wbk Institut für Produktionstechnik

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Karlsruher Institut für Technologie (KIT)

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Development of a Digital Twin for Product Allocation and Robust Line Configuration

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Vorwort des Herausgebers

Die schnelle und effiziente Umsetzung innovativer, nachhaltiger und wirtschaftlicher Technologien stellt den entscheidenden Wirtschaftsfaktor für produzierende Unternehmen dar. Universitäten können als "Wertschöpfungspartner" einen wesentlichen Beitrag zur Wettbewerbsfähigkeit der Industrie leisten, indem sie wissenschaftliche Grundlagen sowie neue Methoden und Technologien erarbeiten und aktiv den Umsetzungsprozess in die praktische Anwendung unterstützen.

Vor diesem Hintergrund wird im Rahmen dieser Schriftenreihe über aktuelle Forschungsergebnisse des Instituts für Produktionstechnik (wbk) am Karlsruher Institut für Technologie (KIT) berichtet. Unsere Forschungsarbeiten beschäftigen sich mit der Leistungssteigerung von additiven und subtraktiven Fertigungsverfahren, den Produktionsanlagen und der Prozessautomatisierung sowie mit der ganzheitlichen Betrachtung und Optimierung von Produktionssystemen und -netzwerken. Hierbei werden jeweils technologische wie auch organisatorische Aspekte betrachtet.

Prof. Dr.-Ing. Jürgen Fleischer

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Preface of the author

I am deeply grateful to everyone who supported me while writing this thesis during my time as a research associate at the wbk Institute of Production Science. I want to extend my sincere appreciation to my supervisor, Prof. Dr.-Ing. Gisela Lanza, for her invaluable guidance and assistance, which played a crucial role in the successful completion of this thesis. I am also indebted to Prof. Aydin Nassehi for hosting me, engaging in fruitful discussions, and posing insightful questions that greatly enhanced the quality of my work.

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Oliver Brützel

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Abstract

The accelerated pace of product life cycles and heightened competition in products like microprocessors, semiconductors, and automobiles necessitate cost-effective strategies. To address this, companies globally distribute production sites, creating challenges in aligning product allocation with long-term network planning decisions. Increasingly, model-based decision support systems (DSS) are adopted to enhance planning reliability amid complexity. The inherent uncertainty of demand further complicates global production network (GPN) configurations. Motivated by the author's practical experience at Bosch, this thesis explores GPN planning complexities, focusing on model-based DSS to improve collaboration and responsiveness in adapting to the dynamic industry landscape.

This thesis introduces an innovative approach to address critical gaps in industrial GPNs. By incorporating and quantifying outcomes through multiple demand scenarios, the thesis focuses on flexibility within the network model, particularly volume and product mix flexibility in production systems.

The thesis also addresses the challenge of determining representative scenarios in stochastic models, proposing a methodology to enhance solution robustness and revealing shifts in the cost structure.

Practical adoption challenges in implementing Decision Support Systems (DSS) in GPNs are explored, including design considerations, user experiences, training, data governance, and organisational change management.

The thesis also navigates the integration of data from diverse sources to construct effective digital twins for GPNs, enhancing data collection methods and providing advantages such as time reduction, performance scalability, and improved reliability.

The implemented components have proven effective in addressing real-world industrial needs, exemplified by their successful application at Robert Bosch GmbH. The outcome resulted in a DSS successfully deployed for various GPNs. The approach is highly adaptable, and application to further GPNs at Bosch is planned.

Kurzzusammenfassung

Beschleunigte Produktlebenszyklen und ein verschärfter Wettbewerb bei Produkten wie Mikroprozessoren, Halbleitern und Automobilen machen kosteneffiziente Strategien erforderlich. Um dem entgegenzuwirken, verteilen die Unternehmen ihre Produktionsstätten global, was die Koordinierung der Auftragsallokation mit Entscheidungen über die mittel- bis langfristige Netzwerkplanung zu einer Herausforderung macht. Um die Planungssicherheit in diesem komplexen Umfeld zu erhöhen, werden zunehmend modellbasierte Entscheidungsunterstützungssysteme (DSS) eingesetzt. Die inhärente Unsicherheit der Nachfrage erschwert die Konfiguration globaler Produktionsnetzwerke (GPN) zusätzlich. Motiviert durch die praktischen Erfahrungen des Autors bei Bosch, untersucht diese Thesis die Komplexität der GPN-Planung und konzentriert sich dabei auf modellbasierte DSS, um die Zusammenarbeit und Reaktionsfähigkeit bei der Anpassung an die dynamische Industrielandschaft zu verbessern.

Diese Thesis präsentiert einen innovativen Ansatz, um kritische Lücken in komplexen GPNs zu schließen. Durch die Einbeziehung und Quantifizierung der Ergebnisse durch mehrere Nachfrageszenarien und durch die Berücksichtigung der Flexibilität des Volumens und des Produktmixes soll es möglich sein, auf unerwartete Ereignisse in der Zukunft schnell zu reagieren. Die Thesis befasst sich dazu mit der Herausforderung, repräsentative Szenarien in stochastischen Modellen zu bestimmen, und schlägt eine Methodik zur Verbesserung der Robustheit der Lösung und zur Erkennung von Verschiebungen in der Kostenstruktur vor.

Praktische Herausforderungen bei der Implementierung von DSS in GPNs werden untersucht, einschließlich Überlegungen zu Design, Benutzererfahrung, Schulung, Datenmanagement und organisatorischem Änderungsmanagement.

Die Thesis befasst sich schließlich mit der Integration von Daten aus verschiedenen Quellen, um effektive digitale Zwillinge für GPNs zu entwickeln, die die Methoden der Datenerfassung verbessern und Vorteile wie Zeitersparnis, Skalierbarkeit und verbesserte Zuverlässigkeit bieten.

Die implementierten Komponenten haben sich in der industriellen Praxis bewährt, wie der erfolgreiche Einsatz bei der Robert Bosch GmbH zeigt. Das Ergebnis ist ein DSS, dass in verschiedenen GPNs erfolgreich eingesetzt wird. Der Ansatz ist in hohem Maße anpassbar und es ist geplant, ihn auf weitere GPNs bei Bosch anzuwenden.

Table of Contents

Abbreviations and Symbols

Abbreviation	Description
AI	Artificial Intelligence
APVA	Automated Plant Volume Allocation
CIMM	Core Information Model for Manufacturing
CMM	Capability Maturity Model
CMMI	Capability Maturity Model Integration
CMSD	Core Manufacturing Simulation Data
CPLS	Cyber-Physical Logistics System
CPS	Cyber-Physical Systems
CT	Cycle Time
DAX	Data Analysis Expressions
DBMS	Database Management Subsystem
DPMN	Design and Planning of Manufacturing Networks
DSS	Decision Support System
DT	Digital Twins
ERP	Enterprise Resource Planning
EIM	Enterprise Information Management
FTA	Free Trade Agreement
GIS	Geographical Information Systems
GPN	Global Production Networks
HC	High-Cost Site
ISO	International Organization of Standardization
KBMS	Knowledge Base Management Subsystem
KIT	Karlsruhe Institute of Technology
KPI	Key Performance Indicator
LC	Low-Cost Site
LHS	Latin Hypercube Sampling

LP	Linear Programming
MES	Manufacturing Execution Systems
MDM3	Master Data Management Maturity Model
MILP	Mixed Integer Linear Programming
MSP	Market and Sales Planning
MTO	Make-to-Order
NCU	Network Coordination Unit
NoSQL	Not only SQL
OEE	Overall Equipment Effectiveness
OR	Operations Research
OTD-NET	Order-To-Delivery-NETwork Simulator
P/N	Part Number
PCA	Principal Component Analysis
PVA	Plant Volume Allocation
SAA	Sample Average Approximation
SC	Supply Chain
SCND	Supply Chain Network Design
SMT	Satisfiability Modulo Theories
SQL	Structured Query Language
TCO	Total Cost of Ownership
TEK	Technical Capacity
T-ID	Order ID
WCSS	Within-Cluster Sum of Squares

Set	Index	Description	Unit
C	c	Set of change drivers	
F	f	Set of possible line features	
K	k	Set of clusters	
L	l	Set of production lines (existing & new)	
O	o	Set of orders	
$\tilde{O}$	$\tilde{o}$	Set of sister orders	
S	s	Set of manufacturing sites	
$\tilde{S}$	$\tilde{s}$	Set of preprocessing sites	
T	t	Set of time periods	Half Year
V	v	Set of preprocesses	
Ψ	ψ	Set of feature vectors	
Φ^{e}	t	Set of time periods in which purchasing of lines is deemed non-recourse	
$\Phi^{u^{receiving}}$	t	Set of time periods in which purchasing of features is deemed non-recourse	
$\Phi^{y^{line}}$	-	Indicates whether line releases are deemed non-recourse	
$\Phi^{y^{facility}}$	-	Indicates whether site releases are deemed non-recourse	
Φ^{z}	t	Set of time periods in which the activation of lines is deemed non-recourse	
Γ	γ	Set of triads	
Ω	ω	Set of representative demand scenarios	
$\overline{\Omega}$	ω	Set of all demand scenarios	

