyengar (2005), due to the requirement of knowing all future states, in many higher dimensional and more complex DP applications, the computational effort can be significant. This limitation may affect the speed or the scope of computation and decision-making. On the other hand, following Moore's law, the development of computational performance is increasingly rapid which decreases the effect of this limitation. Another underlying problem in DP is that as the generated estimates are based on historical data, they are subject to statistical errors which may significantly decrease the performance and accuracy of the results (Iyengar, 2005). This weakness of DP was attempted to be mitigated in Iyengar's paper by proposing a robust formulation of discrete time DP. However, in most of high-interest DP applications, approximate DP should be used instead as the study was limited in its scope of simple applicable problems (Iyengar, 2005) leaving the statistical error problem alive for more complex problems.

2.2 Current state of product portfolio management

In this section the current state of PPM is covered. Firstly, the intersection of TPM and PPM is noted and common methods with these two portfolio management practices are discussed. Several similarities between TPM and PPM can be identified and often the practices are mixed, especially in the context of R&D portfolio management. Secondly, unique methods in PPM are investigated to identify specific management methods that focus on product management. A product management approach that can be applied extensively in PPM, product lifecycle management, is covered in chapter 2.3.

Mustonen et al (2020) stated that product portfolio are the company's most valuable business asset. In product-based business, well-planned product strategy and product portfolio provide the foundation for competitive advantage (Saaksvuori and Immonen, 2008). Saaksvuori and Immonen demonstrated with a generic model a visualization of the positioning of product portfolio in overall product management framework (see Figure 11). Referring to the generic model, PPM can be seen as the first step to concretize product strategy by systemizing, organizing and controlling product offering setting the way for execution highlighting PPMs crucial role in product-based business.

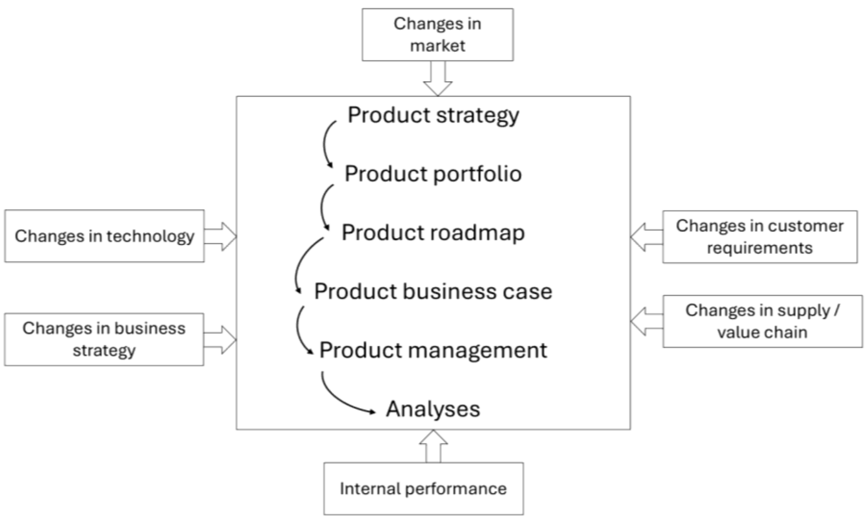

Figure 11. The impact of business strategy and business environment in product management (Saaksvuori and Immonen, 2008, p. 209)

The centric role of PPM is evident as in Figure 12 it can be observed that PPM combines the inputs of business strategy, technology strategy and R&D and analyses of markets, supply networks and performance metrics into a time-bounded action plan, a product roadmap. Unlike in Figure 12, technology strategy often affects business strategy making their connection two-way. Considering all internal and external variables, company strategies and technological development, PPM is the function to integrate all this information and guide the implementation of product development and product management (Saaksvuori and Immonen, 2008). Being in the intersection of strategic decision-making, analytical research and product management execution is what highlights the importance of PPM for sustainable competitiveness and success. Referring to Doorasamy (2017), PPM decision process for new and existing product evaluation, selection, prioritization and discontinuation is dynamic and characterized by uncertainty, changes and interdependencies with multiple goals and decision-makers.

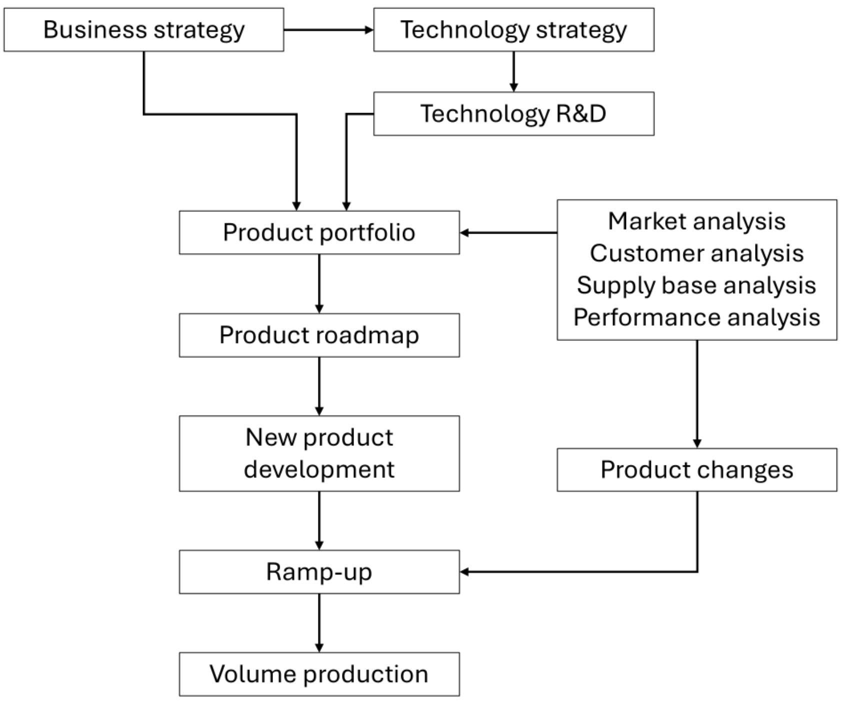

Figure 12. Connections between strategies, analyses and product management (Saaksvuori and Immonen, 2008, p. 209)

Tolonen et al (2014) described PPM as a platform for strategic product roadmaps, innovation enablement and corporate-level product management supervision. They noted that PPM is the intersection of product strategy, technology development, market analysis and lifecycle management of the entire product portfolio. Product portfolio itself can be defined in various ways by classifying it by customer segments, technology generations and product families or product natures such as hardware, software and services (Tolonen et al 2014). According to Tolonen et al, neglect of PPM and focus on individual product ownership may lead to uncontrolled portfolio expansion, low profitability over products' excessively long lifecycles and the type of internal competition that hinders overall corporate performance.

According to Doorasamy (2015), out of all new products introduced to markets up to 80% fail highlighting the importance of deciding on the discontinuation of a product, especially as approximately 50% of revenue is generated by under 5-year-old products. As a potential affecting factor, Doorasamy stated that products often lack voice of the customer due to poor market research and thus lack problem-solution fit. Following the principles of modern portfolio theory, a diversified product portfolio acts as a risk reduction strategy when the portfolio is constructed so that it includes products that can succeed also in economic downcycles (Doorasamy, 2015). Also, taking an analogue from finance theory, a sufficient number of products and R&D projects in portfolio naturally lowers the overall portfolio risk level by lowering the amount of unsystematic risk.

Doorasamy (2015) noted that in technology-oriented project business, one PPM best practice is to do the right projects (or products) the right way highlighting the importance of PPM decision-making. This best practice considers two key elements of business-making: strategic effectiveness (the right products) and operational efficiency (the right way). There are opposing opinions among academics about whether strategic orientation or process efficiency orientation is more important. According to Doorasamy, some NPD top performers prioritize their projects based on strategic alignment over financial returns. On the other hand, it was stated by Doorasamy that other academics support process approach and project execution efficiency over strategic value in product portfolio and NPD management.

Lahtinen et al (2021) noted the PPM challenges emerging from increasing variety and expansion of product offerings and studied key performance indicators for PPM in global engineering company. They mentioned from previous literature product cannibalization, decreasing operational efficiency and customer confusion as the negative side effects of expanding product portfolios. As additional challenges of PPM, they listed unclarity of portfolio, lack of business acumen and lifecycle planning and poor reporting. Tolonen et al (2016) found that a common lacking point lies in documentation of PPM process descriptions. Gramberg et al (2024) studied challenges and disruptive factors in PPM of business-to-business (B2B) manufacturing and noted that the transformative trends of servitization, digitalization and sustainability affecting B2B manufacturing companies are not well-explored in terms of PPM. The common challenges encountered by these companies are more rapidly evolving product lifecycles, neglected product phase-out actions, increasing complexity of product portfolios, sustainability adoption and adaptation and early trend recognition (Gramberg et al, 2024). The two aggregated actions Gramberg et al presented considered the use of generative AI for increased speed and flexibility and including strategic drivers in product portfolio evaluations.

2.2.1 Common methods in product and technology portfolio management

Tolonen et al (2016) investigated PPM methods in 10 case companies that offered a mix of hardware, software and service products and concluded that product roadmaps, R&D project follow-ups, stage-gate model application in NPD projects, financial reports and yearly updated business strategies are the most commonly adopted techniques. Due to the common nature of portfolio management, the basic methods of TPM and PPM are often analogous. Therefore, methods presented previously for TPM also dominate the field of PPM. The three basic methodologies, mapping, mathematical programming and classical scoring, are used similarly in varying ways in PPM. Cooper et al (2004) investigated the popularity of PPM methods including financial and strategic approaches concluding that financial methods are the most popular while strategic methods often result in the best-yielding portfolios. Riesener et al (2019) stated that product portfolio optimization has generally focused on merely financial approaches excluding strategic and portfolio balance approaches.

Kwon and Son (2018) studied the use of market attractiveness level and customer readiness level in combination with technology readiness level in new product selection and prioritization of small and medium-sized enterprises. In their paper, market attractiveness level was a market pull indicator based on market size, growth rate and policy suitability while customer readiness level measured need expectations on scale of timeline and volume. They based their work on Florin Paun's demand readiness level framework considering concepts of technology push and market pull in technology and product commercialization.

A number of factors have been studied and identified to evaluate the probability of technical and commercial success. The probabilities of success could be utilized in Markowitz portfolio theory calculations to generate the portfolio's efficient frontier. Consequently, products with the relatively poorest position efficient frontier could be discontinued and resources be re-allocated more efficiently. Doorasamy (2015; 2017) noted a common integration of project management method, stage-gate model, to PPM and NPD for continuous tracking and evaluation of product's technical and commercial success probability in order to make decisions on NPD continuation and discontinuation. Wali (2010) introduced an evaluation criterion of 28 factors for probability of success technically and commercially to screen new product ideas more objectively through an average weighted scoring model. The Wali's criterion was designed for industrial organizations and included criteria such as technical readiness and technological fit, R&D and manufacturing capabilities, time-to-market, competitive landscape and market maturity. Olawore and Wong (2023) conducted a technology commercialization success factor analysis in another industrial organization and identified also success probability factors such as resource availability, patentability, market potential and other organizational, financial and societal factors. Mawaddah et al (2020) analyzed success factors of innovation commercialization and found 9 individual factors such as technology relative advantage, organizational networks and market demand. Owlia et al (2019) identified 32 different factors in total to evaluate probability of technology commercialization success and proposed a weighted assessment model for their application.

Product roadmapping (PRM), similar to technology roadmapping, is one of the most commonly adopted PPM techniques. Geum et al (2011) noted the challenge of long-term PRM in dynamic environment and rise of servitization by proposing a roadmapping process for product-service integration including assessment of technology being enabler, mediator and facilitator. Lo Nigra et al (2016) demonstrated the use of real options analysis in PPM in pharmaceutics industry by introducing a ROA- and Pareto-analysis based R&D decision support system.

The application of mathematical modelling and linear and dynamic programming is evident in the field of PPM having numerous possibilities for mathematical modelling and optimization. Hannila et al (2022) noted that while modern PPM should not be restricted by data availability, a proper adoption of data-driven PPM is still limited. They found that academic literature has not properly assessed the use of corporate data assets for PPM purposes. Ma (2016) mentioned the tendency of traditional PPM to focus on technical and market feasibility while often neglecting the competitive landscape especially in mathematical optimization. Ma introduced a PPM optimization model using bi-level programming and continued to prove the model’s robustness and ability to enhance product portfolio performance. Riesener et al (2020) stated that product portfolio decision-making traditionally has based on subjective evaluation while data-driven decision-making is required for more effectiveness in PPM with increasingly complex portfolios. They noted that this field is academically underexplored and proposed and validated a neural network and machine learning -based PPM methodology to model correlations. After modelling correlations, they used reinforcement learning to provide PPM decision recommendations. Jiao and Zhang (2005) utilized data mining techniques with sales and product performance records to improve knowledge extraction for product portfolio improvement.

2.2.2 Contemporary methods in product portfolio management

Various business strategy models can be applied relatively straightforwardly to PPM as they often consider the positioning of products in relation to competition, markets and profitability. Among the most commonly known and adopted models are blue ocean strategy and a number of matrices such as GE-McKinsey, BCG and Ansoff matrix. Whittington et al (2023) described these models for financial investment and divestment decision support with the business and product portfolios directly in relation to the PPM objectives: attractiveness, balance and alignment. A group of Finnish academics have focused on product portfolio and productization research and proposed in-depth frameworks and concepts for PPM. Various methods such as joint product portfolio, strategic buckets and financial profile monitoring have also been proposed.

Blue ocean strategy is about identifying value opportunities in the market and creating new competitive advantage. Whittington et al (2023) described blue ocean strategy through the use of strategy canvas. It envisions critical success factors for competitive advantage or customer values, value curve resembling performance over those factors and value innovation by identifying new market spaces in unrecognized customer values (Whittington et al, 2023). Blue ocean strategy tackles the risk of getting locked in a historic market space with highly stacked competition by creating a possibility for new, creative and competitive offerings (Whittington et al, 2023). Blue ocean strategy can be applied through visualization and comparison of customer performance requirements, competition performance and company performance to identify gaps of under- and overperformance. Product portfolio can be reflected on strategy canvas and its performance in customer values can be evaluated providing support for product portfolio management and new product innovation and development.

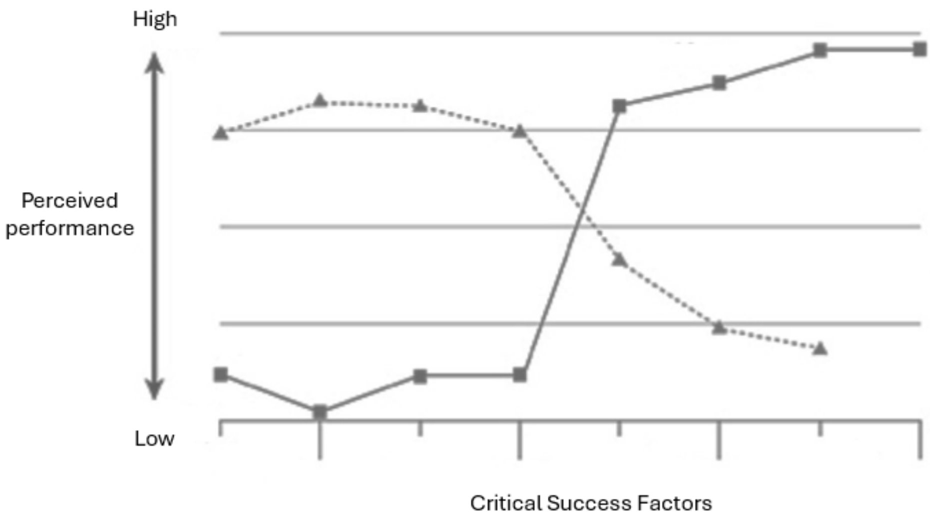

Figure 13. Strategy canvas for blue ocean strategy (Whittington et al, 2023, p. 242)

GE-McKinsey-matrix is used to categorize business units by their strategic strength and market attractiveness (Whittington et al, 2023) while also products and product families can be positioned in the matrix (see Figure 14). Referring to Whittington et al, management can allocate the company focus and investments to the business units (or products or product families) that show the most growth potential and competitive strength illustrated by the matrix. On the other hand, the low performing products and product families can be considered to be divested or phased out. This method was originally developed for General Electric, a renowned conglomerate in the energy, healthcare, and aerospace industries, by the world's leading management consultancy company McKinsey (Whittington et al, 2023). Described by Whittington et al, the matrix positions the item in the matrix by its relative long-term market attractiveness and competitive strength. This matrix can be applied to product portfolio management by positioning the products in the matrix for business performance tracking and investment evaluation.