Parameter	Description	Unit
$\chi_{o,v}$	Indicates the amount of pre-processing products required to produce a specific order.	Units
$\eta_{o,t,\omega}$	Indicates the order size.	Units
$\iota_{o,f}$	Indicates if a technical feature is required for an order.	
μ	Enables the decision maker to decide if sister orders are to be respected when considering release purchases.	
τ	Number of periods required to build a new line.	Half-Year
$\theta_{l,t}^{existing}$	Overall equipment effectiveness for existing lines. It is used to adjust the capacities by operational efficiency and includes local shift breaks and maintenance requirements.	
$\theta_{l,t}^{new}$	Overall equipment effectiveness for new lines. New lines initially have efficiency drawbacks after construction.	
$\varphi_{l,f}$	Indicates whether a line can be upgraded by a feature.	
$\psi_{o,l,t}$	Indicates the periodical relative decrease of cycle time.	
$\varsigma_{o,\gamma}$	Indicates the triad where the customer of an order is located.	
$\kappa_{s,\gamma}$	Indicates if a site is in a triad.	
$\zeta_{o,l,t}$	Indicates the cycle time for producing one unit of an order.	Sec
$\varrho_{o,l,t}$	Adjusts the nominal cycle time $\zeta_{o,l,t}$ by the learning effect $\psi_{o,l,t}$.	Sec
$a_{o,l}^{line}$	Indicates if an order is initially assigned to a line.	
$a_{o,s}^{facility}$	Indicates if an order is initially assigned to a site.	
$b_{l,s}$	Indicates if a line belongs to a site.	
c^{build}	Basic Costs for building a new line.	€
$c_{l,f}^{feature,existing}$	Costs for upgrading an existing line with a feature.	€
$c_{l}^{feature,new}$	Costs for a feature during construction of a new line.	€
c_{l}^{fixed}	Fixed costs of a line.	€
$c_{v,s,\tilde{s}}^{inbound}$	Inbound logistics costs per unit.	€
$c_{o,l,t,\omega}^{outbound}$	Outbound logistics costs per unit per scenario.	€
$c_{l}^{overutilization}$	Costs for overutilisation of a line. These costs are incurred once the standard capacity of a line is exceeded.	€
$c_{o,l}^{releaseline}$	Costs for purchasing a customer release for a line.	€
$c_{o,s}^{releasefacility}$	Costs for purchasing a customer release for a site.	€

$c_l^{underutilization}$	Costs for underutilisation of a line. These costs are incurred once a line's standard capacity is not reached.	€
$c_l^{variable}$	Variable costs for lines.	€
$c_o^{flexible}$	Costs for purchasing an order to be flexible	€
$d_{l,f}$	Indicates if a feature is initially available at a line.	
$f_s^{mininbound}$	Minimum required inbound flexibility at a site	
$f_s^{minoutbound}$	Minimum required outbound flexibility at a site	
i_l^{hc}	Parameter for the periodic cost increase of headcount	
i_l^{invest}	Parameter for the periodic percentage cost increase of investments (internal interest rate) per line	
$k_{l,t}^{maximum,exisit}$	Maximum capacity of an existing line.	Sec
$k_{l,t}^{standard,existin}$	Standard capacity of an existing line.	Sec
$k_{l,t}^{maximum,new}$	Maximum capacity of a new line.	Sec
$k_{l,t}^{standard,new}$	Standard capacity of a new line.	Sec
$k_{v,\tilde{s},t}^{preprocess}$	Capacity of the site for pre-processing products.	Units
M	Large number used to influence the sing of a term	
$m_{o,s,t}$	Indicates whether an order should be fixated to a site during certain periods.	
$p_\omega^{ScenarioAd}$	The adjusted probability weight of a scenario	
$r_{o,l}^{line}$	Indicates whether a customer release is available for a line.	
$r_{o,s}^{facility}$	Indicates whether a customer release is available for a site.	
$w_{s,t}^{facility}$	Indicates the requirement for a minimum share of total production volume at a site.	
$w_{\gamma,t}^{triad}$	Indicates the requirement for a minimum share of total production volume in a triad.	
$x_{o,s,t}$	Defines a minimum volume share of production per order to be fixed to a site.	

Continuous Variables	Description	Unit
$\delta_{l,t,\omega}^{overutilization}$	Degree to which utilised capacity exceeds available capacity.	Sec
$\delta_{l,t,\omega}^{underutilization}$	Degree to which available capacity exceeds utilised capacity.	Sec
$v_{o,l,t,\omega}$	Production duration of the allocated volume of an order.	Sec
$q_{o,l,t,\omega}$	Indicates the allocation of producing an order on a line.	Units
$q_{o,s_1,s_2,t,\omega}^{flex}$	Indicates the flexible volume of producing an order on a line at a site s_1, which would also be producible at s_2.	Units
$\rho_{v,\tilde{s},s,t,\omega}$	Amount of pre-processing units of orders v that are transported from $\tilde{s}$ to s.	Units
$f_{s,t,\omega}^{in}$	Inbound flexibility of a site in a period	Units
$f_{s,t,\omega}^{out}$	Outbound flexibility of a site in a period	Units

Binary Variables	Description	Unit
$e_{l,t,\omega}$	Indicates if a new line is opened in a certain period.	
$u_{l,f,t,\omega}^{existing}$	Indicates that a line possesses a certain feature.	
$u_{l,f,t,\omega}^{receiving}$	Indicates that a line receives a certain feature upgrade in a single period.	
$y_{o,l,\omega}^{line}$	Indicates if a customer release purchase is available for a line.	
$y_{o,s,\omega}^{facility}$	Indicates if a customer release purchase is available for a site.	
$y_{o,\omega}^{flex}$	Indicates if an order is flexible or not	
$z_{l,t,\omega}$	Indicates if a line is active.	

Additional Scenario Symbols	Description	Unit
C_k	Cluster centroid of a cluster	
$p_{\omega}^{Scenario}$	The occurrence probability of a scenario	
p_c^{Change}	The occurrence probability of a change driver.	
I_c	The percentage by which demand is increased or decreased, should the change driver occur.	
$J_{\omega,k}$	Indicates if the feature vector of a scenario belongs to the cluster	
T_c^{Low}	Lower bound of the affected period range.	Half Year
T_c^{Up}	Upper bound of the affected period range.	Half Year
W	The sum of Euclidean Distances	
$X_{\omega,c}$	Stochastic parameter within [0,1]	
$Y_{\omega,c}$	Stochastic parameter within $[T_c^{Low}, T_c^{Up}]$	Half Year
$Z_{\omega,c}$	Stochastic parameter within $[Y_{\omega,c}, T_c^{Up}]$	Half Year
λ	Risk Aversion Parameter	

1 Introduction

1.1 Motivation

Product life cycles in several industries, such as semiconductors, consumer electronics, and automobiles, have become shorter in recent years (Becker, Stolletz & Stäblein 2017, p. 59). This has resulted in increased product variety and a higher number of production ramp-ups. Combined with increasing competition from new competitors in developing markets, this resulted in a need for companies to reduce production costs by distributing production sites and allocating production activities on a global stage.

However, shortened product lifecycles and a constantly changing range of product variants contrast with network planning decisions' long-term and irreversible nature (Mourtzis 2016, pp. 16–17). Thus, product-mix-allocation, which means allocating products to production network entities while adapting global structures and deciding about their capabilities for production, is a complex task. To address this complexity, companies increasingly use model-based decision support systems (DSS) for planning tasks of global production networks (GPNs) to increase planning reliability in medium- and long-term planning (Lanza et al. 2019, p. 809).

In many markets, demand is highly volatile and considered nondeterministic. Accordingly, optimal supply chain and production configurations change for different demand realisations (Govindan & Fattahi 2017, pp. 688–689). Global developments in recent years have increased demand uncertainty (Matthews et al. 2022, p. 368). Companies need approaches quantifying uncertainty in representative demand scenarios and supporting to not only find reasonable solutions for one demand scenario but also to find robust decisions on configuration planning for various scenarios.

Lastly, the motivation for this thesis is based on insights the author gained by participating in GPN planning within the automotive industry at Robert Bosch GmbH, further called Bosch. These perspectives include logistics, global production, sales, and local site perspectives. By considering different perspectives and their impact on the GPN, companies can make more informed decisions and achieve better overall performance.

This thesis addresses the complexities in the production planning and control process and the increasing use of DSS. It sheds light on how DSS can improve collaboration between the mentioned perspectives, streamline the product-mix-allocation process, and enhance the robustness of its results to meet the evolving industry landscape.

1.2 Problem Statement

This thesis tackles the challenge of optimising product mix allocation and predicting essential capabilities for production lines at multiple sites. Despite its complexity, this task is currently predominantly executed in a highly heuristic manner. The issue is worsened by inadequate consideration of uncertainties.

For instance, when dealing with various line types, i.e., “Racing”, “Old”, and “Exotic”, and allocating future orders, e.g., a truck variant of a combustion product, with specific volumes, production start dates, and delivery locations, it often can be observed that lines lack either capacity or necessary capabilities. This highlights a need for line upgrades to meet production demands (see Figure 1-1).

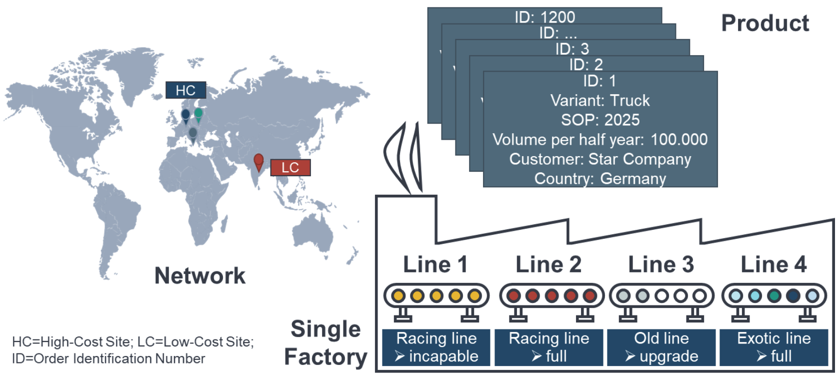


Figure 1-1: Problem statement including different orders to be allocated on a specific line at the factory and network (GPN-)level

The challenge of cost-optimal allocation and line configurations further increases when considering diverse lines across different sites in the GPN. Logistics costs and wage variations further contribute to the complexity.

The volatility of the global environment requires repeating the process of product-mix-allocation in shorter cycles and taking various potential future developments into account to ensure optimal investments, i.e., network configuration and the underlying order allocation in the planning. This, together with more modular hardware in ever greater GPNs, increases the solution space and leads to an overall lengthening of the necessary planning processes, which stands in contrast with shorter planning cycles. Furthermore, this problem is not isolated; it is transferable across industries.

In addition, Figure 1-2 shows that the combination of different perspectives on the planning process and the dynamic nature of the automotive industry leads to several further challenges and issues regarding the planning process itself, including:

- Intransparency: The complexity of coordinating activities across different perspectives can lead to a lack of clarity and visibility into the overall GPN.
- Local Optimisation: Each perspective may prioritise its own local objectives, leading to suboptimal decisions for the overall network.
- High Coordination Effort: Aligning different perspectives requires significant coordination efforts, which can be time-consuming and resource-intensive.
- Slow Reactions: Long planning and decision-making cycles can delay responses to market changes and customer demands.
- Non-standardised databases: The prevalent lack of standardised data across the network introduces further complexity. This forces the utilisation of data at varying levels of abstraction.

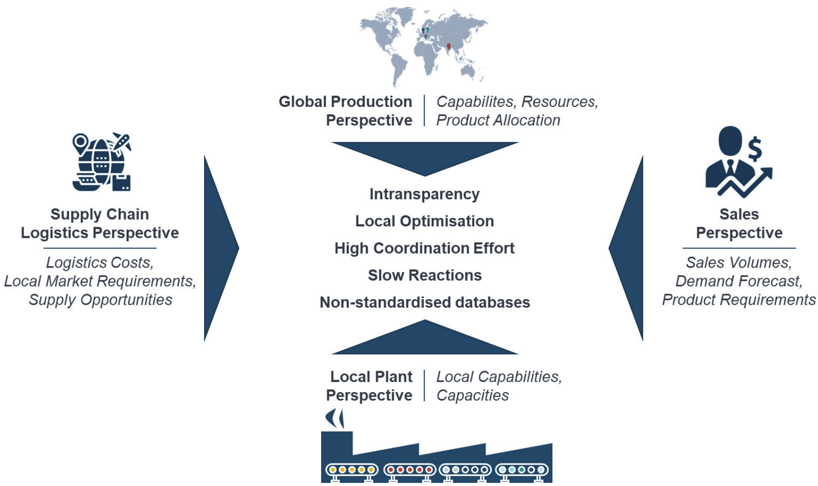


Figure 1-2: Perspectives on the planning process

In summary, this thesis addresses the still manual and uncertain nature of product-mix-allocation and evaluates an investment in production line capabilities across various sites. The challenge is complicated by diverse line types, site complexities, and the need for rapid adjustments to changing market conditions. Additionally, the process itself, including the different perspectives, needs to be supported and accelerated.

1.3 Research Objectives

This thesis aims to improve solution finding and support the process of product-mix-allocation by formulating an optimisation model for GPN planning that seamlessly integrates multifaceted aspects of network configurations, robustness, and data collection. While serving as a potent aid to the planning process, this model shall possess the versatility to operate efficiently across varying data quality (levels) or degrees of abstraction. The goal encompasses the pivotal research objectives shown in Figure 1-3:

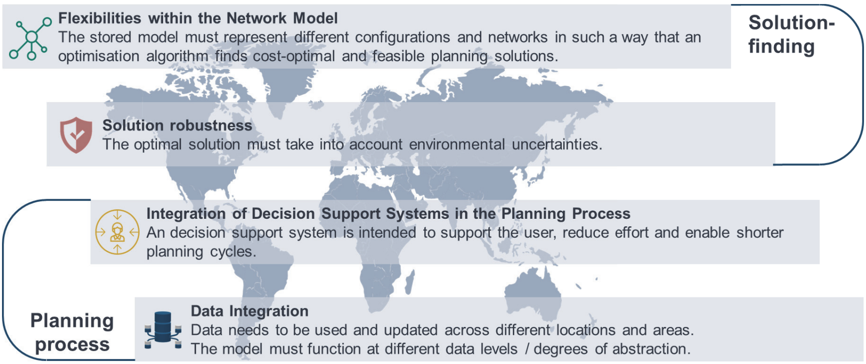


Figure 1-3: Research objectives

This developed model will be empirically applied within GPN planning, focusing on mitigating the challenges confronting production companies amidst a progressively unpredictable environment. This holistic approach seeks to enable more agile and efficient GPNs, paving the way for heightened adaptability and operational excellence.

1.4 Research Structure

The remainder of this thesis is structured as follows. Research objectives comprise developing a network model, solution robustness, implementation in the planning process, and data integration. These objectives will serve as a structure for this thesis in dealing with fundamentals (Chapter 2), as well as in literature analysis and assessment of former research contributions (Chapter 3), and own research (Chapters 4 and 5).

In Chapter 2, core principles of production planning within global production networks (GPNs) are outlined. This includes tasks of network planning, product allocation, operations research, environmental considerations, change drivers, uncertainty handling, scenario analysis, robustness, assistant systems, and data management.

Chapter 3 provides a comprehensive overview of the current state of the art regarding production planning in GPNs. It dissects topics such as flexibility modelling, stochastic scenario construction, robust decision-making, their strategic implementation in planning, and stressing the challenges of data integration. Identified research gaps serve to define research questions driving the subsequent direction and purpose of the research.

Chapter 4 outlines an approach to network configuration and solution robustness (research objectives 1 and 2). It presents a comprehensive framework for decision support systems (DSS) to identify robust decisions in GPN, detailing model design, parameters, variables, objective function, constraints, scenario forecasting, change driver identification, simulation, and decision identification.

Chapter 5 focuses on the implementation in the planning process and data integration (research objectives 3 and 4). It comprises a practical application of the presented framework', data pipeline establishment, database identification, and automated data acquisition.

The outcomes are quantified within a GPN context in Chapter 6, evaluating demand scenario forecasting, robust decision application, flexibility restrictions, and the maturity of implementation. Furthermore, successful operative applications are presented, demonstrating the quality of the research and model development. This results in a maturity model serving for the validation of the stage of implementation (research objective 3).

Chapter 7 reflects the research outcome in a comprehensive discussion, synthesising findings and implications in the context of GPN. The thesis concludes by summarising insights and suggesting future research directions within the domain of production planning in global networks.

Chapter 8 offers a condensed summary of the research paper, incorporating pivotal facts.

2 Fundamentals

In order to comprehend an understanding of the thesis, definitions of some terms and contexts are indispensable. The following section tries to tackle fundamentals regarding the four research objectives, each by each. To be able to design a model representing different configurations and networks, the tasks of production planning in global production networks (GPNs) itself have to be introduced to understand the model's limitations and boundaries and how it generally can be formalised in operation research (OR) models. To identify robust solutions, environmental conditions have to be understood, including the concept of change driver, scenario analysis and its consideration in planning leading to robustness. For the third research objective about the support of the user decision support systems (DSS) get introduced. At last, different commonly used databases in production and their integration within digital twins are explained to target the last research objective.

2.1 Production Planning in Global Production Networks

Production networks may be defined in diverse ways. Definitions have in common that a network is seen as a set of nodes connected by edges (Shi & Gregory 1998, p. 199; Rudberg & Olhager 2003, p. 30; Coe, Dicken & Hess 2008, p. 274). Suppose products or services are created and forwarded to being completed in a network and, for this, distributed between nodes connected by edges. In that case, the network is called a production network (Coe, Dicken & Hess 2008, p. 274).