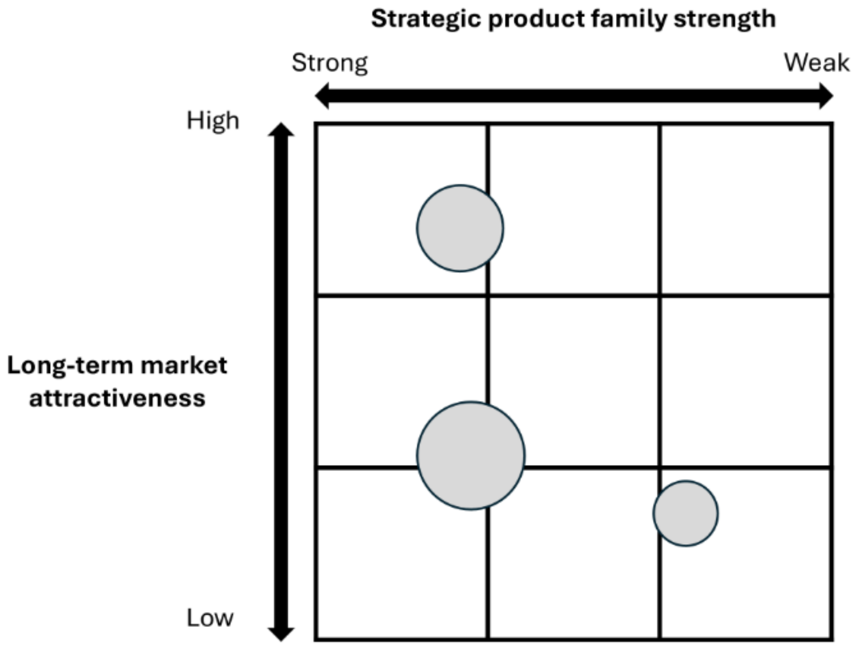

Figure 14. GE-McKinsey matrix (Whittington et al, 2023, p. 284), adapted with product family perception

BCG-matrix is one of the most common methods in business portfolio management (Whittington et al, 2023) and it can also be applied to PPM. As Whittington et al described, the BCG matrix is used to evaluate the overall portfolio balance and attractiveness by positioning businesses, products or product families in the matrix (see Figure 15). In addition to high-growth businesses, "stars", the portfolio needs to be balanced with low-growth businesses to fund the growth investments (Whittington et al, 2023). This highlights the PPM objective of balance and having products in different lifecycle phases as "cash cows". "Question marks" suffer from low market share requiring heavy investments to transition into stars but these are often products or businesses that eventually fail and therefore there should be several of them simultaneously to ensure any success case (Whittington et al, 2023). According to Whittington et al, "dogs" have low market shares in static or declining markets causing resource inefficiency and negative cashflow which is why they are suggested to be divested or phased out. BCG-matrix works as a practical visualization tool for portfolio balancing and optimization. However, the weaknesses of this method include reliance on market assumptions, oversimplification and ignoring linkages between products or businesses (Whittington et al, 2023).

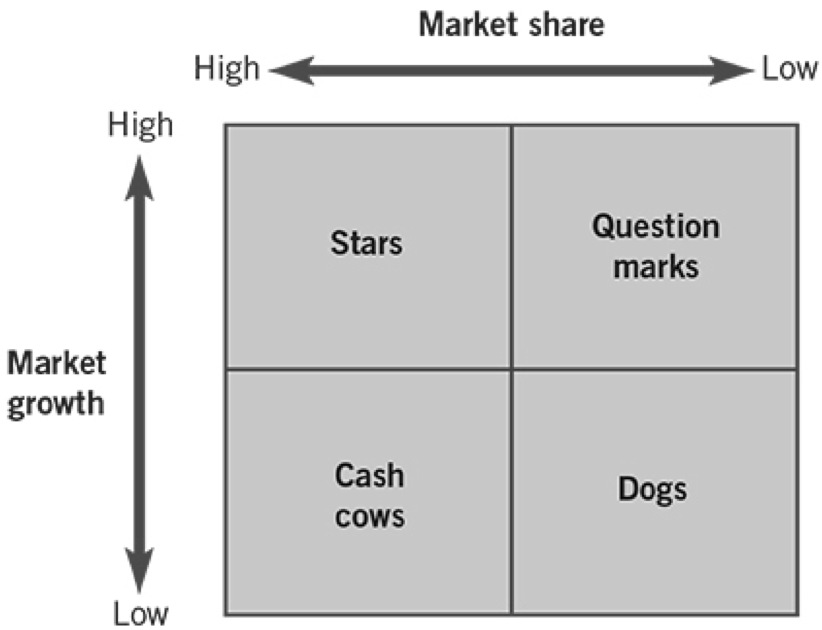

Figure 15. BCG-matrix (Whittington et al, 2023)

Yin (2016) studied the application of analytical hierarchy process and Ansoff matrix in business diversification to analyze products and markets. According to Yin, Ansoff matrix is also known as product expansion grid and growth vector matrix. It is a common strategic management method to more accurately and objectively analyze and evaluate market expansions and new product developments (Yin, 2016). Referring to Yin, the matrix offers four different strategy approaches for new and existing products and new and existing markets: product expansion, market penetration, market development and combination strategy (see Figure 16). Ansoff matrix can be utilized in PPM by positioning each product in the matrix and matching the product's growth strategy with the suggested one. While Ansoff matrix can provide support for growth strategy planning with heuristic approach, it can be criticized for oversimplification and definitional unclarity.

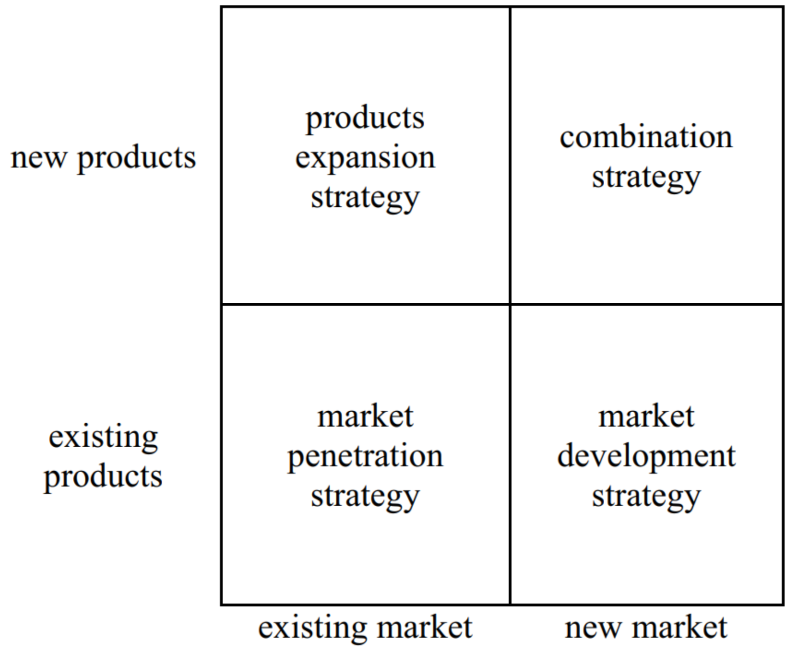

Figure 16. Ansoff matrix (Yin, 2016, p. 2)

Lahtinen (2021) stated that PPM should be based on key performance indicators derived from PPM objectives: value maximization, strategic fit and portfolio balance. Imperfect KPIs of PPM result in poor strategic project prioritization and excessive expansion of the portfolio. Tolonen et al (2015) studied the key performance indicators around the PPM main objectives, strategic fit, maximum value and balance and proposed a list of 17 distinct metrics to be tracked. Their list included subjective indicators such as NPD strategic alignment, market attractiveness and balance metrics and objective indicators such as financial value of NPD investments, NPV and number of portfolio items. Tolonen et al noted that PPM has been mainly focused on NPD performance management while, and partly due to which along with mergers and acquisitions, product portfolios have been expanding as product phase-outs have been rare. Mustonen et al (2020) studied key performance indicators of PPM and proposed a number of these metrics for strategic activity prioritization, product portfolio focus, sales item chart, profitability matrix, freeloaders and portfolio renewal in addition to horizontal and vertical portfolio balance.

Tolonen et al (2014; 2015) introduced and described 4 different product portfolio practices based on different lifecycle stages of the product's business: NPD, maintain, warranty and archive portfolio. NPD portfolio focuses on product development and ramp-up to renew the portfolio (Tolonen et al 2015). The second phase, maintain portfolio, focuses on product sales and ramping up the delivery volumes of new products while ramping down existing products (Tolonen et al (2015). They stated that in warranty portfolio phase, the focus should be on product care business as in spare parts and services with the existing customers and eventually ramping down the product specific care business. Archiving product information of phased-out products according to legal requirements is in the focus of archive portfolio stage (Tolonen et al, 2015). Tolonen et al (2014) proposed a framework for horizontal and vertical product portfolios that would consider product lifecycle stages and levels of product structures (see Figure 17). On the vertical axis, they considered commercial and technical portfolios from comprehensive solution perspective down to component level while the horizontal axis considered the four product portfolio lifecycle perspectives.

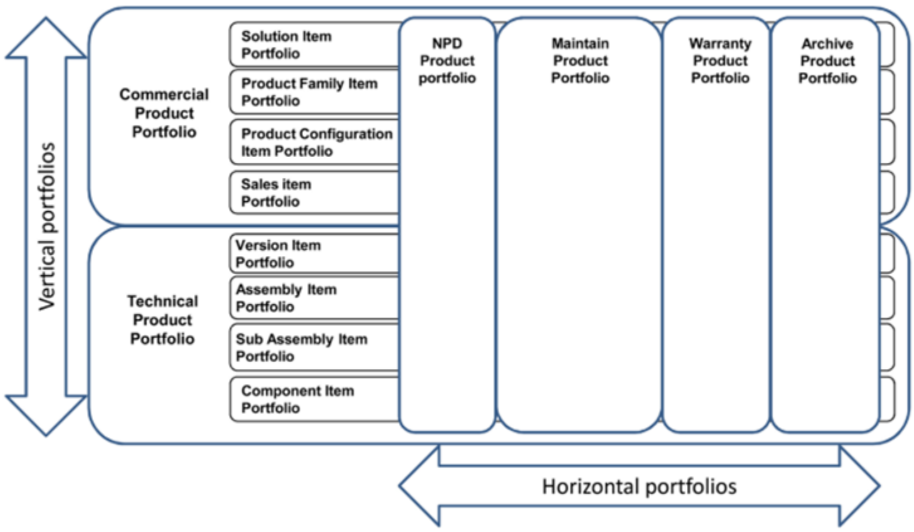

Figure 17. Horizontal and vertical product portfolio governance framework (adapted from Tolonen et al, 2014, p. 8)

Hannila et al (2020) investigated the challenges of a data-driven PPM and studied the requirements of master, transaction and Internet-of-Things data, data governance and business processes and IT for product-level profitability analysis. Through interviews with 8 mature companies, mostly in B2B business with global market reach and offerings in hardware, software and services, they found challenges in product definitions, product structures, product classifications and corporate data models. Following their previous work, during the year 2022, Hannila et al published a concept of a generic digitalized and data-driven PPM model that would cover PPM performance in all main areas, strategic fit, value maximization, and portfolio balance to support real-time reporting and analytics linking product lifecycles and portfolio types (see Figure 18).

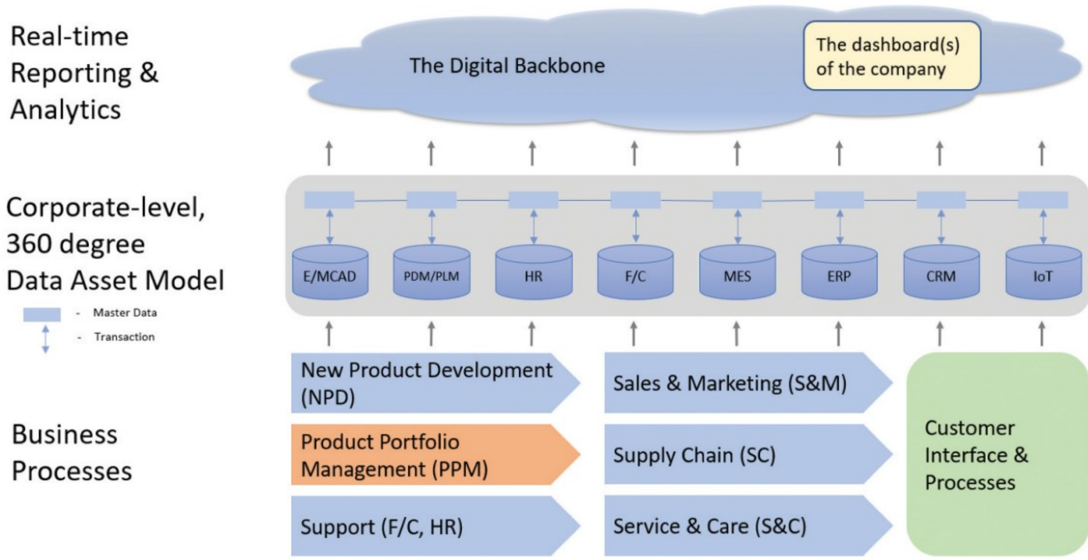

Figure 18. A generic framework of a digitalized data-driven product portfolio management model (Hannila et al, 2022, p. 273)

The concept of Hannila et al (2022) enables simultaneous assessment of products, markets, customers, their strategic natures and profitabilities. The process-focus considered a combination of PPM, data-driven decision-making, corporate data assets, and business IT (Hannila et al, 2022). They found that PPM metrics need to be first fully internalized and aligned for proper business IT and data asset utilization. Hannila et al (2022) pointed out that the growth of data volumes has simultaneously created needs for data storing and possibilities for data-driven and analytical decision-making. They highlighted the criticality of data governance and consistency as a cornerstone for data-driven PPM. According to Hannila et al (2022), the unclarity of cashflow sources in terms of products and customers prevents proper assessment of their strategic value and profitability.

Mustonen et al (2019) constructed a new method of joint and customer-oriented product portfolio for improving market operations of co-operating companies through a 5-step approach. This type of commercial co-operation had not been assessed earlier in research literature (Mustonen et al, 2019). They acknowledged the competitiveness utility of uniting the resources, capabilities and customer value propositions of multiple independent companies by combining their product offerings into one comprehensive product offering portfolio. The 5-step approach they introduced consisted of independent product portfolio descriptions in relation to common portfolio structure, identifying complementary values and features, identifying generic product types and core customer values and construction and validation of joint commercial product portfolio.

Chao and Kavadias (2008) studied the use of strategic buckets with NPD portfolios. The concept of strategic buckets is about defining innovation effort of NPD projects into types of incremental and radical. According to Chao and Kavadias, the required time commitment is the one determining factor to balance and define incremental and radical innovations. To support the division of innovation efforts into strategic buckets, they noted that radical innovations are encouraged by environmental complexity while environmental instability empowers incremental innovations. Strategic buckets for investments could also be defined by themes such as sustainability, digitalization, platform etc.

Herzer et al (2023) investigated the use of financial multivariate regression model over the product lifecycle to analyze time-series behaviour profiles and find changes that would indicate the revision need of product portfolio. They noted that current PPM methods are often limited in practicality due to complexity of dimensions. Their model variables included financial variables related to product portfolio, performance of individual products and macroeconomic data. They applied Monte Carlo simulations to validate their method that included principal component analysis, multivariate regression model and profile monitoring.

2.3 Current state of product lifecycle management

This section covers the most common models of product lifecycle management (PLM) in relation to portfolio management and the effects of digital transformation in PLM. Stark (2011) defined PLM as managing both the individual product’s lifecycle from ideation to disposal and product lifecycles in portfolio. The significance of PLM has and can be expected to increase as the trends of sustainability, Industry 4.0 and product-business servitization are becoming more integral in corporate strategies. According to Niemann and Westkämper (2005), industrial business strategies are progressively focusing on optimizing system performance and maximizing value through-out the whole product lifecycle. PLM has recently gained a significant attention in scientific research and has evolved from mere product data management to holistic PLM activity.

As the recent market development has pushed product lifecycles and time-to-market requirement for new products to shorten, companies need to have a strong control and clear vision of their products’ lifecycles and product portfolio in order to introduce products to markets quickly and kill poor-performance products early from wasting resources (Saaksvuori and Immonen, 2008). Referring Saaksvuori and Immonen, requirements for higher level of control in financial and environmental perspectives further incentivize the application of PLM systems. Main objectives of PLM are to maximize the current and future product portfolio value, increase revenues and reduce costs over the product lifecycle by improving innovation and NPD, shortening time-to-market, and providing support services for current products (Stark, 2011).