This thesis follows the definition of Rudberg and Olhager as well as Shi and Gregory, which understands a production network consisting of a network of sites that are connected (Shi & Gregory 1998, p. 199; Rudberg & Olhager 2003, p. 30).

In addition to the description of structural characteristics of a production network, interaction and relationship between the sites involved in the network are other relevant descriptive features. This classification of characteristics leads to two respective views in the literature: the production perspective and the logistics perspective. In the literature, the site is usually examined at a more detailed level, so the focus of the production perspective is on the (production) nodes, i.e., sites in a network. The logistics perspective, on the other hand, focuses on the edges or connections of the network. These represent the material and information flows, especially between different participating companies (Rudberg & Olhager 2003, pp. 29–31).

The smallest element of a network, according to the definition of Rudberg and Olhager, is the site (Rudberg & Olhager 2003, pp. 35–36) (see Figure 2-1). Several sites of a company form an intra-company production network. If several companies with a single site are involved in a network, the network is called a supply chain. If several sites of several companies form a network, this is an inter-company production network (Rudberg & Olhager 2003, p. 36).

Figure 2-1: Classification of production networks based on Rudberg & Olhager (2003, p. 35)

In this thesis, the focus lies on intra-company networks, but also containing costs for their sourcing and their customer. Therefore, Lanza et al. (2019) introduce the term Global Production Network (GPN). A GPN is further defined by its "geographically dispersed production entities, which are interlinked by material, information and financial flows" (Lanza et al. 2019, p. 824). GPNs are man-made structures in which all participating entities carry out direct value-adding activities in accordance with a common corporate strategy. The overall structure of the network and the relationships within it are relatively stable. The main objective is to serve markets and customers efficiently (Lanza et al. 2019, p. 824). Figure 2-2 shows a generic structure and elements (kinds of nodes) of GPNs. The arrows indicate the flow of material, implying information needs to be exchanged bidirectionally between any connected nodes.

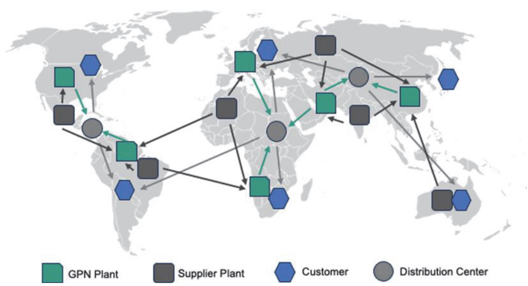


Figure 2-2: Structure of GPNs (own representation, cf. (Lanza et al. 2019, p. 825)

Despite underlying a shared strategy, all nodes in a GPN vary in their degree of autonomy and competitive dynamics. Individual business interests and access to resources and information within the network can be disparate (Váncza et al. 2011, p. 798). These characteristics distinguish GPNs from supply chains, which focus on the sequential delivery of specific products and services to internal and external customers, involving activities from procurement to recycling. Supply chain management emphasises inter-organisational planning and control of material, information, and financial flow across the value-added chain (Wiendahl & Lutz 2002, p. 6). In contrast, strategy-driven GPNs involve three main tasks defined by Lanza et al. (2019, p. 825): „ (1) the formation of the production strategy, (2) the design of the network footprint, (3) and the management of the production network “.

2.1.1 Tasks in Production Networks

The understanding and discussion of the design and operation of GPNs in this thesis follow the structure outlined in a paper by Lanza et al. (2019). Based on a comprehensive investigation of the current state of research, a framework for the management of GPNs is shown in Figure 2-3. The figure integrates influencing factors, challenges, enablers, core tasks, and decision support systems (DSS) in a holistic view (Lanza et al. 2019, p. 828).

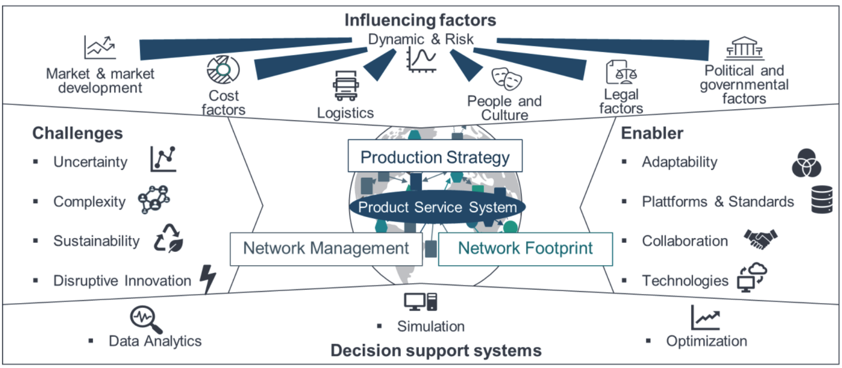


Figure 2-3: Design of GPN based on Lanza et al. (2019, p. 828)

Influencing factors are split into actual market and market development, cost factors, logistical aspects, people, and culture, as well as legal and political factors. In particular, location-dependent cost factors are important in practice (Lanza et al. 2019, p. 828).

The term enabler describes the concept that certain circumstances facilitate the core tasks of network management. In the framework, the enablers are adaptability, standardisation and platforms, collaboration, and innovative technologies. They represent the counterpart of the challenges. These include sustainability, the importance of which has increased significantly in the past, and disruptive innovations that can significantly change the environment of the production system. Complexity, which increases with the number of objects in a network and their connections, is also a challenge. Central in the context of GPN, however, is the factor of uncertainty as a challenge. Uncertainty of demand should be mentioned here. Importance is attached to this, as demand is the motivation for all production (Lanza et al. 2019, pp. 828-829, 831). The particular importance of demand uncertainty is also taken up by Váncza et al. (2011, p. 805).

Regarding DSS, it can be observed that optimisation is used as a method for decisions on the design and operation of GPNs. However, as the complexity of real-world problems often does not allow for deterministic formal modelling, simulation, various data analysis techniques, heuristic, and qualitative approaches are used in practice (Lanza et al. 2019, p. 834). This thesis focuses on optimisation, as later explained.

The significant tasks within GPNs are the definition of the *Production Strategy*, the design of the *Network Footprint* and the *Network Management*.

The production strategy includes long-term decisions regarding market segments, products, and services, as well as sustainability aspects. From the decisions made at this point, the first implications may arise for network design. After implementation, the achievement of a chosen strategy can be checked by the application of a suitable performance measurement system (Lanza et al. 2019, pp. 830–831).

The primary tasks of the network footprint design are medium-term, containing site decisions, resource allocation, product-mix-allocation, and site capabilities. Resource allocation includes planning, dimensioning, and positioning of production resources or certain input factors of production in the network. Analogously, product-mix-allocation concerns decisions on the location of production (Lanza et al. 2019, p. 832). A common approach to describe site capabilities has been provided by Ferdows (1997, p. 77), suggesting a typology of site capabilities based on two dimensions. The first dimension refers to the scope of activities that can be carried out by a site ("site competencies"), and the second dimension refers to the strategic reason for a site's choice of location. This model has been tested by Vereecke & van Dierdonck (2002). Thomas et al. (2015)

suggested a model comprising more descriptive possibilities. The role of the site will not be discussed in detail here; for an approach often cited in the literature, please refer to Ferdows (1997).

The management of production in the network comprises several tasks. In addition to defining the role of the site, demand must be planned, and the supply of sites providing the necessary elementary production factors must be ensured. Furthermore, the execution and distribution of orders must be planned. In particular, this requires the allocation of orders to sites. In the event of uncertainty regarding demand, demand scenarios may be used as a base for allocation (Buergin et al. 2018, pp. 749–750).

Planning for decisions in a large and diversified company, it is hardly sensible and often not even possible to consider the organisation as a whole as it would result in too high a degree of complexity and a too broad scope of information. One way to deal with this is to break down decision problems into manageable units. Subsequently, the resulting decision problems with a lower degree of complexity can be solved and synthesised into an overall solution (Scholl 2001, pp. 20–21).

Hierarchical planning is a concept that allows for dividing and coordinating decision problems into a consistent overall solution in companies (Volling 2009, p. 46). Three principles can be used to divide and coordinate decision-making problems within hierarchical planning. The first principle is decomposition or subdivision into sub-problems and, in turn, their coordination. Furthermore, aggregation of information and rolling planning can be applied (Steven 1994, p. 25).