Adding to traditional tripartite enterprise business information technology systems (enterprise resource planning, customer relationship management and supply chain management), Udroiu and Bere (2018) stated that PLM systems should be included among them. They described PLM as a digital paradigm for product management, highlighting the effect of digitalization in modern holistic product management. The PLM system provides advantages in aspects of time-to-market, quality, productivity, cost management etc. (Udroiu and Bere, 2018). Nemudrova (2024) noted that to successfully be competitive, PLM requires combination of skills in marketing, technology, data analysis and design. Pinna et al (2018) found that inclusion of PLM in NPD has a positive impact on NPD performance improving capabilities in process management and coordination.

Cao and Folan (2012) reviewed the history of PLM and made a distinction between the two key concepts: traditional product lifecycle and more novel product engineering lifecycle. The model of product lifecycle considers the product's market performance by sales revenue over time and generally consists of four phases: introduction, growth, maturity and decline (Cao and Folan, 2012). Engineering lifecycle takes the perspective of individual product and product use from design to decommissioning, dividing the product lifecycle into three phases: beginning of life, middle of life and end of life (Cao and Folan, 2012). Udroiu and Bere (2018) stated that these three engineering lifecycle stages would construct the PLM process flow. Process-wise this statement can be accepted while it does not assess the market and after-market performance perspectives and not considering them can significantly affect the duration and intensity of engineering lifecycle. Shahmarichatghieh et al (2015) incorporated technology lifecycles as a perspective for PLM as they demonstrate the level of technology maturity (comparable with TRLs) crucially integral with product lifecycle phases. They stated that optimal results can be achieved by integrating all these concepts of PLM into decision making. Shahmarichatghieh et al also noted that each phase from different concepts can contain multiple phases from other concepts.

2.3.1 Generic product lifecycle model

Chillala (2024) defined product lifecycle as a theoretical framework that illustrates product's market existence and performance in the aforementioned lifecycle phases: introduction, growth, maturity and decline (see Figure 19). Sychrová (2012) stated that the product in each different lifecycle stage possesses different cost and profitability levels, pricing and marketing strategies and varying mass of customers and competitors. Chillala described the introduction phase as a time of modest initial sales and heavy investments in distribution and marketing. The growth phase is entered when exponential sales growth can be identified, competition intensifies, and profitability levels increase (Chillala, 2024). When sales growth slows down reaching its peak, the maturity phase has been entered in which increased competition incentives companies for further differentiation (Chillala, 2024). According to Chillala, the decline phase is characterized by market saturation, technology advancement and customer need changes.

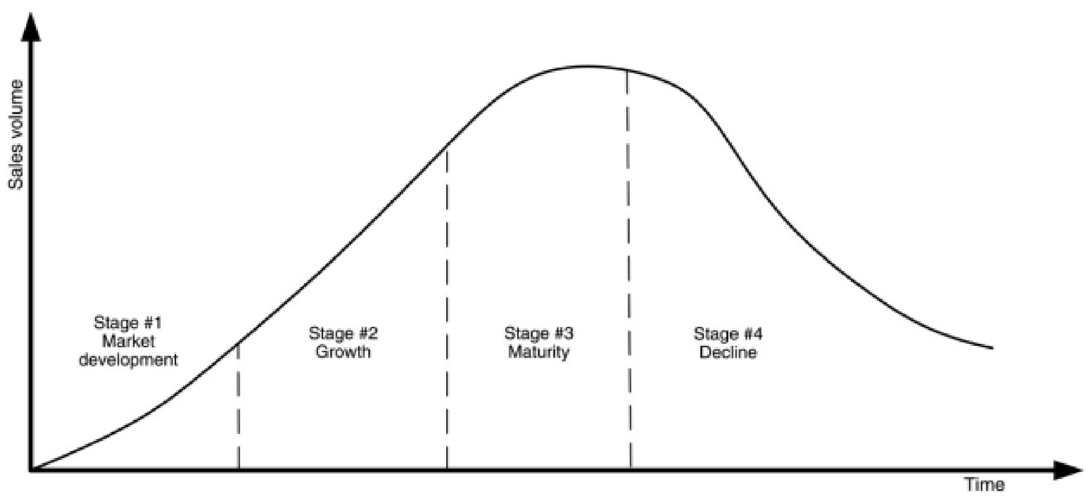

Figure 19. Generic model of product market lifecycle (Cao and Folan, 2012)

Shahmarichatghieh et al (2015) stated that fluctuations in sales volume over time are illustrated in product lifecycle model with focus on an individual product. Referring to Cao and Folan (2012), one way to carry out the distinction between lifecycle phases is to pre-define sales change rates for each lifecycle phase, calculate the change percentages in sales volumes over time and compare the definitions with calculation results. Naturally, this means that the change percentages should be positive in the introduction phase, highly positive in the growth phase, slightly positive or zero in the mature phase and negative in the decline phase. Shahmarichatghieh et al (2015) also introduced a concept of market lifecycle that considers the development of market segments and market areas for a product or technology taking the perspective of market over product.

The generic product lifecycle model can be combined with technology push-market pull categorization. Technology push-market pull categorization classifies the drivers of product innovation and gives guidance for product and market development prioritization. As product lifecycle model depicts market evolution over time, it can also be interpreted as an intensity curve of market pull. Combining this interpretation with the product lifecycle stages, the lifecycle model can be enriched with the two innovation drivers to increase dynamism into otherwise rather static classification (see Figure 20). During introduction, technology push is high while market pull is low. Market pull increases during the growth phase as adoption rates take off while technology push stays strong. During the maturity phase, market pull dominates but the technology push decelerates and product development shifts from radical to incremental innovations. Finally in the decline phase, market pull fades and technology starts to outdate.

Combination of product lifecycle model and technology push-market pull categorization could be used to explain product failure points: for example, classic technology push failure by implying that as market pull does not emerge, the product sales never grow. It also links innovations strategies to product lifecycle stages: heavy and radical NPD in early phases shifts towards incremental and iterative product improvements over time until the decision comes in decline phase to invest in new and disruptive innovation or to phase out the product. Linking the two concepts also allows to interpret the figure as an opportunity window in case it is possible to freeze the timeline for the market (pull) evolution. The technology needs to be able to propose new value to the market generating demand. Technology push through R&D is needed to entry the market with a proper product-market fit but if the opportunity window starts to close before expected NPD completion, it could be feasible to search for other opportunity windows. Another interpretation is that the shorter the introduction phase and the steeper the growth phase are, the higher the market pull is. A balanced technology product portfolio should involve products in all phases of the lifecycle, and this combination of concepts could provide support for strategic decision-making for lifecycle development.

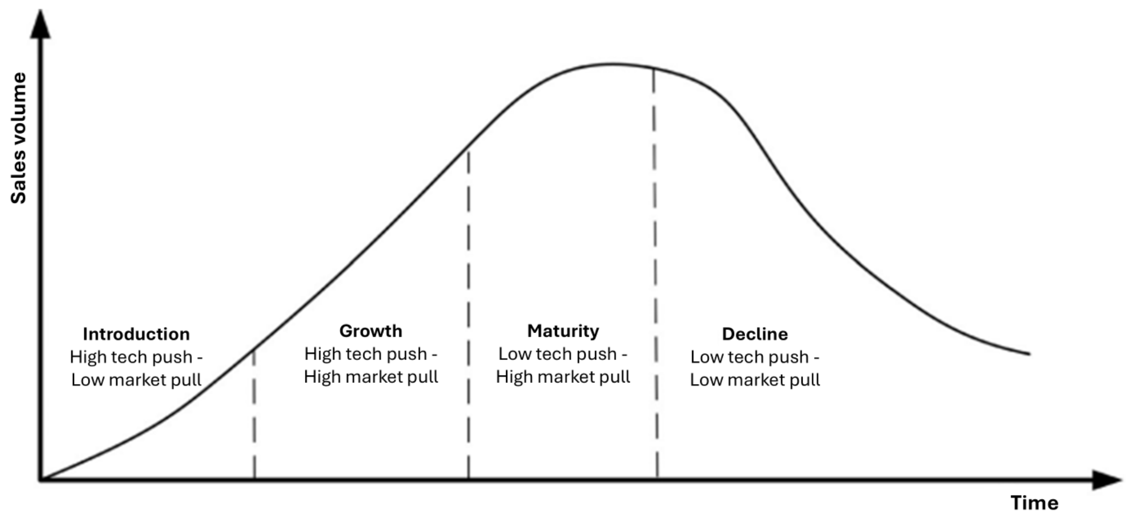

Figure 20. Combination of product lifecycle model and technology push-market pull categorization

Saaksvuori and Immonen (2008) noted that the generic product lifecycle model can be useful in maturity analysis of products and technologies. This can be combined with frameworks like TRL, TRM and PRM for multi-perspective portfolio analysis. Referring to Saaksvuori and Immonen, products in every lifecycle phase are included in optimal product portfolio: promising innovations in planning phase, potential new product introductions, products in rapid sales growth phase, cash generating products in maturity phase and declining products to be retired. In introduction phase, a high focus on marketing is often apparent to establish the desired positioning and market awareness and to attract the first buyers looking for the newest innovations (Saaksvuori and Immonen, 2008). As described by Saaksvuori and Immonen, during the growth phase sales increase with rising market interest while the first competitors emerge. Maturity phase is characterized by stabilized sales volumes and competition diminishing to few players (Saaksvuori and Immonen, 2008). Referring to Saaksvuori and Immonen, when a continuous sales decline, appearance of new replacing products or technologies and price competition with lowering profitability can be identified, the decline phase of product lifecycle has been entered and retiring the product comes into question.

Saaksvuori and Immonen (2008) presented a compilation of four key performance indicators to monitor the business performance and competitive ability in different product lifecycle phases, especially in manufacturing industries (see Figure 21). Time-to-market is a performance indicator of the introduction phase that measures the time required to productize and introduce a new product to the market starting from product definition and design to the first market delivery (Saaksvuori and Immonen, 2008). According to Saaksvuori and Immonen, excessively complex and inefficient new product introduction process can cause poor time-to-market performance resulting in loss of market share, profitability and competitive advantage. Their proposition in this case is to establish a formal stage-gate model and track the turnaround times. The performance indicator that Saaksvuori and Immonen suggest for the growth phase is time-to-volume that measures the time required for full-scale ramp-up of the production volumes without compromising quality and throughput time of product changes during growth phase. This metric can be hindered by supply chain development obstacles, poor manufacturability or poor product information transmission (Saaksvuori and Immonen, 2008). Time-to-react refers to agility and the time it takes to implement the incremental product changes emerged from the market or supply network during the growth and maturity phases (Saaksvuori and Immonen, 2008). They stated that this ability is vital to maintain the competitiveness and profitability of the product in the middle of evolving market needs and conditions. As a fourth performance indicator and metric for decline phase, time-to-service measures the response time to deliver a service order to customer which is a crucial ability not just during the decline phase of product lifecycle but also during growth and maturity phase of service lifecycle (Saaksvuori and Immonen, 2008). As service lifecycle duration is extensive, service business is a more and more popularized way to generate stable cashflow highlighting the importance of customer satisfaction achieved with good performance in time-to-service.

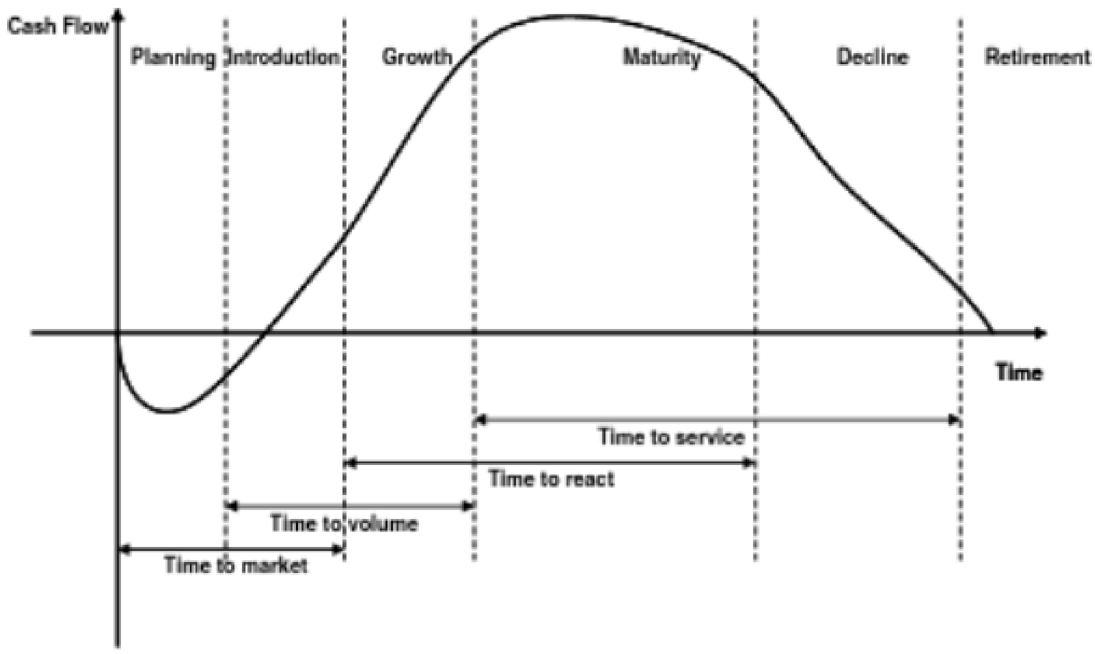

Figure 21. Generic product lifecycle with lifecycle phase metrics (Saaksvuori and Immonen, 2008)

Saaksvuori and Immonen (2008) presented the concept of service lifecycle in unison with product lifecycle (see Figure 22). While product's market lifecycle can have an approximate duration of 5-10 years, the service lifecycle especially with heavy equipment like marine engines, energy production plants and mining equipment can extend up to 25-50 years (Saaksvuori and Immonen, 2008). The concept of service lifecycle is increasingly important in manufacturing industries transitioning towards service business in the current era of servitization. Many companies struggle with the product kill decision and due to this reason, they suffer from poor product portfolio performance (Saaksvuori and Immonen, 2008). It can take years for a company to kill a product that has just strained resources and generated costs due to maintenance of support organizations, product information and required skillsets (Saaksvuori and Immonen, 2008). The product kill decision has a significant impact on service lifecycle and resource management (Saaksvuori and Immonen, 2008) as in principle as long the product is in use, the user needs spare parts and maintenance services. Until declaring discontinuation of service and spare parts, the company needs to keep alive all the resources, capabilities and supply chains even if there would be only one piece of equipment in operation around the globe and the profitability of such arrangement would have negative profitability. Thus, managers should carefully consider the decision about product enhancement or extension to squeeze out the last customers from the market.

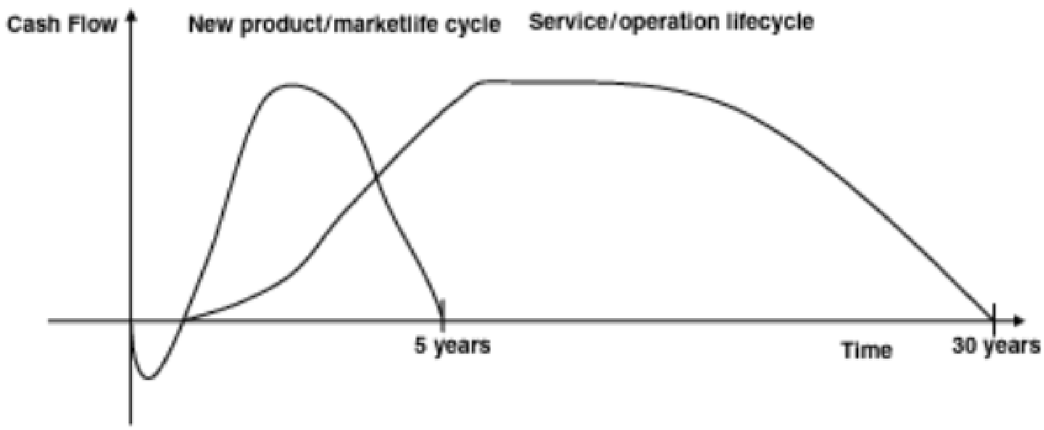

Figure 22. Relation of product lifecycle and service lifecycle (Saaksvuori and Immonen, 2008)

Nege and Werke (2024) studied different growth strategies for products that have reached the maturity phase and stated that maturity phase growth management is essential for long-term profitability and business sustainability. Products face challenges as markets saturate with competition and profitability shrinks due to price competition (Nege and Werke, 2024). As potential strategies for growth in the mature lifecycle phase, Nege and Werke listed product enhancement, market segmentation and expansion to new niches, partnerships, cost optimization through economies of scale, price adjustment and overall lifecycle planning.