When decomposing into sub-problems, the resulting sub-problems may differ in level of logical order (Scholl 2001, p. 238). The problems are, therefore, subordinate or superordinate to each other. The superordinate problems result in restrictions on the possible planning decisions in the subordinate problems (Kiener et al. 2018, p. 25). The hierarchical relationship between the sub-problems also requires allowing for the exchanging of information, at least between the directly neighbouring problems of different levels. Furthermore, sub-problems may receive inputs from the environment and deliver outputs to the environment (Steven 1994, p. 26). Decomposing the overall planning problem of a company into subproblems at strategic, tactical, and operational levels may serve as a typical example of a substructure (Kiener et al. 2018, p. 25). This subdivision, according to the subsequent order of decisions, decomposes the planning process according to the temporal horizon as well as to the business areas. At the given example, at each level, market planning, operational planning, and financial planning must be synchronised. Tactical planning is to be derived based on the outcomes of strategic planning detailing it, i.e., by allocating resources. Subsequently, operations are about the fulfilment of tactical planning. Suppose outcomes at subordinated levels don’t meet outcomes defined at the superior level. In that case, planning at the tactical level must be adjusted to meet strategic targets or to take corrective action in case of operational frictions. This is often done in several iterative steps until sufficient consistency has been achieved (Steven 1994, p. 33).

At the various levels of hierarchical planning, the degree of complexity can be further influenced by aggregating information. Depending on the individual design of a subproblem, the degree of complexity may be reduced by aggregating information or increased by a more detailed presentation. Aggregation, for example, may be achieved by grouping products into product groups, resources into capacity groups and by extending the time periods under consideration while keeping the length of the planning horizon the same (Fleischmann, Meyr & Wagner 2015, p. 75).

Planning problems at lower planning levels usually must be solved repeatedly. In doing so, the plans for the first sub-period must be followed until the planning is carried out again. From the second sub-period onwards, an overwriting of the plans is possible and allows the adaptation to changes that have occurred regarding different environmental conditions and forecasts. When the plan is re-executed, the planning horizon is also moved further back. This procedure is called rolling planning (Kiener et al. 2018, pp. 25–26; Volling 2009, p. 50).

In our days, well-developed computer-aided planning systems (so-called “advanced planning systems) are available in order to support the production planning process (Kilger & Wetterauer 2015, p. 301). A general structure of these planning systems was described by Rohde et al. and is suitable for presenting the planning tasks arising in production and adjacent operational functional areas in a structured and detailed manner (Rohde, Meyr & Wagner 2000, p. 10).

In this thesis, the rolling planning process of product-mix allocation will be supported by a planning system not for the whole company but for GPNs of specific products, including various product variants running on more than one line at multiple sites. Then, the results can be centrally aggregated for all products within the company to plan the site staffing, which might lead to further strategic constraints for the products' GPN.

2.1.2 Product Allocation in the GPN

This thesis comprises a detailed examination of the allocation of order-specific production quantities to sites. This process represents a pivotal aspect of the addressed problem. The research aims to align it with broader literature, highlighting this topic as a central challenge in GPN. (Lanza et al. 2019, pp. 828-832).

Allocating products and quantities to sites is referred to as “allocation planning” (Hochdörffer et al. 2018, p. 20). The terms "product-mix-allocation" (Lanza et al. 2019, p. 832) and "product-to-site allocation" are used synonymously (Alden, Costy & Inman 2002, p. 1). The terms “master planning” and “production program planning” include comparable content. However, they cover a broader view, as they also include, for example, personnel planning and outsourcing of orders (Rohde, Meyr & Wagner 2000, p. 12; Fleischmann, Meyr & Wagner 2015, p. 80). “Reallocation” describes reassigning a production quantity to a site. It may happen within a framework of rolling planning, for example, allowing a company to react to changing environmental conditions (Wittek 2013, pp. 49–56).

In this thesis, “product allocation” or “order allocation” describes the allocation of the quantity of a product ordered by a purchase order or a customer order to a site or a production line at a site. The quantity to be produced is defined per each site- or line- and per each period in the planning horizon under consideration.

2.1.2.1 Product Variants

Rather than producing a uniform product for a market with homogeneous customer requirements, markets require the production of so-called product variants. A “product variant” is characterised by the fact that it can be adapted to customers' requirements regarding specific features. Suppose products are manufactured in large numbers, allowing for many options of adaptations. In that case, this is referred to as “variant-rich series production” (Volling 2009, p. 9). A product variant thus represents a kind of product class (ElMaraghy et al. 2013, p. 629).

An increase in the number of product variants may occur for various reasons. On the one hand, it may be driven by the demand for new functions and capabilities. On the other hand, adaptations of the primary product may be necessary to meet different requirements by regional markets or individual customer segments (ElMaraghy et al. 2013, p. 629). The high number of variants contributes to an increase in the complexity of production in networks (ElMaraghy et al. 2012, p. 794).

2.1.2.2 Technical Capabilities, Releases and Line Configuration

The consideration of product variants is accompanied by describing which site or production line can produce a specific product variant. The definition of product variants must consider the capabilities of individual sites or production lines. The concept of the capability of a site has been described in the literature. According to Zhang, Vonderembse & Lim (2003, p. 174), a site's capability is determined by the machinery equipment, labour, and material flow sites available at it. Cleveland, Schroeder & Anderson (1989, p. 658) define the term more broadly; they, in addition, consider technology available at the site as well as resulting cycle times belonging to the concept of capability in the context of production. Rather than synthesising an integrated version of the various definitions, this thesis assumes that a site or a line is described as capable of producing a product variant if, remarkably, all operating resources required for production are available.

The task of the production line configuration, which is part of the product-mic-allocation, is, therefore, to ensure that for the whole planning horizon, necessary investments in operating resources are executed or planned in order to be capable of serving the customer orders according to their desired product variants.

Associated with the term capability is the release. In this thesis, it describes the customer's permission to produce his order on a specific production line or at a site.

2.1.3 Operations Research in Production Planning

This section will introduce operations research and show how planning problems can be formulated mathematically. The rationale for solving production planning problems using operations research methodologies will be analysed. Subsequently, various possibilities for considering uncertainty in planning models will be shown. The section concludes with options for reducing the complexity of operations research models.

2.1.3.1 Fundamentals of Operations Research

Operations research (OR) refers to a research field that deals with the analysis of practical, complex problems within the framework of a planning process to prepare the best possible decisions by applying mathematical methods.“ (Domschke et al. 2015, p. 1)

The process of OR-based planning can be divided into six steps, presented below in Figure 2-4. In practice, iterations are often required in order to consider the outcome of particular phases, feedback, or other dependencies between the planning steps (Domschke et al. 2015, p. 2; Klein 2012, p. 58).

OR-supported planning models start from a real problem that creates the need for action and decision-making. To solve the problem in a later step, it must first be abstracted, and an overriding goal and restrictions need to be formulated. Restrictions reduce the space for possible solutions. Once the goal and the solution space have been defined, the description of the problem must be transferred into a mathematical model where the solution meets the goal and considers the restrictions. In the next step, data required to define the individual parameters of the OR model must be collected; if not available, problem parameters must first be guessed at this point. Once an alternative course of action has been derived in the next step, it must be checked for plausibility before it is transferred to reality (Domschke et al. 2015, pp. 1–2).

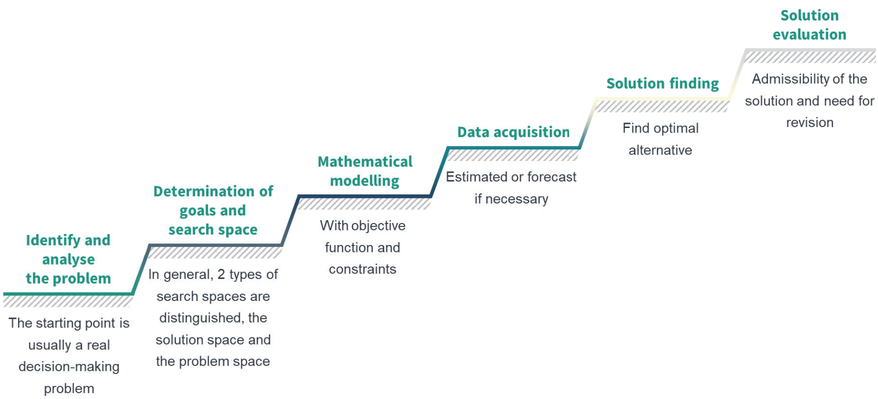


Figure 2-4: Planning procedure in OR according to Domschke et al. (2015, pp. 1–2)

The mathematical model is the core part of OR-based planning. It is also referred to as an optimisation model and part of the DSS (see Figure 2-3). It provides a formalised representation of reality. In its simplest form, it has at least one objective function that can be used to calculate the quality of a solution found. It may also comprise a set of alternative solutions resulting from constraints (Domschke et al. 2015, pp. 3–4). The individual setting of a model formulated at the general level is called an instance. A valid solution can only be derived at the instance level (Briskorn 2020, p. 8). OR models can be classified according to various characteristics. An important distinction is made between deterministic and stochastic models. In a stochastic model, the data on which the model is based, or interrelationships and evaluation rules, are not known with certainty. In a deterministic model, these characteristics are known and can be put in numbers. According to the time factor, a distinction may be made between static and dynamic models. A model containing only one planning period is called static; multi-period models are called dynamic (Zimmermann 2008, p. 127).

This thesis will implement a stochastic, multi-period optimisation model.