Cao and Folan (2012) presented criticism towards market product lifecycle by pointing out its unclear product definition, theory's exclusion of possibility for new growth in mature phase and therefore becoming a self-fulfilling prophecy, dependency on marketing, overemphasis of new product introductions and theory-based product killing. Other criticism the validity of market product lifecycle has faced considers the pre-decided finite nature of product lifecycle, limitations in value chain extension and negligence of interconnections between lifecycle phases (Cao and Folan, 2012).

2.3.2 Engineering lifecycle model

Engineering lifecycle model emerged in literature during the 1990s. The model considers the technical or technological lifecycle of a product. There is not one common or foundational model for engineering lifecycle other than high-level distinction between beginning, middle and end of life. The sub-phases within these phases are varying between authors while the literature generically is uniform.

Stark (2011) defined Beginning-of-Life (BoL) as three-phase part including imagination, definition and realization of the product. Udroiu and Bere (2018) describe BoL as the most complex phase of lifecycle. According to them, BoL includes conceiving, designing, prototyping, testing, developing, elaborating and manufacturing of the product. Cao and Folan (2012) on the other hand described BoL as a phase with concept generation, design, manufacturing and assembly.

Middle-of-Life (MoL) was described by Stark (2011) as a lifecycle phase including use, support and maintenance of the product. In the definition of MoL by Udroiu and Bere

(2018), the lifecycle phase includes distribution, sales, use, maintenance, repair and overhaul of the product. Cao and Folan (2012) included also the service, spare parts management, training and inspections in MoL lifecycle phase.

Referring to Stark (2011), the End-of-Life (EoL) consists of retirement, disposal and recycling of the product. Udroiu and Bere (2018) include in EoL activities of product retirement, disposal and recycling. The product in the EoL phase can also be disassembled, reassembled, and reused (Cao and Folan, 2012)

2.3.3 Industry 4.0 in product lifecycle management

As product data management being an essential part of PLM, it is evident that the advancements of digital technologies in software, networks and computing have an effect. Such Industry 4.0 technologies connect the products and generate data throughout their lifetime providing opportunities for development and improvement in practicing PLM. Industry 4.0 technologies enable flow of data across the entire product lifetime enabling supply chain traceability, advanced manufacturing and real-time operations monitoring. This enhanced data flow has in particular affected the PLM of a single product but also can enable a window for insights into product development and improvement at a wider scale of product lifecycle and product portfolio. However, the literature on the combination of Industry 4.0 and PLM is focused on single product lifecycle and manufacturing rather than extension of market lifecycle of a product through innovations.

Santos et al. (2025) found that integration of information management systems, PLM and Industry 4.0 technologies such as Internet of Things, AI and automation provides improvements in organizational process effectiveness and market performance. They noted that the improved information flow enhances the capability of resilience in dynamic markets. Xin and Ojanen (2017) argued that through digitalization the traditional form of PLM can be extended to closed loop lifecycle management over the entire product lifecycle and activities towards partnerships and standardized industry-wide data could be adopted among manufacturing businesses to achieve higher level of competitiveness. Pfenning et al. (2020) stated that while digitalization has a definite impact on PLM, also PLM has a key role in digitalization by providing a platform for a number of use cases. According to Schweitzer et al. (2019), NPD performance can be enhanced by the use of digital technologies in PLM.

3 Research methodology

This section describes how the thesis research was conducted as a whole. The research design and structure are illustrated step-by-step. Methodology for data collection is explained, and the case company's inclusion is reasoned. Lastly, the validity and reliability of the research is discussed.

3.1 Research design

The complete thesis research design is demonstrated in Figure 23. Thesis got its ideation from the case company need and early identification of research gap. At the second phase of the research, literature review was conducted and utilized to identify functional requirements for the management system by mapping the current status of management practices. Literature was also leveraged in defining the concept's system architecture. The preliminary concept was created in the fourth phase by integrating the requirements and system architecture adapted from the literature.

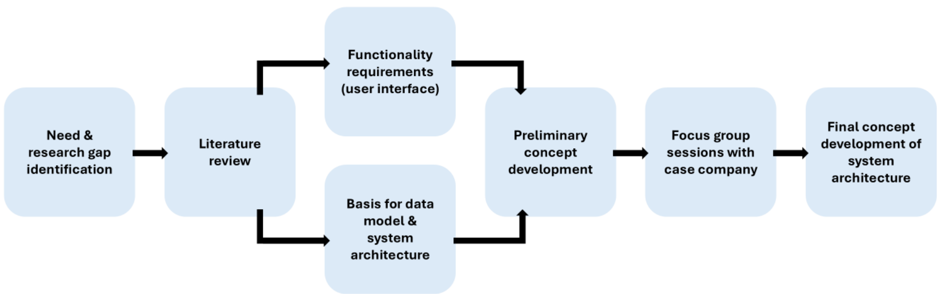

Figure 23. Thesis research process structure

The fifth phase of the research was to apply empirical method, focus groups. Focus group sessions were arranged to review and provide input for the concept development. The objective was to gain insights about system needs and requirements from the case company’s portfolio management teams. The focus group participants consisted of 6 people from product management, 7 from portfolio management and 6 from strategy management. The concept was refined based on the input from focus groups and finalized as a high-level system design.

These methods were applied to cover comprehensively the literature and previous work on the topic to identify generally accepted, applied and relevant management methods and to avoid unnecessary work overlapping with earlier research but to build on it. The empirical method, focus group, was essential to ensure the applicability of the concept and validate its practical value with the case company. A solid foundation for concept development was required and thus the comprehensive coverage of literature and the inclusion of empirical method were both included and mixed.

The concept development workflow and scope were adopted from systems engineering process framework. V-model of system engineering process (see Figure 24) is a widely recognized and adopted framework to track system development lifecycle from concept to production. As illustrated in the V-model, the development lifecycle consists of five general phases which continuously iterate through verification and validation (Fowler and Silver, 2015). Reflecting on the V-model, thesis covered the first phase and stepped into the second phase of system engineering process, concept and preliminary design phases. Applying the principles of object-process methodology (OPM), the system architecture was designed on a high level. OPM is a system modelling language used for conceptualization of complex systems with the integration of structural, functional and behavioral views in a single illustration (Grobshtein et al, 2007; Hause and Day, 2019).

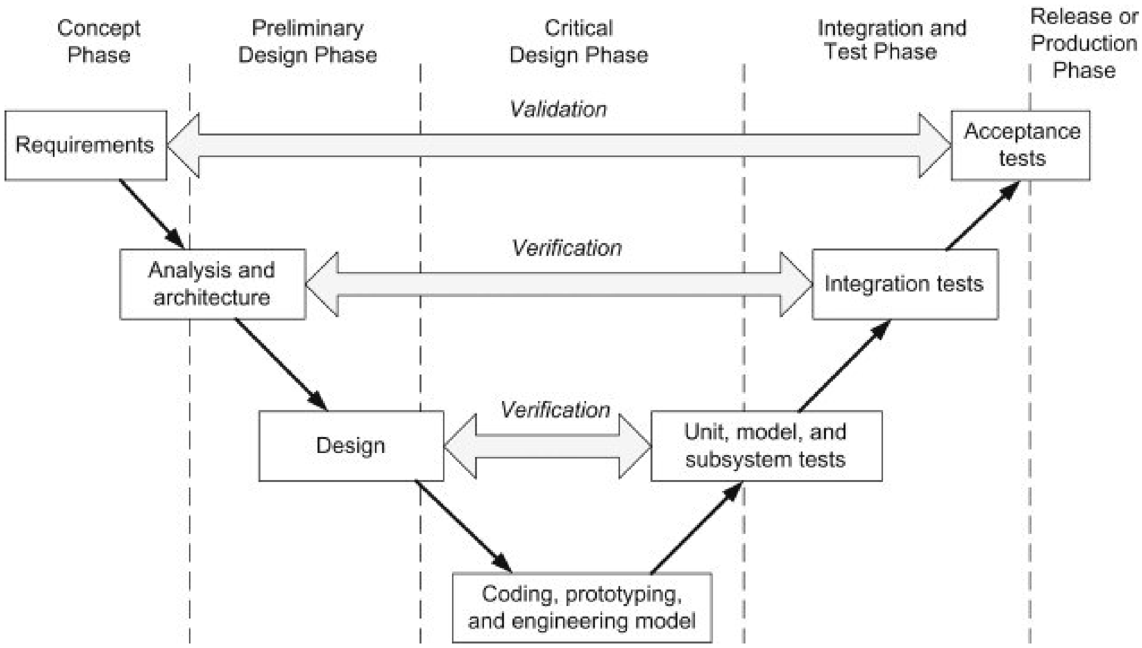

Figure 24. V-model of system engineering process (Fowler and Silver, 2015)

3.2 Data collection

The data collection for literature review was conducted through searches with Google Scholar, Vaasa University library services and AI research agent SciSpace. All the publications used as information sources were checked to be peer reviewed. The timeline for information source publications was set to be from the year 2000 to 2025. The initial research gap identification was used by analyzing the number of publications in JSTOR, EBSCO, Directory of Open Access Journals (DOAJ) and Science Direct.

The input for the industry practitioner insights were obtained from three focus group sessions each with different focus group. The focus groups covered three relevant groups of managers for the thesis research: product, portfolio and strategy managers. The focus group sessions were conducted through video conference calls and in-person meetings each lasting for 1 hour. The focus group inputs were collected in text format in presentation slides during the sessions. The input notes were summarized and confirmed in unison with the focus groups at the end of each session.

3.3 Case study approach

The case study approach was a natural selection for this thesis research as its objective was to create great practical and managerial value. Additionally, it was identified through the literature research that a great number of management methods exist and foundations for data model were conceptualized while their integration for in-practice application-ready concept was missing. This gap matched with the identified need of the case company thus providing a favorable environment to create and refine the concept. Thesis research benefitted from the co-operation with the case company as the focus group participants, who were experts in fields related to the research area, were possible to get to collaborate more easily.

The case company represented a technology-pioneering enterprise with high business and organizational maturity along with structured ways of working. The industries it operates in, marine and energy industries, are in the epicenter of energy transition that pushes the need for new technologies while it is unclear what the winning technology would be. This uncertainty combined with the turbulences from shortening but long product lifecycles, heavy development investment needs, servitization, digitalization and intensified competition were also identified as challenges of modern industrial corporations in literature highlighting the benefit of case study approach. Through this approach, it was possible to assess the challenges identified by case company and the current literature, the need of case company and the literature gap all at once. This approach also provided a possibility for empirical validation of the concept supporting its theoretical foundation. As the case company matched with the identified literature gap being an industrial manufacturing company offering technology products with variations, it was identified that it would be beneficial to utilize case company approach to validate the thesis results and bridge the academic gap.

3.4 Data analysis procedure

The data analysis from literature review consisted of listing and positioning different concepts of TPM, PPM and PLM in relation to each other and portfolio management scope to identify the most critical and relevant methods. Based on the analysis, methods that showed (1) the most success and validity through their adoption rate and proof-of-performance in literature and (2) the most multidisciplinary and strategic nature combining the three management fields were chosen to be included in the concept development. The data input from focus group sessions were summarized during the sessions with the focus groups to avoid misinterpretation of the answers during the thematic analysis. Thematic analysis was chosen as the analysis method as it is a common method used to identify, analyze and interpret patterns within qualitative data, such as focus group session notes. It allowed to interpret reoccuring themes and identify patterns or similarities useful for system design. During the thematic analysis, similarities between the focus group answers were identified and prioritized. Previously unidentified requirements and needs were explored and evaluated. Both data sources and analyses benefited the user requirements and system requirements identification and integration into the concept system.

3.5 Validity and reliability

The research validity and reliability were first ensured by using only timely and peer-reviewed literature from trusted information sources. The preliminary concept was generated by adopting, integrating and applying information from them. Secondly, the reliability was ensured by collaboration with case company a top-quality enterprise with its long history, stability and good performance over time. The preliminary concept was evaluated and commented on through co-operation of case company experts to ensure its validity. The final concept was validated, approved and adopted for further development by the case company increasing the credibility of thesis findings. The case company was a publicly listed company forcing its code of conduct to be solid and supporting the additional validity and reliability received from its co-operation. The concept development was conducted using a widely validated system engineering process, V-model, and ISO standardized system architecture design method, OPM, supporting the validity and reliability of the concept development process. The type of triangulation in conducted thesis research combined theoretical approach, practicioner insights and real-world validation increasing the thesis's robustness as it is not biased nor reliant only on one method or approach.

The validity and reliability could be improved even further by extrapolating the study to include focus groups from multiple case companies. Generating numeric data as output from the focus group sessions could also improve the reliability and validity of the research by providing a more quantitative approach for the analysis. On the other hand, as the case company was a beneficiary of the thesis research, it was in the case company's interest to have a reliable and valid concept. This note tackles any claims about case company's subjectivity as the research did not take any stand on case company's performance, nor did it evaluate case company's performance in its ways of working.

Another way to criticize the validity or reliability of the thesis research would be to comment on its timeliness of literature review. The timeline was selected to include publications from the last 25 years during which technology industries, especially information and energy industries, have been under a great transition and rapid advancement. However, as found from the literature, the core principles of management had not been changed during this time. Also, it was identified that most often the cited literature in used publications dated back to the same timeline that was used in this thesis underscoring the uniformity of the thesis and the rest of academic literature in selected timelines for source information.

The objective for the data obtained from the focus groups was to identify and understand the key needs and requirements from the industry and practicioners. The objective was not to in particular cover all aspects but their needs and requirements as they saw as practicioners. Open questions were used to not direct the focus group participants but to let them provide their insights without biasing them. The research questions number 2 and 3 were considered during the sessions by providing them the research questions and the preliminary system architecture. All this was done to ensure the content validity and unbiasedness of the focus group results.

All system requirements were derived from the challenges, needs or work steps of technology product portfolio management. They were decomposed and underlying problems were identified. These problems then converted into requirements what the concept system should be able to do and how it should be functioning. This process describes the cause-effect relationships between the challenges, needs and work of technology product portfolio management and the system requirements. As an example, misaligned and outdated data available for management could be solved with the system requirement of real-time data integration across systems. As another example, laborious data analysis and making of visualizations could be solved with the system requirement of autonomous advanced analytics engine and user interface with visualizations.

4 Results and analysis

This section covers the results and analysis of literature review and focus group sessions. Preliminary concept was developed based on the literature review and the finalized concept was developed by integrating the focus group inputs. The results and analyses are presented in the following order: literature review analysis, preliminary concept development, focus group input analysis and concept finalization.

4.1 Literature review analysis

The analysis of the methods explored and identified in the literature review was conducted by utilizing the thesis research area and the process of portfolio management. In Figure 25, the methods are positioned in a Venn diagram with three parts: PLM, TPM and PPM. As depicted in Figure 25, the overlap of the three management fields is evident. PPM was the dominating field of research in the number of methods included in the research by being linked to 16 out of 19 methods. It can be observed that PLM had only one and TPM two methods that were linked specifically to them while PPM had four. Out of the 19 methods, six methods were linked to all of the three management fields. These methods were roadmapping, NPD portfolio efficient frontier, scenario analysis, AI techniques, multivariate regression and types of optimization programming. Another six methods were linked to two management fields. Three methods, product lifecycle model, digitalized PPM model and horizontal and vertical product portfolio governance, were cross-disciplinary between PPM and PLM. On the other side, probabilities of success, ROA and utility theory were cross-disciplinary between PPM and TPM. Through the analysis of method positioning in research areas, a holistic integration of the management fields in a management system was observed to be evident and valuable.

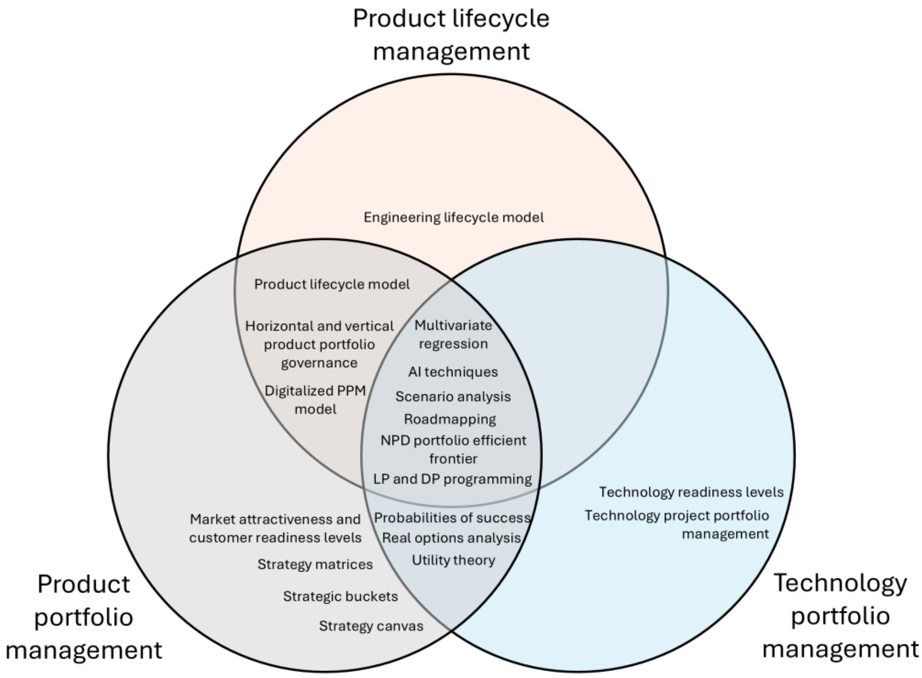

Figure 25. Management method positioning in a Venn diagram of research areas

Figure 26 illustrates the positioning of the 19 management methods in the process of portfolio management derived from Yu's general description of TPM (2006). While the focus of the thesis was set on the practice of portfolio management, it is significantly important to understand the whole process and how the management and planning methods are linked to each other. This comes clear from observation of Figure 26 and understanding that in order to track, modify, manage and achieve the optimal portfolio, previous process stages need to be properly quantified and executed. Different KPIs, matrices, canvases and analyses useful for continuous tracking and dynamic management of portfolio are derived from the previous process stages. While positioned in the second process phase, the strategy methods can also be utilized in the fifth phase to track the portfolio. It can be observed from Figure 26 that the technology product portfolio management portion is notably less crowded than the planning portion highlighting the value of the thesis research and concept development of a management system.

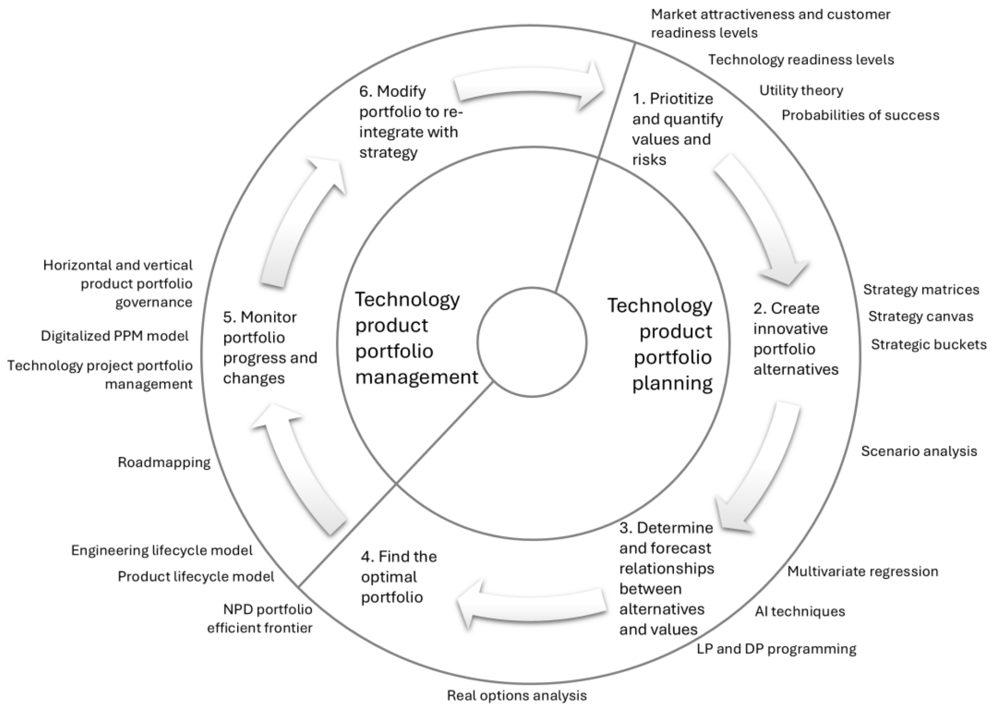

Figure 26. Management method positioning in technology product portfolio management process

4.2 Preliminary concept development

The preliminary concept of system architecture was developed as a holistic model for strategic portfolio management based on the literature review information. The preliminary concept development integrates identified key needs and requirements, top management methods and previous portfolio management concepts with the objective of turning portfolio complexity and complex analysis into simple visualizations. It was highlighted by literature review that there is a need for a dynamic, scalable and practical tool with real-time analytics integration. The importance of including strategic value in addition to financial value, portfolio management objectives support and product-level analytics were other key findings. The concept applies knowledge management principles as it treats data as a strategic asset transforming it into knowledge in real-time. The system concept illustrates a type of end-to-end data integration and analytics model that provides descriptive and predictive analytics through visualizations and an opportunity for prescriptive analytics with scenario simulations. The identified complexity of TPM, PPM and PLM and information overflow are assessed with advanced analytics and intuitive visualizations with the aid of the most adopted management methods. The system architecture itself can be characterized as a complex adaptive system due to its component interconnections, external dependencies, non-linearities and continuous evolution. This is a derivative from the modelled nature of portfolio in which products interact and continuously generated new data causes changes.

4.2.1 Functionalities

The concept development is based on the identified the user requirements and translating them into functionality requirements in user interface (UI) utilizing management methods as views and developing the concept further from the functionality standpoint to system architecture. The functionalities were compressed into five different outlooks: current NPD portfolio on value-risk map, dynamic technology-product-market roadmap, product portfolio lifecycle models, general KPI tracking and strategic positioning graphs. These together provide a comprehensive overview of the portfolio offering different types of essential information in one place for the two key tasks of portfolio management: tracking and adjusting the portfolio.

Mapping of the current NPD portfolio is based on ROA in order to include the strategic value of the technology and new product in addition to its projected financial value. The risk factor is determined by evaluating the probabilities of commercial and technical success and the spread of sales volume forecasts in different scenarios. Based on this information, the NPD projects are then mapped on value-risk coordinate system. Also, an optimal portfolio is calculated and illustrated on the map by using the Markowitz portfolio optimization theory. This functionality supports all the portfolio management objectives. It also includes the missed strategic value in portfolio management practices and provides definite support for NPD portfolio management decisions.

A dynamic and interactive technology-market-product (TMP) roadmap offers an overview of the portfolio's status overtime. By being based on a digital database, it does not require laborious manual work for updating and is always up to date. Extending the scope from product roadmap to include also technology and market aspects, the roadmap provides information more comprehensively. This enables the possibility to follow technology development separately from product development and to follow market development in terms of changes in regulation, competition and customer behaviour. This type of roadmap would help to align development activities across the portfolio while addressing market conditions supporting management of the whole offering portfolio. It would also be possible to integrate the technology and product development department's resource utilization rates on the timeline to identify possible overloads and to adjust the resource allocation. Interactivity would offer the possibility to view the status of a certain technology project, product or market incident for convenient tracking.

Product portfolio lifecycle management outlook adopts the generic product lifecycle model from PLM and is essential for proper balance of the portfolio. By its incorporation, it is possible to track the portfolio's maturity level product-by-product and execute adequate renewal through new product introductions and product phase-outs. Product portfolio lifecycle outlook supports future sales volume estimations on a high level, indicates what kind of growth strategies to consider and if the focus should be put more on new product development or product improvement.

KPI tracking outlook can be used to follow various metrics related to technology product portfolio management and business performance in real-time. Such KPIs as profitability, market share, net promoter score, quality notifications, sales opportunities, lead time etc. are business-critical and it is important to be able to track them on product level to identify problematics and improvement opportunities. It can also be used to track different time-to-X metrics and resource utilization.

Strategic positioning graphs are useful in portfolio balance management and investment prioritization. The portfolio can be reflected in positioning matrices, strategy canvas and strategic buckets providing useful information for tracking and monitoring of portfolio performance, fit and allocation. As the data and analytics for the positioning graphs are updated in real-time, the graphs provide up-to-date insights supporting decision-making in investments and focus shifts.

4.2.2 Preliminary system architecture

The preliminary system architecture is represented in Figure 27. OPM was applied in system architecture conceptualization to integrate structural, functional and behavioral views all in one. The preliminary concept consists of five main blocks: UI, analytics engine, data warehouse, source systems, and business processes and installed base.

The UI consists of dynamic visualizations described earlier as functionalities in addition to workspace and simulation tool to work on portfolio decisions. The focus of the UI is to provide real-time and user-friendly portfolio tracking ability for management support. Analytics engine operates the automated data processing of advanced analytics. It performs simple and complex equations, dynamic programming and machine learning algorithms with basis on mathematical modelling and statistics. Data warehouse functions as centralized and structured digital database of various enterprise data enabling the real-time analytics with quality data. It could contain relational database with multiple interlinked tables applying the snowflake schema. Source systems consist of the key enterprise business and product information systems such as ERP, CRM, SCM, PLM and IoT. These systems can be already operational and existing ones as the aim is to utilize their data and not to add another reporting system. Business processes and installed base generate the actual data for proper data collection. Installed base can provide operational data through IoT systems for the uses of KPI tracking, strategy canvas and service lifecycle management.

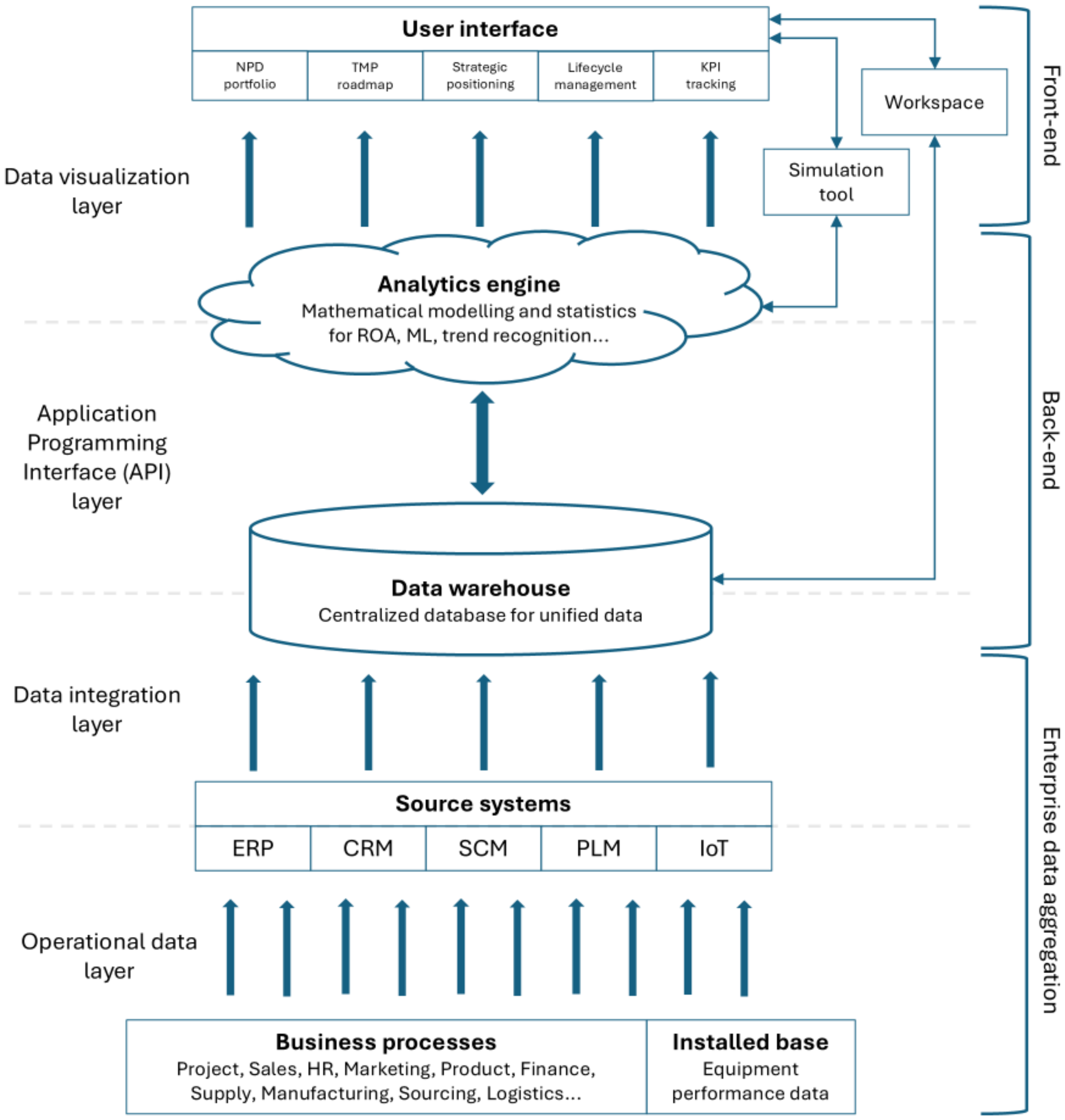

Figure 27. Preliminary conceptual architecture of integrated technology product portfolio management system

The data flows between the main blocks are in four layers which are operational data, data integration, application programming interface (API) and data visualization (see Figure 27). Operational data layer consists of the interplay of business processes, installed base and source systems. Data integration layer combines source systems and data warehouse. System integrations evidently play a crucial role in addressing the requirements of real-time and dynamic analytics. They act as an enabler for the common data warehouse through enterprise data aggregation. The API layer connects data warehouse to the analytics engine. API acts as a scalable solution for getting the data for processing and modelling. Data visualization layer transforms the analytical insights and mathematical models into visualized graphs and figures.

The function of analytics engine is the most complex part of the concept. Its first major function is to apply statistics, probabilities and machine learning algorithms to form mathematical formulas, forecasts and optimization models, recognize trends, and track the portfolio performance. The second major function is to enable the practice of scenario analysis with the aid of simulation tool that would utilize statistical methods in creation and comparison of different scenarios with varying parameter values and risk levels. Various types of data are needed for the multi-disciplinary analysis of portfolio management. As this versatile data is continuously generated, it is important to define the required data, determine its integration or migration time intervals, label it appropriately and structure it properly in the data warehouse to ensure efficient, adequate and reliable data analysis process. The analytics engine should be capable of performing risk assessment, profit forecasts, lifecycle stage determination, weighing of different parameters and various other advanced calculations to provide the advanced analytics behind the visualizations. Further explanation of detailed data model design and detailed calculation descriptions were not included in the scope of the thesis.

4.3 Focus group results and input analysis

The inputs from focus groups sessions are summarized in Table 4 (see Appendix 1 for unedited inputs). From Table 4, it can be observed that the identified requirements and needs of focus groups were to a large extent similar with the ones identified in literature. The needs for dynamic and intuitive visualizations, product roadmap with market, technology and competitor perspectives and overview of product-level status and performance were identified by each focus group. Each group also underlined the importance of high data quality and advanced data processing. Focus groups were convinced of the value of the concept system. They were able to communicate their needs and requirements for the system while stating that such systems are often non-existent or non-sophisticated enough to address the needs and requirements.