2.1.3.2 Solving Linear Optimisation Problems

A linear optimisation problem has the aim of maximising or minimising a linear objective function under compliance with linear constraints and can be formulated as follows:

$$\begin{gathered} min\ c_1x_1 + \ldots + c_nx_n \\ subject\ to \quad a_{11}\,x_1 + \ldots + a_{1n}\,x_1 \leq\ b_1 \\ a_{m1}\,x_1 + \ldots + a_{mn}\,x_n \leq b_m \\ x_1, \ldots, x_n \geq\ 0 \end{gathered} \tag{1}$$

A vector $\vec{x} = x_1, \ldots, x_n$ is called a solution if it meets all constraints of the problem. Suppose there is no $\vec{x}$ with a larger objective function value (in the case of maximisation) or smaller objective function value (in the case of minimisation). (Domschke et al. 2015)

The simplex algorithm is a well-known method for solving linear optimisation problems. The algorithm searches the vertices of a multi-dimensional solution space or polyhedron for the optimal solution (Domschke et al. 2015). The algorithm also uses the fact that an optimal solution to a linear problem always lies on the edge of the solution space defined by the constraints (Briskorn 2020, p. 108). The basic procedure is finding an initial solution first and subsequently improving it in iterative steps. The outcome of the simplex algorithm either is an optimal solution or it realises that the problem is unbounded or unacceptable (Briskorn 2020, pp. 123–134).

For a limited range of decision problems, linear programming modelling may be sufficient. However, in many instances, this is not the case. In a purely linear option, only continuous variables may be used. If a problem cannot be described this way, mixed-integer linear programming (MILP) may provide an applicable methodology to solve the problem. MILP allows for considering binary or integer variables, too. As a consequence, MILP allows more complex interdependencies and logical links to be mapped. For instance, this may help in modelling site activations or closures mapped with the help of a binary variable. As indicated by this short example, mixed integer linear approaches may often be used in modelling in the context of supply chain management.

In general, OR methods can be divided into 1. optimal (or exact), 2. approximation, and 3. heuristics at this point. All three will be briefly described in the following sections, concentrating on strategies relevant to further work. For a complete description, please refer to the literature used in this chapter (Briskorn 2020; Domschke et al. 2015; Zimmermann 2008).

1. Exact methods may be differentiated into decision tree procedures, sectional assessment procedures, and combination procedures. In decision tree procedures, multi-stage decisions are represented along a decision tree. The most straightforward procedure of this class is the complete enumeration. First, the objective function values of all possible solutions are calculated. Subsequently, the best solution is selected by comparison.
2. As complete enumeration is usually associated with too much computational effort, incomplete enumeration may provide a more applicable alternative. A representative of this kind is the branch and bound method (Domschke et al. 2015, p. 134). It divides the complete solution space into several parts and calculates them according to lower bounds. These subspaces are then optimised individually or may be excluded from further treatment due to their lower bounds (Briskorn 2020, p. 179). It can, therefore, provide an approximation of the extent to which the current solution is, at most, worse than the actual optimum.
3. Cutting plane methods aim to limit the set of admissible solutions to a related problem by adding cutting planes as constraints until a solution has been derived for the original problem (Briskorn 2020, p. 220). The so-called branch and cut method combines decision tree methods and cutting plane methods, providing an example of this kind. It represents an improvement of the branch and bound method by using cutting planes (Briskorn 2020, p. 270).

Heuristic solution methods may also be applied to mixed-integer optimisation problems. Without looking at these in more detail (for a detailed description, see, e.g., Domschke et al. 2015), it shall be noted that the incomplete or aborted implementation of exact procedures may also be assigned to heuristic methods (Domschke et al. 2015, p. 135).

2.1.3.3 Software-based Solution of Optimisation Problems

The solutions described in previous sections may be implemented in programming languages. However, there is an increasing trend to avoid the use of individual software packages and to rely on standard software packages (Domschke et al. 2015, p. 14).

In optimisation, the use of spreadsheet software, in most instances, provides an adequate and straightforward solution. Either already implemented solvers can be used, or spreadsheet software may be extended with add-ins. So-called solvers, such as Gurobi or CPLEX, have an extended range of functions. They can be controlled either through the use of programming interfaces or through their integrated programming languages and development environments (Domschke et al. 2015, p. 14). The performance of solvers has improved significantly in recent years, so they can be used in numerous applications to find optimal, approximation, or heuristic solutions (Briskorn 2020, p. 27).

2.2 Consideration of Environmental Conditions

GPNs are influenced by a wide range of factors from the business environment. These influencing factors are dynamic and uncertain, particularly in the case of medium- and long-term decisions (Lanza et al. 2019, p. 828; Westkämper & Löffler 2016, p. 33).

Decision theory distinguishes between decisions under certainty and those under uncertainty. In contrast to decisions under certainty, decisions under uncertainty must be made under imperfect information (Klein 2012, p. 17; Neuner 2009, pp. 9–10). Lanza et al. (2019) identify uncertainty, in particular market demand, as one of the main challenges in the design of GPNs (Lanza et al. 2019, p. 828). Uncertainty describes a situation where influencing factors are in place, whose characteristics and effects on the production system are neither known nor can they be influenced by the decision-makers. This results in a variety of potential states of the future environment. Therefore, predictions about these states must be made for decisions over several periods. However, their occurrence is uncertain. (Neuner 2009, pp. 9–10; Klein 2012, p. 17)

If it was possible to assign probabilities to the environmental states within the scope of these predictions, Bamberg, Coenenberg & Krapp (2019, pp. 22–23) qualify it as risk; otherwise, it qualifies as uncertainty. In this thesis, like most literature, the term uncertainty is used synonymously for both forms (Neuner 2009, pp. 9–10). However, most decision-making situations can state probabilities based on empirical values or expert estimates (Bamberg, Coenenberg & Krapp 2019, pp. 67–69).

Therefore, the following will first introduce the concept of change drivers and their respective receptors in Section 2.2.1. Based on these change drivers, Section 2.2.2 will focus on the scenario analysis by explaining how scenarios can be generated and clustered. The remainder explains how these scenarios can be considered during planning (Section 2.2.3) and how the resulting robustness can be defined (Section 2.2.4).

2.2.1 Change Drivers

A GPN is constantly exposed to environmental disturbances that influence and overlap each other. The occurrence of these disturbances is usually uncertain, and their effects are difficult to predict. Because they drive change and transformation, they are called change drivers. (Westkämper & Löffler 2016, p. 54; Nyhuis et al. 2008, p. 333)

Their origin may be internal or external to the company, and they may have both negative and positive effects. External change drivers are events that arise from turbulences in the company's environment. Examples of these are the individualisation of products (product variants), the withdrawal of customers, or the market entry of new competitors (market), as well as disruptive innovations and changes in legislation, such as new environmental guidelines. (Wiendahl 2014, pp. 16–17; Moser, p. 91)

Internal drivers of change are, on the one hand, the elimination of weaknesses in technical and logistical services and, on the other hand, preventive strategic considerations such as the development of new products or the reorganisation of the company (Wiendahl 2014, pp. 16–17; Mersmann, Goßmann & Klemke 2013, p. 22).

The influence of a change driver on the production system is difficult to characterise. The receptor theory of Cisek, Habicht & Neise (2002) (see Figure 2-5), with its interrelationships, offers an approach to solving this problem. A receptor represents the receiver of a stimulus from the environment, which passes this information on to the production system. The stimuli are the drivers of change that overlap and influence each other, thus creating a turbulent environment. Despite this complexity, they only affect the production system via a few channels. The resulting changes are then mapped via the receptors and passed on to the product. It should be noted that stimuli for which there is no receptor are not transmitted. (Cisek, Habicht & Neise 2002, pp. 441–442)

The receptor product describes the requirements for production regarding the properties and functions of the product. These include, for example, variants or materials. The number of pieces reflects the quantity to be produced per product or variant, and the time contains specifications regarding the delivery time. The cost receptor passes on changes in the prices for the production factors to the production system. Quality describes the requirements regarding the quality that the product must fulfil (Cisek, Habicht & Neise 2002, pp. 441–442). In the context of this thesis, the receptor's product and quantity are of particular importance. To illustrate this, a brief example is given. The entry of a competitor, whereby this event represents a change driver, leads to a reduction in sales without a reaction. This, therefore, affects the receptor quantity. If, on the other hand, the company reduces costs to remain competitive and maintain the number of units, the cost receptor is affected.