Table 4. Results summary of inputs from focus group sessions

Focus group	Needs	Requirements	Concept development
Product Management	A comprehensive product overview supported by detailed insights at the product-level; Seamless integration and communication between systems enabling efficient data flow; Decision-making supported by decision log of roadmaps; Linkage to business case analyses; Risk factors incorporated to ensure robust planning; Clear visualizations to enhance and support strategic decisions	Clear portfolio roadmap with product-level KPIs such as sales, profit margin, product cost, readiness levels etc.; Extractable data for analysis; Overview of key actions and development tracked on product-level	*No comments*
Portfolio Management	Common platform for people and products; Scalability; Ability to identify market development and match the offering and product technologies with it; Timeline of 10+ years for large project industries; Whole offering as business case portfolio including capital, service and auxiliary; Ability to include the total business case value	Ability to tailor the system according to company specification; Dynamic data tracking with reach to installed base; High standards for data cleaning, reliability, availability, quality and enhancement; Ease of system maintenance; Visibility into simultaneous technology and new product development projects	Databricks as an optional data storage method
Strategy Management	Ability to match product portfolio with identified market development ; Forward-looking information rather than backward information; Tracking of competitive landscape; Regulative impact to be included on product-level; Overview of product-level status in terms of ROI, generated services and auxiliary sales, capitalization cost, weight in portfolio etc.; Ability to configure the dashboard with an AI prompt	Ability drill down to product level from portfolio level; Interactivity with visualizations; Simulations for scenario analysis; Forward-looking data to identify weak signals and recognize trends recognition	External data sources for the need for additional information on markets, competitors and regulation; Data quality assurance and synchronization methods; Developer UI and feedback loop for continuous machine learning training, development and validation

Product management focus group highlighted the practical value of visualizations and the importance of informative overview of the portfolio at product level, clear product portfolio roadmap, system integrations and linkages to business case analyses. Portfolio management focus group emphasized the data requirements and processing aspects, system scalability, maintainability and customizability, visibility of market development and simultaneous technology and NPD projects over an extended timeline and business case analysis inclusion. Strategy management focus group underlined the ability of matching product portfolio with future market needs, regulation development and competitive landscape with forward-looking data from various internal and external sources. This focus group noted the importance of product-level status information, data quality and synchronization and scenario simulations in addition to suggesting a prompt-based interaction with the visualization and separate machine learning development and validation feedback loop and UI. A note from strategy management focus group related to large project industries was that due to low volumes, the ability of using machine learning algorithms is hindered as too little training data for the algorithms increases vulnerability and probability of mistakes and wrongful predictions. They noted that the product roadmap should indicate regulative impacts on products' obsolescence.

The collected focus group inputs were thematically analyzed, combined and converted into system requirements. The focus group -based system requirements are listed by each system architecture block in Table 5. It was observed that 16 out of 20 focus group -based system requirements were already addressed at some level in preliminary system architecture. The four totally new system requirements originating from focus groups were decision log for product roadmaps, product-level information on key actions, developments and supplier strategies, developer UI and feedback loop for ML training and validation, and external data sources for information search of market development, regulative environment and competitive landscape. A general, concept-wide system requirement was to keep the concept as solution-neutral in order to enable system tailoring and have the freedom of application technologies and techniques. The importance of business case analysis inclusion was especially highlighted by product and portfolio management focus groups. Through ROA's inclusion of strategic value in business case analysis the total business case value can be evaluated. By mapping of the portfolio applying Markowitz's portfolio theory, the NPD portfolio visualization functions as business case portfolio visualization. Strategic positioning matrices support business case re-evaluation, market space navigation and investment decision-making. Lifecycle management visualization supports products' maturity assessment and strategic action planning. KPI tracking view acts as a monitoring tool for historical product performance.

Table 5. System requirements based on focus group input analysis

System block	Requirement
Concept-wide	Solution-neutral concept to enable tailoring and freedom of application methods
User interface	Interactivity and modifiability with visualizations; Risk management inclusion in NPD portfolio visualization; Offering as business case portfolio in NPD portfolio visualization; Overview of technology development and product portfolio with market development, regulative environment and competitive landscape in TMP roadmap; Product roadmaps and roadmapping decision log in TMP roadmap; Product-level information on key actions, development and supplier strategies in TMP roadmap; Product-level status, KPIs and statistics in KPI, lifecycle management and strategic positioning visualizations
Analytics engine	Developer UI and feedback loop for ML training and validation; Predictive analytics with various calculation principles and ML algorithms; Trend recognition and weak signal identification with ML; Linkage to business case analyses based on ROA; Risk management inclusion in ROA calculations; Ability to include total business case value with ROA; System scalability enforced with API data transmission
Data warehouse	Data quality assurance and enhancement for reliable analytics; Efficient data labelling for streamlining the system capacity; Advanced technologies for data storage and synchronization
Source systems	System integrations for real-time data transmission, dynamic data tracking and data coherency
Data sources	External data sources for monitoring of market development, regulative environment and competitive landscape

4.4 Concept refinement

The value, form and contents of system concept were validated in focus group sessions by the case company practitioners and further improved based on the input analysis. As the system requirements based on focus group input analysis showed significant similarity with the system requirements identified from the literature, the development of preliminary system architecture consisted of less major changes but rather refinement and iteration of the preliminary concept presented in chapter 4.2. The refined concept system architecture is presented in Figure 28.

The new system requirements identified with focus groups were integrated in the refined concept. The ability of drilling down and rolling up in the analytics visualizations was also identified to be one of the key practical capabilities while it did not have a visible effect on the holistic concept of system architecture. The same applied with the requirement of having visibility over product-level information in terms of key actions, developments and supplier strategies. Both of those requirements can be integrated in functionalities of TMP roadmap view. The idea of prompt-based AI agent for UI interactivity also did not affect the system architecture itself. Such natural language processing-based tool would utilize the analytics engine and thus could be one feature in UI implementation. Solution-neutrality of the concept was persevered in order to enhance concept's generalization and tailorability in addition to enabling different ways of implementation. A solution-neutral concept does not pre-determine the methods of implementation leaving space and freedom for application-specific detailed design. System boundaries were added in the refined concept system architecture to further describe the system's interaction with other enterprise management systems and external data sources.

The user interface system block encountered sub-level additions in terms of inclusion of decision logs and more comprehensive coverage of product-level data for technology-market-product roadmap view. The analytics engine system block was refined with an additional box of developer UI for ML validation and training. Source systems system block got an additional sub-block of business intelligence system. This block demonstrates examples of systems to be included in data sources while not limiting the type of systems to be included in. External data sources to retrieve data and information on market development, regulative changes and competitive landscape were added next to internal business process and installed base data sources.

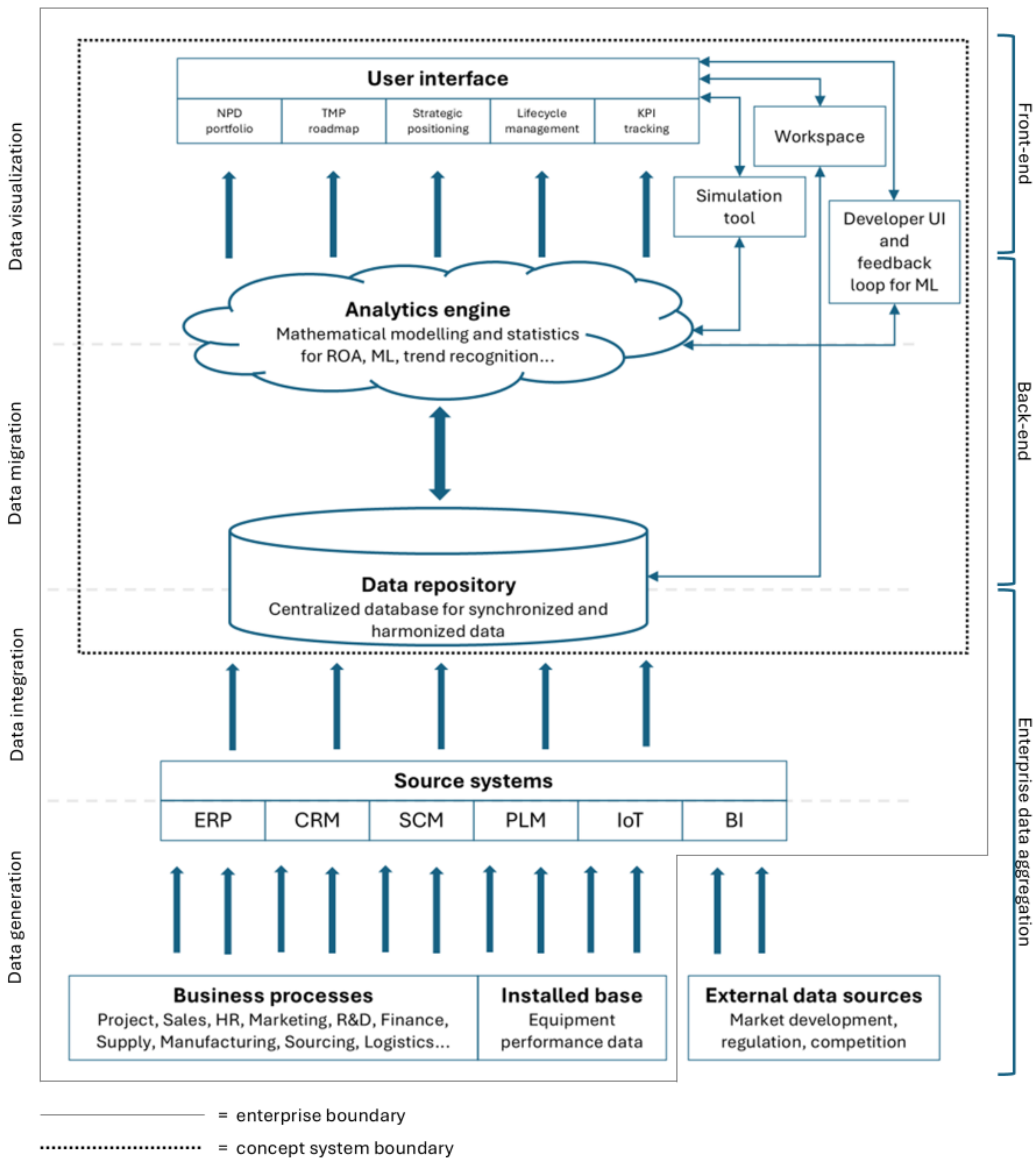

Figure 28. Refined conceptual architecture of integrated technology product portfolio management system

As there are numerous ways to implement data storing, the naming of data warehouse system block was changed to “data repository”. This term is more general and does not limit the technologies and techniques to be used. With this term it is also possible to include semi-structured and non-structured data in addition to structured data. Alternatives for the data warehouse block in the architecture were identified during concept refinement. Various technologies and techniques such as databricks, data lakes, and relational databases in addition to initial method of data warehouse were discussed.

Enterprise service bus (ESB) can also be another alternative to be used as a seamless master data directory, data flow and quality manager and systems integration platform. In addition to structured data warehouse, ESB could include a data lake for semi-structured data which could be utilized in advanced machine learning analyses. The system can apply ETL or ELT data transmission to achieve consistency and quality with the data. Harmonized and unified financial and strategic data on products mitigates the risks of data fragmentation and misinformation. Ultimately, the core idea of the system block is to establish a digital data storage that ensures data quality, synchronization and harmonization.

The classic OPM elements of the refined system architecture concept are summarized in Figure 29. Operands of the system include the various data types as they are under manipulation and transformation through the system. Value processes include data integration and processing as well as performing analyses and visualizing the different management methods. Value instruments include data integration tools, data storage technology, analytics software and visualization tools. Supporting processes include data quality, maintenance and security measures and supporting instruments provide the tools, systems and protocols for them. Security measures are especially required in data integration interfaces to ensure protection of confidential corporate data.

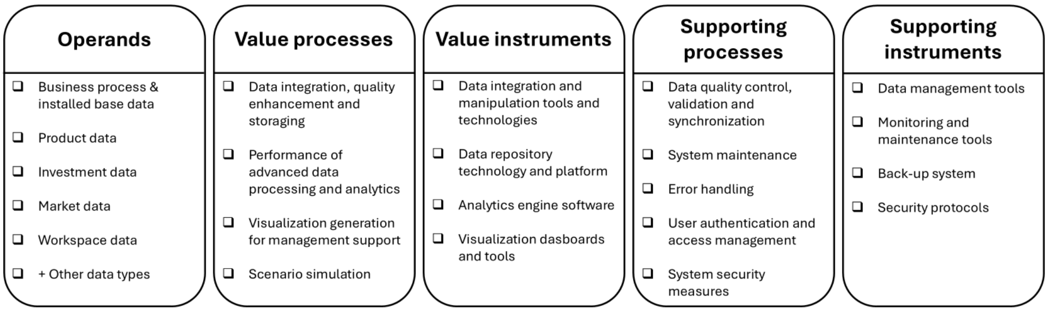

Figure 29. OPM elements of the refined concept system architecture

5 Conclusions

Many technology-oriented industrial companies face major disruptive factors such as energy transition, increasing market dynamics and customer segment fragmentation causing uncontrolled expansion and complexity in product and technology portfolios. This thesis was conducted as a case study for an industrial manufacturing corporation in the business of marine technology. The case company had encountered an emerging problem with the complexity of managing technology and product offering portfolios. The case company's identification of value for a technology product portfolio management system for such purpose set the starting point for the thesis.

Thesis's literature review covered the fields of management in technology portfolios, product portfolios and product lifecycles. Publications only with academic sources and only from 21st century were used as the information sources for the literature review. A gap in literature was identified in the integration of the aforementioned management fields and in systems for their integrative management. The most adopted management methods of TPM, PPM and PLM based on literature were mapped around a portfolio management process wheel and in a Venn diagram.

A concept system and its system architecture were developed by leveraging proven system engineering models: V-model and OPM. A robust foundation for the holistic concept development was provided by these models. The first user requirements were collected from the literature in the form of most adopted and industry-proven management methods in TPM, PPM and PLM. Identifying and prioritizing the management methods with the most cross-disciplinary nature and value for strategic portfolio management, the required user interface functionalities were identified, and a preliminary concept system architecture was designed.

Focus group sessions were held with the case company's strategy, portfolio and product management teams. Input was gathered during these sessions for the users' needs and requirements and for the feedback on the preliminary concept system architecture. The inputs were summarized, analyzed and converted into system requirements. The preliminary concept system architecture was consequently refined and iterated based on these additional system requirements.

Thesis research was limited to covering concept development to the point of high-level design for the integrated technology product portfolio management system and its system architecture. Detailed exploration and description of data analysis, systems integrations or other components of system configuration were not included in the thesis. Thesis focused on measures and methods of portfolio management rather than portfolio planning while these are interlinked activities. The research focused on industrial manufacturing and technology-oriented product business industries. The inputs from empirical research part for the development of the concept was limited to case company practitioners while getting input from several companies and industries would benefit the generalization of the developed concept. Concept development was based on qualitative data analysis while inclusion of quantitative data and analysis could have benefitted the robustness of the concept. While OPM as a system architecture design method served its purpose on holistic concept development and was the correct method for the scope of the thesis, SysML, another system architecture design method used especially for software systems, would have provided a more detailed view of the system.

5.1 Findings

The main objective of the thesis was to bridge the identified gap in literature and add value to the practice of TPM, PPM and PLM by developing a concept for an integrated technology product portfolio management system. The first research question considered the current states of TPM, PPM and PLM in terms of the most adopted management methods within the fields. 19 management methods were identified during the literature review. They are mapped in a Venn diagram (Figure 25) and positioned around a portfolio management process wheel (Figure 26). The second research question considered the key needs and requirements from a technology product portfolio management system. The management methods identified in the literature review provided an academic basis for the user needs and requirements. These were complemented by the input from focus groups, its analysis and conversion into system requirements summarized in Table 5. The third research question considered the outlook of the concept system which is illustrated in Figure 28 and in Appendix 2.

The most essential system requirements emerging from the literature are dynamic UI, scalability of the system, real-time data integration, product-level analytics and ability to evaluate and include strategic value in addition to financial value into the analytics. System requirements highlighted by the focus groups were data quality assurance, roadmapping capabilities and functionalities, strategic value inclusion in business case analyses, dynamic, intuitive and interactive UI, and product-level information. From functionality point of view, the requirements can be converted into five separate UI views: NPD portfolio mapping, technology-market-product roadmap, lifecycle management model, strategic positionings and KPI tracking. These should be taken into account in detailed design and implementation of the concept system.

Thesis conceptualized a system architecture of an integrated technology product portfolio management system for portfolio tracking and management with advanced data-driven analytics and intuitive visualizations. The value of the developed concept was validated and enhanced by the case company’s practitioners of strategy, portfolio and product management. The concept system is integrative in two ways: firstly, it integrates the best practices of the three management fields and secondly, the data it transforms into advanced analytics goes through multiple system integrations. Thesis results contributed to literature and industry by bridging the previous work of digital PPM model with the most commonly practiced and validated management methods in TPM, PPM and PLM in a holistic and synthesized concept. By integrating the three aforementioned technology and product management fields, a comprehensive and in-depth analyses and decision-making support can be provided for practitioners with the implementation of the concept system. As the conceptualized system architecture is designed on high-level, it is required to conduct application-specific detailed design and customization for adequate implementation with organization-specific needs, requirements, data and systems.

Thesis's value to the existing literature comes from linking the previously separately practiced fields of TPM, PPM and PLM into one holistic practice of technology product management. The most adopted management methods from all the three management fields were identified and as a novel approach, they were positioned in relation to each other in portfolio management process wheel and in Venn diagram. The integration of TPM, PPM and PLM ensure that technology innovations, investments and developments are carefully done with clear product visions and converted into a successful mix of products in different lifecycle phases and with different characteristics for intelligent portfolio balance, alignment and optimization. Integration of TPM, PPM and PLM support management of technology development, productization, product growth strategies and phase-outs with deep understanding of portfolio's status and future. The conceptualized integrated technology product portfolio management system can create value by enabling higher strategic alignment, balance and value of the portfolio. This can be achieved with data-driven decision-making backed with advanced analytics and intuitive visualizations. The concept system has the capability to help optimize portfolio's profit-risk level, identify new market spaces, accelerate new products' time-to-market, optimize resource allocation to the most valuable technologies and products, leverage synergies across product families and ensure portfolio's robustness in the future.

5.2 Discussion

Thesis results showcased that while there are established theoretical models for TPM, PPM and PLM, their value is not fully utilized by adopting and integrating them. A holistic approach to technology product portfolio management has been missing in the academia and in the industry but the foundations for it have now been built as a result of this thesis. The Figure 25 and Figure 26 on management method positioning in technology product portfolio management research areas and process illustrate how different methods complement each other in the holistic picture. At the same time the figures illustrate how limited each of the methods is highlighting the importance of their integrative use. Especially Figure 26 on technology product portfolio management process demonstrates that each of the methods is a part of the holistic management field and reaches its full potential only when combined with the others. Combination of 19 different management methods requires a sophisticated system and that is what the suggested concept system depicts. While Hannila and Tolonen with their research teams in numerous studies on product portfolio management have introduced new frameworks, they stay on theoretical framework level while this thesis introduced an applicable system architecture. Hannila et al (2022) introduced a digital data model for product portfolio management demonstrating real-world applicability while it focused on data management levels. In this thesis, an applicable concept of management system architecture for technology product portfolio management practicioners was developed focusing on the practical value, user needs and requirements and transformation of real-time integrated data into advanced analytics and visualizations.

While it was expected that some system requirements for the concept could be derived from the existing literature, it was surprising how clearly the focus groups were able to communicate their needs and requirements for the concept considering the lack of such system. Also, the level of similarity of system requirements identified from the literature and identified by focus groups was unexpectedly high. All the same aspects were found through both ways. Some additional features were identified by the focus groups while literature provided additional tools and information for business case analyses and portfolio planning. This means that as the requirements were mapped using two different approaches, they are solid considering not just the case company but also industrial technology companies on a larger scale. The system requirement of dynamic and interactive UI implies the practitioners need to tailor the system for their own purposes, simulate different scenarios and understand the portfolio from various different aspects. The applied system engineering models were valuable for the concept development in structuring the research process and ensuring valid and reliable results and adequacy of the concept system.

While the focus group input data collected solely from the case company, system requirements based on it were in line with the system requirements derived from the literature to large extent. This observation tackles the findings' generalizability and concepts applicability issue. It also shows that the focus groups did not cause bias for the thesis results. As qualitative research methods and creativity were used to configure the concept, it could be argued that the system is solely based on assumptions without quantitative analysis. However, conceptualization of system architectures is about creatively reducing the ambiguity of needs, requirements and values and system complexity. In addition, the similarities of qualitative results were quantitatively analyzed. On the other hand, in-depth quantitative research could provide further reliability for the thesis results. Thesis results consider the context of industrial technology companies and do not take a stand on how the suggested concept could look like in digital business companies or public sector organizations while the approach of holistic technology product portfolio management can be applied in both. Nonetheless, these are areas for possible following research. Implementation of developed concept system will require a level of digital maturity and required data streams should be established for the concept to reach its full potential. While the concept system itself is complex due to its interconnections and system integrations, it does not outstand in complexity when compared to other enterprise management systems. Thus, the complexity would not be a reason for it not to be implemented in real-world applications. It is clear that the concept system implementation would require significant amount of work with existing systems due to system integrations. Although, as suggested concept -like of advanced systems currently do not exist as such, there should not be as much resistance on replacing legacy systems in applying organizations. Additionally, the concept's idea is to utilize existing systems so consequently the concept system could utilize the legacy systems through integrations.

Thesis findings and developed concept can be used as a foundation for product portfolio management systems in industrial technology companies. It provides generic frames and system requirements and offers implications for the preferable functionalities and management methods to be included. While thesis was focused on developing a concept system, it takes a strong stand on what type of data, information, analysis and knowledge should be backing the decision-making process when it comes to technology and product portfolio management. The inclusion of strategic value in ROA and business case analysis is a clear managerial implication that thesis research identified.

Ultimately, the concept's objective is to help industrial technology companies to enhance their performance with their offering portfolio management objectives: strategic fit, value maximization and portfolio balance. The purpose of the concept system is to clarify the practice of technology product portfolio management and to create new value from existing systems and existing data while reducing the workload of the company's management teams. Concept can help companies to develop a system that they can leverage to do better decisions, allocate their resources correctly and achieve a balanced, well-succeeding, strategically aligned and future-proofed portfolio of technologies and products. While establishing a concept-like management IT system can be too much of an effort for smaller companies, the holistic technology product portfolio management approach thesis is based on can be and is suggested to be applied in industrial technology companies at the level of processes and managerial mindsets at minimum.

5.3 Research limitations and future research

The literature review was limited to peer-reviewed journals, textbooks, and white papers relevant to the research topic, excluding unofficial sources such as social media to ensure information validity. All sources used were published from the year 2000 onward to maintain relevance and timeliness. The thesis context was limited to technology product manufacturing industries. The focus groups were limited to include practicioners only from the case company in marine technology industry. Thesis presented a high-level concept for a technology product portfolio management system while detailed system design and implementation were outside the scope. Research methods were limited to literature review, focus groups and thematic analysis along with system engineering models while further quantitative data was not obtained.

As a consequence of this thesis paper, future research on three different realms is suggested by the author. First, research on detailed design, for example in the form of model-based systems engineering or SysML diagrams, of technology and product portfolio management systems could be conducted as a natural continuum for thesis's high-level concept. Second, empirical research of applying the suggested concept or adaptations of it in high technology and industrial manufacturing industries would be needed to ensure the validity of the concept. This would allow identifying improvement opportunities for further generalization and seeking subsequent measurable effects for validating its value to businesses. Third, research on technology and product portfolio management systems in digital industries has potential to be contributable to the suggested concept and to the digital industries.

References

Albright, R., & Kappel, T. (2003). *Roadmapping In the Corporation*. Research-Technology Management, 46(2), 31–40. https://doi.org/10.1080/08956308.2003.11671552

Al-Harthy, M. (2007*). Utility Efficient Frontier: An Application in the Oil and Gas Industry.* Natural Resources Research, 16(4), 305–312. https://doi.org/10.1007/S11053-007-9056-3

Aliev, R., Alizadeh, A., Huseynov, O. & Jabbarova, K. (2015*). Z-Number-Based Linear Programming*. International journal of intelligent systems, 30(5), 563-589. https://doi.org/10.1002/int.21709

Baker, E. & Solak, S. (2014). *Management of Energy Technology for Sustainability: How to Fund Energy Technology Research and Development*. Production and operations management, 23(3), 348-365. https://doi.org/10.1111/poms.12068

Bowie, J. (2021). *Advanced Space Technology Roadmapping Architecture (ASTRA).* NASA TechPort. https://techport.nasa.gov/projects/118282

Cao, H. & Folan, P. (2012). *Product life cycle: The evolution of a paradigm and literature review from 1950-2009.* Production planning & control, 23(8), 641-662. https://doi.org/10.1080/09537287.2011.577460

Chao, R. & Kavadias, S. (2008). *A Theoretical Framework for Managing the New Product Development Portfolio: When and How to Use Strategic Buckets*. Management science, 54(5), 907-921. https://doi.org/10.1287/mnsc.1070.0828

Cheng, C.-C., Wei, C.-C., Chu, T.-J., & Lin, H.-H. (2022). *AI Predicted Product Portfolio for Profit Maximization*. Applied Artificial Intelligence, 36(1). https://doi.org/10.1080/08839514.2022.2083799

Chillala, M. (2024). *Review Paper - Study on Product Life Cycle of Netflix*. Indian Scientific Journal Of Research In Engineering And Management. https://doi.org/10.55041/ijsrem34037

Cooper, R., Edgett, S., & Kleinschmidt, E. (2004). *New product portfolio manage-ment: Practices and performance*. The Journal of product innovation management, 16(4), 333-351. https://doi.org/10.1016/S0737-6782(99)00005-3 de Alcantara, D. & Martens, M. (2019). *Technology Roadmapping (TRM): A systematic review of the literature focusing on models*. Technological forecasting & social change, 138, 127-138. https://doi.org/10.1016/j.techfore.2018.08.014

de Weck , O. & Hastings D. (2021). *Advanced Space Technology Roadmap Architecture (ASTRA).* Massachusetts Institute of Technology. https://www.nasa.gov/wp-content/uploads/2021/01/esi20_deweck_quadchart.pdf

Dickinson, M., Thornton, A. & Graves, S. (2001). *Technology portfolio management: Optimizing interdependent projects over multiple time periods*. IEEE transactions on engineering management, 48(4), 518-527. https://doi.org/10.1109/17.969428

Diepold, D., Ullrich, C., Wehrmann, A. & Zimmermann, S. (2009). *A real options approach for valuating intertemporal interdependencies within a value-based IT portfolio management - A risk-return perspective*. European Conference on Information Systems, 2036–2047. https://aisel.aisnet.org/cgi/viewcontent.cgi?article=1014&context=ecis2009

Doorasamy, M. (2015). *Product portfolio management: An important business strategy*. Foundations of management, 7(1), 29-36. https://doi.org/10.1515/fman-2015-0023

Doorasamy, M. (2017). *Product portfolio management best practices for new product development: a review of models*. Foundations of management, 9(1), 139. https://doi.org/10.1515/fman-2017-0011

European Commission. (2025a). *EU ETS EU Emissions Trading System*. European Commission. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

European Commission. (2025b). *Decarbonising maritime transport – FuelEU Maritime*. European Commission. https://transport.ec.europa.eu/transport-modes/maritime/decarbonising-maritime-transport-fueleu-maritime_en

Faheem, M., Aslam, M. & Kakolu, S. (2022). *Artificial Intelligence in Investment Portfolio Optimization: A Comparative Study of Machine Learning Algorithms*.

International Journal of Science and Research Archive, 6(1), 335–342. https://doi.org/10.30574/ijsra.2022.6.1.0131

Fowler, K. R., & Silver, C. L. (2015). Developing and managing embedded systems and products: Methods, techniques, tools, processes, and teamwork. Oxford: Newnes. https://doi.org/10.1016/C2011-0-08758-6

Geum, Y., Lee, S., Kang, D. & Park, Y. (2011). *The customisation framework for roadmapping product-service integration*. *Service business, 5*(3), 213-236. https://doi.org/10.1007/s11628-011-0111-0

Gramberg, T., Bauernhansl, T. & Eggert, A. (2024). *Disruptive Factors in Product Portfolio Management: An Exploratory Study in B2B Manufacturing for Sustainable Transition.* Sustainability, 16(11) https://doi.org/10.3390/su16114402

Grobshtein, Y., Perelman, V., Safra, E., & Dori, D. (2007). *Systems Modeling Languages: OPM Versus SysML*. IEEE. https://doi.org/10.1109/ICSEM.2007.373339

Hannila, H., Koskinen, J., Harkonen, J. & Haapasalo, H. (2020). *Product-level profitability: Current challenges and preconditions for data-driven, fact-based product portfolio management.* Journal of enterprise information management, 33(1), 214-237. https://doi.org/10.1108/JEIM-05-2019-0127

Hannila, H., Kuula, S., Harkonen, J. & Haapasalo, H. (2022). *Digitalisation of a company decision-making system: A concept for data-driven and fact-based product portfolio management.* Journal of decision systems, 31(3), 258-279. https://doi.org/10.1080/12460125.2020.1829386

Hara, K., Ok, E. & Riella, G. (2019). *COALITIONAL EXPECTED MULTI-UTILITY THEORY*. Econometrica, 87(3), 933-980. https://doi.org/10.3982/ecta14156

Harahap, F., Nurdiawati, A., Conti, D., Leduc, S. &Urban, F. (2023). *Renewable marine fuel production for decarbonised maritime shipping: Pathways, policy measures and transition dynamics.* Journal of Cleaner Production, Volume 415, 137906, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2023.137906.

Hause, M. C., & Day, R. L. (2019). *Frenemies: OPM and SysML Together in an MBSE Model*. INCOSE International Symposium, 29(1), 691-706. https://doi.org/10.1002/j.2334-5837.2019.00629.x

Herzer, R., Korzenowski, A., Richter, C., De Medeiros, J., Goecks, L., & Mareth, T. (2023). *Multivariate Profile Monitoring Method: An Application in Product Portfolio Management*. Periodica polytechnica. Social and management sciences, 31(1), 52-62. https://doi.org/10.3311/PPso.19992

Hilli, P., Kallio, M., & Kallio, M. (2007). *Real option analysis of a technology portfolio*. Review of financial economics, 16(2), 127-147. https://doi.org/10.1016/j.rfe.2005.07.002

Hirshorn, R., Voss, L. and Bromley, L. (2017). *NASA Systems Engineering Handbook*. NASA. https://ntrs.nasa.gov/citations/20170001761

Hobbs, K., Lyons, J., Feather, M., Bycroft, B., Phillips, S., Simon, M., Harter, M., Costello, K., Gawdiak, Y. & Paine, S. (2023). *Space Trusted Autonomy Readiness levels*. IEEE Aero-space Conference. http://dx.doi.org/10.48550/arXiv.2210.09059

Hunt, R., Killen, C. & Yu, O. (2008). *Application of real options analysis to technology portfolio planning: A case study.* The International journal of quality & reliability management, 25(1), 52-59. https://doi.org/10.1108/02656710810843577

Iyengar, G. N. (2005). *Robust Dynamic Programming*. Mathematics of Operations Research, 30(2), 257–280. http://www.jstor.org/stable/25151652

International Maritime Organization. (2025*). Marine Environment Protection Committee (MEPC): Meeting Summaries and Schedule*. International Maritime Organization. https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/MEPC-default.aspx

Jiao, J. & Zhang, Y. (2005). *Product portfolio identification based on association rule mining.* Computer aided design, *37*(2), 149-172. http://dx.doi.org/10.1016/j.cad.2004.05.006

Killen, C., Hunt, R. & Kleinschmidt, E. (2007). *Managing the New Product Development Project Portfolio: A Review of the Literature and Empirical Evidence.* PICMET '07 -

2007 Portland International Conference on Management of Engineering & Technology, Portland, OR, USA, pp. 1864-1874, https://doi.org/10.1109/PICMET.2007.4349514 .