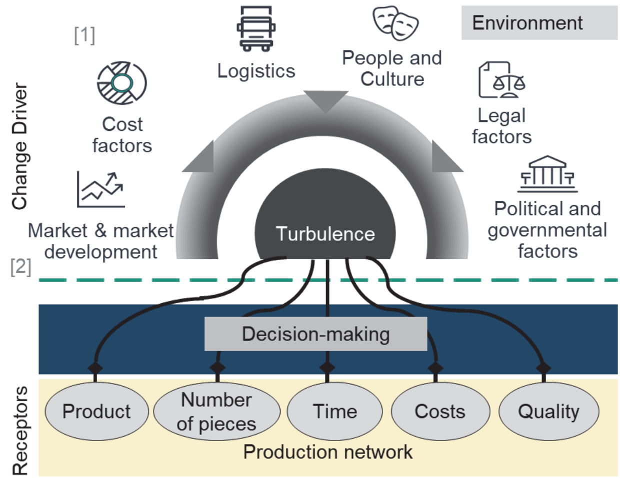


Figure 2-5 Receptor model based on [1] Lanza et al. (2019) & [2] Cisek, Habicht & Neise (2002)

A decision-maker must first interpret the change drivers before the change can be assigned to a receptor. Such a decision-making authority is the strategy department or the company management. This strategic control level is necessary because its reaction to the change influences which receptor is addressed. (Nyhuis 2008, p. 22)

2.2.2 Scenario Analysis

This section deals with the process of gathering change drivers and bringing them to concrete scenarios. Scenarios are to be understood as different, consistent, and plausible pictures of the future based on a complex network of influencing factors for which different developments are possible. This definition of scenarios is used in this thesis and is based on the definition by Mietzner (2009). Scenario analysis, as a method of foresight, aims to develop such scenarios. (Mietzner 2009, p. 101)

According to Gausemeier & Plass (2014), foresight is the systematic examination of the future environment with the aim of identifying risks and opportunities for the company (Gausemeier & Plass 2014, p. 38), which results in two primary principles. The fact that the future is not precisely predictable and that there are several possible ways in which the future will develop is referred to as multiple futures. The need to consider the combination of individual influencing factors in order to reflect the variety of different developments and the resulting complexity is summarised under the term networked thinking. (Gausemeier & Plass 2014, pp. 45–46)

These basic principles can be illustrated with the help of a scenario funnel, as shown in Figure 2-6 as an example. The scenario funnel shows the multiple futures in the form of scenarios that result from the combination of possible developments of various influencing factors, i.e., from networked thinking. The current state of the scenario funnel at time t_0 is the starting point for the multiple scenarios. Based on this, potential future states can be identified for each future point in time. The development paths result from the occurrence or non-occurrence of different events, the change drivers explained in Chapter 2.2.1. The boundaries of the funnel represent the two extreme scenarios, best-case and worst-case. In between is the potential future space. It should be noted that the funnel, and thus the potential future space, widens with increasing consideration of the future. This can be explained by the increasing uncertainty and complexity. (Teich, Brodhun & Claus 2015, p. 62-63)

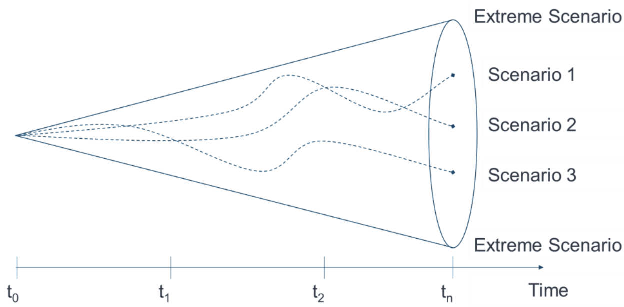


Figure 2-6: Scheme of a scenario funnel following Reibnitz (1992, p. 27), Götze (1991, p. 40) and Gausemeier & Plass (2014, p. 46)

2.2.2.1 Deterministic and Stochastic Scenario Analysis

The classical approaches of scenario analysis described represent procedures of deterministic scenario analysis and deliver a few qualitative scenarios as a result. Thus, the extreme scenarios (best/worst case) of the scenario funnel are usually depicted.

In some cases, a trend scenario, which represents the extrapolation of the present, or a few probable scenarios are also created (Götze 1991, pp. 39–40; Teich, Brodhun & Claus 2021, pp. 62–63). This is justified by the fact that considering the whole or more significant parts of the scenario funnel seems impossible or economically unreasonable due to the high effort involved. (Götze 1991, p. 39; Westkämper & Löffler 2016, p. 33).

However, stochastic scenario analysis (also called scenario simulation) attempts to do precisely this by simulating many potential future paths through many similar case experiments, thereby covering more significant parts of the scenario funnel (Romeike & Hager 2020, p. 245). The so-called Monte Carlo analysis (also called Monte Carlo simulation) is usually used for this purpose. Here, probabilities are defined for each input parameter, and the stochastic process is simulated by drawing random numbers. An approximation to reality is achieved by a sufficient number of simulation runs, whereby the mathematical basis for this is the weak law of large numbers (Romeike & Hager 2020, pp. 249–250). For a consideration of the mathematical background of Monte Carlo analysis, see, for example, MacKay (2003, pp. 357–361).

Applied to stochastic scenario analysis, the procedure described means that in each scenario, the occurrence of each uncertain influencing factor or parameter is determined using random numbers, and the results are combined into a scenario. Each simulation represents a scenario. The probabilities required for this can be obtained, for example, through expert estimates. (Gausemeier et al. 2019, pp. 169–170; Klein 2012, p. 285)

The advantages of stochastic scenario analysis lie in the possibility of covering more extensive parts of the future space in planning and thus increasing the robustness of a plan (Friese 2008, p. 51). The disadvantages compared to deterministic methods, on the other hand, lie in the required probability estimates, the difficulty of explaining the results and the high number of runs needed (Gausemeier et al. 2019, p. 169; Friese 2008, p. 51). In principle, the procedures of deterministic and stochastic scenario analysis are not mutually exclusive but may also complement each other (Gausemeier et al. 2019, p. 154).

The main area of application of scenario simulation is risk analysis (Klein 2012, p. 286). However, due to the increasing uncertainty in the production context, a few scenarios of deterministic scenario analysis are not always considered sufficient, and scenario simulation is used instead. This is also justified by the complexity of the influences and the effects on different receptors. In addition, the quantified results make further processing easier. (Stähr 2020, pp. 34–35; Friese 2008, pp. 50–52)

2.2.2.2 Cluster Analysis

Cluster analysis can be used in scenario analysis to summarise similar scenarios. (Gausemeier, Fink & Schlake 1996, pp. 273–274). It is a data analysis method that groups objects according to similarity, so-called clusters. The objects in a cluster should be as similar as possible. This is called homogeneity. In between the clusters, on the other hand, objects should be as different as possible, i.e., heterogeneous. A unique feature of cluster analysis is that all available properties of the grouping objects are used simultaneously to form groups. (Backhaus et al. 2018, p. 437)

Cluster analysis is used in a wide variety of disciplines. For example, it can be used in marketing for customer segmentation, for grouping search results from search engines, in data mining to gain a better understanding of data or, as already mentioned, to summarise similar scenarios. Other areas of application include image recognition, biology, and psychology. (Gausemeier, Fink & Schlake 1996, pp. 273–274)

In the cluster analysis setup, two main questions regarding the procedure must be answered. These are the choice of the proximity measure, i.e., how the similarity is statistically defined, and the selection of the fusion procedure. In principle, similarity can be defined in any way, but metric distance measures such as Euclidean distance are often used. (Backhaus et al. 2018, pp. 437–440)

A variety of fusion methods exist for group formation, with partitioning and hierarchical methods being the most important. The former starts with a given grouping and rearranges the individual elements until a predefined objective function becomes optimal. The latter distinguishes again between agglomerative and divisive procedures. The divisive procedures start with a cluster that contains all components and divides them up. In the agglomerative procedure, each element represents a separate cluster at the beginning. In the course of the procedure, the clusters are combined until the desired number of clusters is reached. (Backhaus et al. 2018, p. 457)

The following paragraph takes a closer look at the partitioning cluster algorithm *K*-Means, which will later be used for this thesis. A detailed description of various similarity measures can be found in (Backhaus et al. 2018, pp. 439–475).

The K-Means algorithm is a partitioning clustering method. Here, a cluster (C_k) is represented by its geometric centre of gravity, the "centroid". The Euclidean distance is used as a proximity measure. Thus, the distance and thus the difference between an object of the cluster ($o \in C_k$) and the centroid (c_k) is calculated by the Euclidean distance ($dist(o, c_k)$), while the sum of their squares represents the according cluster variance. The quality of the cluster assignment is determined by the within-cluster sum of squares ("*WCSS*"). This is the sum of the squared deviations between all objects and the centre of gravity of the cluster. (Han, Pei & Kamber 2012, p. 451)

The within-cluster sum of squares (*WCSS*) is defined for *k* clusters as:

$$WCSS = \sum_{i=1}^{k} \sum_{o \in C_k} dist(o, c_k)^2 \qquad 2$$

The goal of the K-Means algorithm is to minimise this sum. This is also called variance minimisation since the sum of the cluster variances is minimised. To do this, the algorithm proceeds as follows: First, a desired number of clusters *k* must be determined. Then, *k* cluster centroids are determined randomly or according to specific heuristics and the objects are assigned to their nearest centroid according to the Euclidean distance. Now, the error sum of squares is iteratively improved by recalculating the geometric centroids for each cluster based on the assigned objects. Then, the objects are reassigned to the nearest centroids. This is repeated until the assignment is stable, i.e. the "centroids" no longer change. (Han, Pei & Kamber 2012, p. 452)

The result of the K-Means algorithm depends on the starting assignment of the centroids and is not always determined at the global optimum but often at a local optimum. Therefore, the K-Means algorithm is usually carried out several times with different starting values. The advantages of the procedure lie in its simplicity, the fundamentally good cluster results, and, compared to other cluster procedures, the perfect computing time due to a linear time complexity. (Han, Pei & Kamber 2012, p. 453)

In addition, the advantage compared to hierarchical algorithms is that assignments made can be revised by the algorithm (Backhaus et al. 2018, p. 457).