Kumar, R., Ajjan, H. & Niu, Y. (2008). *Information Technology Portfolio Management: Literature Review, Framework, and Research Issues*. Information resources management journal, 21(3), 64-87. https://doi.org/10.4018/irmj.2008070104

Kumari, S. (2024). *AI-Enhanced Portfolio Management: Leveraging Machine Learning for Optimized Investment Strategies in 2024*. Journal of Informatics Education and Re-search. https://doi.org/10.52783/jier.v4i3.1487

Kwon, Y.-I. & Son, J.-K. (2018). *A Case Study on the Promising Product Selection Indicators for Small and Medium-Sized Enterprises (SMEs).* Journal of Open Innovation: Technology, Market, and Complexity, 4(4), 56. https://doi.org/10.3390/joitmc4040056

Lahtinen, N., Mustonen, E. & Harkonen, J. (2021). *Commercial and Technical Productization for Fact-Based Product Portfolio Management Over Lifecycle*. IEEE transactions on engineering management, 68(6), 1826-1838. https://doi.org/10.1109/TEM.2019.2932974

Lange, M. & Cummins, V. (2021). *Managing stakeholder perception and engagement for marine energy transitions in a decarbonising world*. Renewable & sustainable energy reviews, 152, 111740. https://doi.org/10.1016/j.rser.2021.111740

Li, S., Xing, X. & Du, S. (2017). *A multi-dimensional assessment system for technology readiness levels*. IEEE Xplore. https://ieeexplore.ieee.org/abstract/document/8248394

Liang, B. (2013). *Chapter 5 – Portfolio Management*. The Pragmatic MBA for Scientific and Technical Executives, p. 67-82. https://doi.org/10.1016/B978-0-12-397932-2.00005-3

Litvinchev, I., Arratia, N. & López, F. (2013). *Large scale portfolio selection with synergies.* Journal of computer & systems sciences international, 52(6), 980-985. https://doi.org/10.1134/S1064230713060087

Liu, H., Li, Z., Zhang, R., Liu, Y. & He, Y. (2024). *A Novel Method for Technology Roadmapping: Nanorobots*. Applied sciences, 14(22), 10606. https://doi.org/10.3390/app142210606

Lo Nigro, G., Morreale, A. & Abbate, L. (2016). *An Open Innovation Decision Support System to Select a Biopharmaceutical R&D Portfolio*. Managerial and decision eco-nomics, 37(6), 392-406. https://doi.org/10.1002/mde.2727

Loch, C., & Kavadias, S. (2002). *Dynamic Portfolio Selection of NPD Programs Using Marginal Returns.* Management science, 48(10), 1227-1241. https://doi.org/10.1287/mnsc.48.10.1227.275

Ma, S. (2016). *A nonlinear bi-level programming approach for product portfolio management.* SpringerPlus, 5(1), 727. https://doi.org/10.1186/s40064-016-2421-0

Mawaddah, P., Huang, B.-N. & Chang, C.-H. (2020*). Analysis of the Key Success Factors for Commercializing Innovation.* The Journal for Technology and Science, 31(2), 111–126. https://doi.org/10.12962/J20882033.V31I2.6330

McDowall, W. & Eames, M. (2006). *Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: A review of the hydrogen futures literature.* Energy Policy, vol 34 (11) 1236-1250. https://doi.org/10.1016/j.enpol.2005.12.006

Moscati, I. (2016). *Retrospectives: How Economists Came to Accept Expected Utility Theory: The Case of Samuelson and Savage*. The Journal of economic perspectives, 30(2), 219-236. https://doi.org/10.1257/jep.30.2.219

Mustonen, E., Tolonen, A., Härkönen, J. & Haapasalo, H. (2019). *Constructing a Joint Product Portfolio to Support Commercial Cooperation.* International journal of management, knowledge and learning (Spletna izd.), 8(1), 3-23. https://doaj.org/article/5f41bfd9cdae4512849da3a088f36079

Mustonen, E., Seppänen, J., Tolonen, A., Harkonen, J. & Haapasalo, H. (2020). *Product Portfolio Management Strategic Targets and KPIs over Life-Cycle: A Case Study in Telecommunications Business*. Managing global transitions, 18(1), 5-23. https://doi.org/10.26493/1854-6935.18.5-23

Nakamura, H., Kajikawa, Y., Kajikawa, Y., & Suzuki, S. (2013). *Multi-level perspectives with technology readiness measures for aviation innovation*. Sustainability Science, *8*(1), 87–101. https://doi.org/10.1007/S11625-012-0187-Z

Nege, T., & Werke, S. Z. (2024). *Managing Growth of Product Lifecycle at Maturity Level: A Systematic Literature Review*. European Business & Management, 10(3), 31–43. https://doi.org/10.11648/j.ebm.20241003.11

Nemudrova, I. (2024). *Product management: A multi-faceted approach to successful product development.* International Journal of Science and Research Archive, 13(1), 2051–2053. https://doi.org/10.30574/ijsra.2024.13.1.1842

Niemann, J., & Westkämper, E. (2005). *Product Life Cycle Management in the Digital Age*. Intelligent Knowledge-Based Systems, (pp. 677–707). https://doi.org/10.1007/978-1-4020-7829-3_19

Nilchiani, R., Caddell, J. & Taramsari, H. (2025). *The Extended Technology Readiness Level (eTRL): From Deployment to Obsolescence.* IEEE Open Journal of Systems Engineering, 1–9. https://doi.org/10.1109/ojse.2025.3527288

Olawore, A. & Wong, K. (2023). *Factors that Influence Successful Technology Commercialization*. IEOM Society International https://doi.org/10.46254/ap03.20220022

Oliveira, M. & Rozenfeld, H. (2010*). Integrating technology roadmapping and portfolio management at the front-end of new product development*. Technological forecasting & social change, 77(8), 1339-1354. https://doi.org/10.1016/j.techfore.2010.07.015

Owlia, M., Yazdimoghaddam, J. & Bandarian, R. (2019). *Development of a Model for Assessing Technology Commercialisation Success.* International Journal of Business Innovation and Research, Vol. 19 (3). https://doi.org/10.1504/ijbir.2019.100326

Paletta, M. (2019). *A Modern Approach to Product Portfolio Management for the ICT-Industry*. Cuvillier Verlag. https://books.google.fi/books/about/A_Modern_Approach_to_Product_Portfolio_M.html?id=ofb-DwAAQBAJ&redir_esc=y

Pfenning, P., Eibinger, H., Rohleder, C. & Eigner, M. (2020). *A Comprehensive Maturi-ty Model for Assessing the Product Lifecycle* (pp. 514–526). Springer, Cham. https://doi.org/10.1007/978-3-030-62807-9_41

Phaal, R. & Muller, G. (2009). An architectural framework for roadmapping: Towards visual strategy. *Technological forecasting & social change, 76*(1), 39-49. https://doi.org/10.1016/j.techfore.2008.03.018

Phaal, R., Chaskel, C., Gonzalez Nakazawa, R. & Ross, J. (2024). *Roadmapping Roadmapping: Strategic planning for roadmapping systems.* Frontiers of Engineering Management, 11(3), 516-527. https://doi.org/10.1007/s42524-024-4072-0

Pinna, C., Galati, F., Rossi, M., Saidy, C., Harik, R. & Terzi, S. (2018*). Effect of product lifecycle management on new product development performances: Evidence from the food industry*. Computers in industry, 100, 184-195. https://doi.org/10.1016/j.compind.2018.03.036

Ramsay, W., Fridell, E. & Michan, M. (2023). *Maritime Energy Transition: Future Fuels and Future Emissions*. Journal of marine science and application, 22(4), 681-692. https://doi.org/10.1007/s11804-023-00369-z

Riesener, M., Dölle, C., Schuh, G., Lauf, H. & Jank, M.-H. (2019). *Performance-driven and company goal-orientated design of product portfolios: A methodological framework*. Procedia CIRP, 84, 725–730. https://doi.org/10.1016/j.procir.2019.03.267

Riesener, M., Dölle, C., Dierkes, C. & Jank, M. (2020). *Applying Supervised and Reinforcement Learning to Design Product Portfolios in Accordance with Corporate Goals*. Procedia CIRP, 91, 127-133. https://doi.org/10.1016/j.procir.2020.02.157

Saaksvuori, A. & Immonen, A. (2008). *Product Lifecycle Management*. Springer Berlin Heidelberg. https://ebookcentral-proquest-com.proxy.uwasa.fi/lib/tritonia-ebooks/reader.action?docID=364195&c=UERG&ppg=5

Santos, C., Correia Filho, P., Canciglieri Junior, O. & Schaefer, J. (2025*). The Role of Integrated Information Management Systems in the Relationship Between*

Product Lifecycle Management and Industry 4.0 Technologies and Market Performance. Sustainability, 17(12), 5260. https://doi.org/10.3390/su17125260

Saxena, S. (2024). *Navigating Energy Transition: A Marine Logistics Perspective*. Paper presented at the ADIPEC, Abu Dhabi, UAE, November 2024. https://doi.org/10.2118/222404-MS

Schuh G., Riesener M. & Jank M. (2018a). *Managing Customized and Profitable Product Portfolios Using Advanced Analytics.* Customization 4.0. Springer Proceedings in Business and Economics. https://www.researchgate.net/publication/325874229_Managing_Customized_and_Profitable_Product_Portfolios_Using_Advanced_Analytics

Schuh G., Riesener M., Barg S. & Lauf H. (2018b). *Methodology for the contextual design of a modular product platform concept*. Product, services and systems design, Curran Associates Inc, Red Hook, NY. https://www.designsociety.org/publication/39605/Methodology+for+the+contextual+design+of+a+modular+product+platform+concept

Schmidt, T. & Mantwill, F. (2024). *Management of rule-based product-portfolios with high variance: a systematic literature review.* Proceedings of the Design Society. https://doi.org/10.1017/pds.2024.78

Schweitzer, F., Handrich, M. & Heidenreich, S. (2019). *Digital transformation in the new product development process: the role of IT-enabled PLM systems for relational, structural, and NPD performance.* International Journal of Innovation Management, 23(07), 1950067. https://doi.org/10.1142/S1363919619500671

Shahmarichatghieh, M., Tolonen, A. & Haapasalo, H. (2015). *Product Life Cycle, Technology Life Cycle and Market Life Cycle: Similarities, Differences and Applications*. ToKnowPress. https://ideas.repec.org/h/tkp/mklp15/1143-1151.html

Srivannaboon, S. & Munkongsujarit, S. (2016). *Project management and project portfolio management in open innovation: Literature review*. 2016 Portland International Conference on Management of Engineering and Technology

(PICMET), Honolulu, HI, USA, pp. 2002-2007. https://doi.org/10.1109/PICMET.2016.7806593

Stark, J. (2011). *Product Lifecycle Management: 21st Century Paradigm for Product Realisation* Springer London, Limited. ProQuest Ebook Central, https://doi.org/10.1007/978-0-85729-546-0

Stewart, R. & Mohamed, S. (2002). *IT/IS projects selection using multi‐criteria utility theory.* Logistics Information Management, 15(4), 254‐270. https://doi.org/10.1108/09576050210436101

Surina, A., Kultin, D. & Kultin, N. (2019). *An Expert System as a Tool for Managing Technology Portfolios* (pp. 746–753). Springer, Cham. https://doi.org/10.1007/978-3-030-34983-7_74

Sychrová, L. (2012). *Evaluation of approaches using the product lifecycle*. Economics and Management, 17(4), 1479–1483. https://doi.org/10.5755/J01.EM.17.4.3017

Tolonen, A., Harkonen, J. & Haapasalo, H. (2014). *Product Portfolio Management—Governance for Commercial and Technical Portfolios over Life Cycle.* Technology and Investment, 5, 173-183. https://doi.org/10.4236/ti.2014.54016

Tolonen, A., Shahmarichatghieh, M., Harkonen, J. & Haapasalo, H. (2015). *Product portfolio management – Targets and key performance indicators for product portfolio renewal over life cycle.* International journal of production economics, 170, 468-477. https://doi.org/10.1016/j.ijpe.2015.05.034

Tolonen, A., Harkonen, J., Verkasalo, M., & Haapasalo, H. (2016). *Product portfolio management process over horizontal and vertical portfolios.* International Journal of Product Lifecycle Management. http://jultika.oulu.fi/files/nbnfi-fe2019120946289.pdf

Uddin, A., Hossen Pabel, M., Alam, M., Kamruzzaman, F., Haque, M., Hosen, M., Sajal, A., Miah, M. & Ghosh, S. (2025). *Advancing Financial Risk Prediction and Portfolio Optimization Using Machine Learning Techniques.* The American Journal of Management and Economics Innovations, 07(01), 5–20. https://doi.org/10.37547/tajmei/volume07issue01-02

Udroiu, R. & Bere, P. (2018). *Product Lifecycle Management - Terminology and Applications*. IntechOpen. https://www.intechopen.com/books/7489

Vatananan, R. & Gerdsri, N. (2012). *The current state of technology roadmapping (TRM) research and practice.* International Journal of Innovation and Technology Management, 09(04), 1250032. https://doi.org/10.1142/S0219877012500320

Wali, A. (2010). *Evaluating Probabilities of Technical And Commercial Success And Using Them In Screening New Product Ideas*. Engineering and Technology Journal, 28(23), 6676–6687. http://www.iasj.net/iasj?func=fulltext&aId=41711

Wang, J. & Hwang, W. (2007). *A fuzzy set approach for R and D portfolio selec-tion using a real options valuation model*. Omega (Oxford), 35(3), 247. https://doi.org/10.1016/j.omega.2005.06.002

Whittington, R., Regnér, P., Angwin, D., Johnson, G. & Scholes, K. (2023). *Exploring Strategy, Text & Cases (13th ed.).* Pearson International Content. https://bookshelf.vitalsource.com/books/9781292428833

Wicht, A. & Szajnfarber, Z. (2014). *Portfolios of promise: A review of R&D in-vestment techniques and how they apply to technology development in space agencies*. Space policy, 30(2), 62-74. https://doi.org/10.1016/j.spacepol.2014.03.003

Wirthlin, M., Seering, W. & Rebentisch, E. (2008). *Understanding Enterprise Risk Across an Acquisition Portfolio: A Grounded Theory Approach*. MIT. https://dspace.mit.edu/handle/1721.1/84132

Wu, C. & Buyya, R. (2015). *Cloud Data Centers and Cost Modeling: A Complete Guide to Planning, Designing and Building a Cloud Data Center*. Morgan Kaufmann. https://www.sciencedirect.com/science/article/abs/pii/B9780128014134000180

Wu, L. & Ong, C. (2008). *Management of information technology investment: A framework based on a Real Options and Mean–Variance theory perspective*. Technovation, 28(3), 122-134. https://doi.org/10.1016/j.technovation.2007.05.011

Xin, Y. & Ojanen, V. (2017). *The impact of digitalization on product lifecycle management: How to deal with it?* Industrial Engineering and Engineering Management. https://doi.org/10.1109/IEEM.2017.8290062

Yin, N. (2016) *Application of AHP-Ansoff Matrix Analysis in Business Diversification: The case of Evergrande Group*. Les Ulis: EDP Sciences. https://doi.org/10.1051/matecconf/20164401006

Yu, O. (2005). *Technology Portfolio Planning and Management: Practical Concepts and Tools.* Springer Science & Business Media. https://books.google.fi/books?id=YqucjaAXYNoC&dq=technology+portfolio+management&lr=&hl=fi&source=gbs_navlinks_s

Zaccone, R., Ottaviani, E., Figari, M. & Altosole, M. (2018). *Ship voyage optimization for safe and energy-efficient navigation: A dynamic programming approach*. Ocean engineering, 153, 215-224. https://doi.org/10.1016/j.oceaneng.2018.01.100

Zhang, Y., Guo, Y., Wang, X., Zhu, D. & Porter, A. L. (2013). *A hybrid visualisation model for technology roadmapping: Bibliometrics, qualitative methodology and empirical study.* Technology analysis & strategic management, 25(6), 707-724. https://doi.org/10.1080/09537325.2013.803064

Appendices

Appendix 1. Focus group inputs per discussion topic

<u>Focus group 1: Product management</u>

What are the key needs for technology product portfolio management system?
- *Visualizations to support decision-making and prioritization*
- *Complete and simple overview of the products*
- *Ability to drill down to product-level*
- *Integration between product engineering systems*
- *Decision log integration with product roadmaps*
- *Linkage to business case analyses*
- *Risk management inclusion*
- *Overview of key component supplier strategies per product*

What are the key requirements for technology product portfolio management system?
- *Overview and roadmap of the portfolio*
- *Statuses at product-level in KPIs such as sales, order intake, margin, product cost, quality cost, readiness levels, auxiliary sales, etc.*
- *Possibility of extracting data*
- *Overview of key actions and development per product*

What could a suitable concept of integrated technology product portfolio management system look like?
- *No comments*

<u>Focus group 2: Portfolio management</u>

What are the key needs for technology product portfolio management system?
- *Common platform for people and products*
- *Scalability*
- *Ability to identify market development and match the offering and product technologies with it*
- *Timeline of 10+ years required for large project industries*
- *Whole offering as business case portfolio including capital, service and auxiliary*
- *Ability to include the total business case value*

What are the key requirements for technology product portfolio management system?
- *Tailoring for specific company needs*
- *Dynamic data tracking*
- *Installed base connection*

- *Data reliability, availability and quality need to be high*
- *Easy to maintain the system*
- *Ability to manage simultaneous technology and NPD projects*

What could a suitable concept of integrated technology product portfolio management system look like?

- *Databricks as data storage method in data warehouse*

Focus group 3: Strategy management

What are the key needs for technology product portfolio management system?

- *Ability to match product portfolio with identified market development*
- *More forward-looking information than backward information*
- *Track competitive land-scape*
- *Regulation to be included, on product level and not just on general, and its impact on products*
- *System to be able to show status of products: ROI, generated services, auxiliary sales, capitalization cost, ability to see what the weight of a product is in different views (quality costs etc.)*
- *Communication with generative AI, not just dashboard, ability to configure the dashboard based on prompt*

What are the key requirements for technology product portfolio management system?

- *Drilling down to product level from general level*
- *Interactivity / exporting*
- *Limits in simulations for scenario analysis*
- *Forward-looking data: weak signals and trend recognition of markets*

What could a suitable concept of integrated technology product portfolio management system look like?

- *Additional data sources for the needs of external information*
- *Data quality assurance and synchronization*
- *Feedback loop from UI to AE for ML development*
- *Developer UI to train ML and validate its performance*

Appendix 2. Conceptual architecture of integrated technology product portfolio management system