A problem with cluster analysis and similarity calculation arises when many different criteria are used for grouping, especially when the information content of the individual components is unclear, and the factors influence each other. Due to factors with little information content, the roughness within the data increases, which makes clustering more difficult. (Backhaus et al. 2018, p. 491)

A possible solution is the Principal Component Analysis (PCA). This makes it possible to combine many dependent factors into a few uncorrelated principal components that contain the central part of the information in the form of the variance. These principal components mathematically represent a linear combination of the original variables. In addition, it can be specified for each principal component what proportion of the variance of the original data is explained by the respective principal component. (Kessler 2006, pp. 22-23; p. 35)

The disadvantage of the representation by linear combinations is that it is more difficult to interpret the factors (Backhaus et al. 2018, p. 491). For a detailed mathematical explanation of principal component analysis, see Kessler (Kessler 2006, pp. 36–46).

An important decision in principal component analysis is the number of factors to be used from the analysis, as this determines which information portion is used to reproduce the data structure and which portion is cut off for dimension and noise reduction. Various criteria are known in the literature according to which this decision can be made. (Handl 2010, pp. 128–129)

The so-called elbow criterion sorts the main components according to their variance and plots them on a screeplot. The variances are plotted on the ordinate, and the sorted factors are on the abscissa. As a rule, at least one "kink" is now visible in the graph. All principal components are now selected that lie before the last "kink", the so-called elbow. The reason for this is that the variance to the right of the elbow decreases only slowly and can, therefore, be neglected. An exemplary screeplot is shown in Figure 2-7. The red line indicates the elbow. Thus, the three factors are selected to the left of the elbow. (Handl 2010, pp. 128–129)

While the ease of use and the overall good results are the advantages of the method, the disadvantage is the high subjectivity (Zwick & Velicer 1986, pp. 434–440).

In addition to being used to determine the number of principal components, the screeplot can also be used to compare the number of clusters in the cluster analysis. For this purpose, the optimisation criterion of the algorithm is plotted on the y-axis. For the K-Means algorithm, this is the error sum of squares. The number of clusters is shown on the x-axis. In addition, the screeplot, in this case, illustrates the trade-off between the higher homogeneity within the clusters with a high cluster number and the associated poorer manageability. (Backhaus et al. 2018, pp. 475–477)

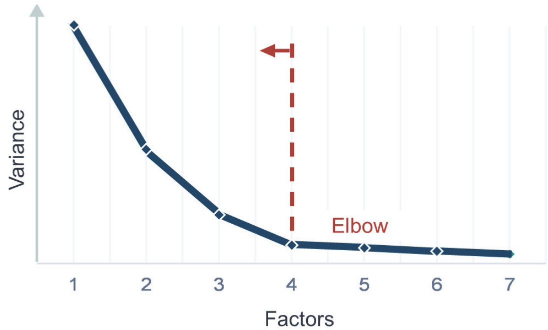


Figure 2-7: Exemplary representation of a screeplot.

2.2.3 Consideration of Uncertainty in Planning

Uncertainty, as explained in the previous chapters, is a significant challenge in production planning. Adaptability, which allows a production system to react to the occurrence of uncertain events, is a crucial factor. The term "adaptability" in this thesis includes the ability to make early and forward-looking adjustments at all levels of the production system to react economically to influencing factors, their uncertainty and the resulting challenges. Flexibility and changeability represent two kinds of adaptability. (Wiendahl et al. 2007, p. 785; Lanza et al. 2019, p. 832)

Distinguishing between flexibility and changeability is predicated on the time and cost entailed in their implementation (Stricker 2016, p. 88). Flexible systems offer predefined ranges of action known as flexibility corridors, which allow reversible adjustments (Wiendahl, Reichardt & Nyhuis 2015, p. 97). Adaptations can be swiftly and economically executed within the system's flexibility limits or corridors. However, suppose the required changes exceed these predefined limits. In that case, the concept of changeability comes into play (Wiendahl, Reichardt & Nyhuis 2015, p. 97). Changeability demands more time and financial investment than flexibility (Stricker 2016, p. 89) while remaining confined within the boundaries of the changeability corridor. This corridor outlines the intended solution space and establishes the parameters for transformation (Wiendahl, Reichardt & Nyhuis 2015, p. 97).

Flexibility and changeability can also be distinguished based on whether the adjustments are made in response to predicted or unforeseen changes in market dynamics. However, this distinction may not always hold for medium- or long-term decisions, as the provision of flexibility can be advantageous for optimising overall outcomes in the future, even in cases where changes are anticipated (Hochdörffer 2018). Sethi & Sethi (1990, pp. 297–309) distinguish between volume flexibility and product mix flexibility. Volume flexibility comprises the ability of a production system to operate profitably at different overall production volumes. Product mix flexibility entails the ability to produce multiple distinct products at one production site without major cost disadvantages.

However, uncertain parameters must be considered during planning since an essential feature of planning is its future-relatedness. As a rule, there needs to be more reliable information on the future development of the examined systems. (Klein 2012, pp. 405–406)

Particularly in the case of long-term decisions, the fast-moving global environment and the high degree of uncertainty mean that a pure projection of the future based on time series is not sufficient (Bundschuh 2008, pp. 85–86; Teich, Brodhun & Claus 2021, p. 64).

Due to the complexity of planning decisions and the need to consider a wide range of restrictions and premises, mathematical models are often used to support them. This is referred to as model-based planning. Of particular importance are optimisation models, which are a formal representation of decision-making problems and for which the most favourable solution possible is to be selected with regard to specific quantitative goals. (Klein 2012, pp. 31–34)

Many examples of the application of such models in the context of production planning and product allocation can be found in the literature (e.g. Bundschuh (2008), Friese (2008) and Wittek (2013)).

A distinction can be made between direct and indirect consideration (Wittek 2013, p. 115). In direct (or multi-valued) consideration, the uncertain information is mapped directly in the model, and random variables describe uncertain parameters. Alternatively, different future states, so-called scenarios, and their probabilities of occurrence can be determined and then implemented directly in the model. This results in a stochastic optimisation model. The prerequisite for this direct consideration of uncertainty is the availability of the required information, especially probabilities or probability distributions for all uncertain parameters. However, in many planning decisions, this information is not available or is only available in insufficient quality. Moreover, direct consideration increases the complexity and, thus, the computing time considerably, which means that only a few uncertain parameters or scenarios can be included. (Wittek 2013, p. 116; Klein 2012, p. 407).

Indirect (or single-valued) consideration includes uncertainty outside the optimisation model and substitutes uncertain parameters in the model, resulting in a so-called substitute value model. This reduces the demand for the forecast and enables the use of deterministic models. These can be solved with little effort and with various standard software packages. The disadvantage of this approach is that the opportunities and risks associated with the possible solutions are only indirectly included, which may increase the risk of planning errors. (Wittek 2013, p. 116; Klein 2012, p. 406)

However, in addition to indirect consideration, rolling planning is possible. In multi-period planning, decisions are only made for a few periods in advance and only provisionally for later periods. This means that they can be revised and adjusted at a limited cost if the environmental situation changes. (Wittek 2013, p. 120)

In expected value models, for example, all uncertain parameters are replaced by their expected value or other estimated values. Correction models allow for safety corrections through additions or deductions and thus increase the robustness of the planning, as explained in the next section. Another possibility is a downstream sensitivity analysis. After the optimisation of a substitute value model, how sensitive the solution reacts to individual changes in input parameters is examined. Thus, it can be determined how much an input factor can fluctuate without causing a change in the optimal solution or which input factors have a high influence on the objective function. Finally, scenario analysis should be mentioned, in which different scenarios are formed by assessing possible developments. When using scenario analysis as a method for indirectly taking uncertainty into account, all scenarios must be solved by the deterministic model.

Despite the resulting high effort, this approach is suitable and will be used in this thesis for the planning of GPNs, especially for the creation of demand scenarios. (Kauder & Meyr 2009, pp. 113–114; Wittek 2013, pp. 118–119)

2.2.4 Robustness

Following Stricker & Lanza (2014), robustness is defined by the “stability against different varying conditions”. According to Scholl, in relation to plans, this means that they remain executable in a modified form for different environmental situations in the future. Scholl assumes a fundamental risk aversion in business planning decisions and, therefore, considers the concept of creating robust plans to be particularly relevant. (Scholl 2001, p. 93)

A plan is called robust if it does not have to be changed, or only slightly, when information about the underlying environmental situation changes. If the plan can be adapted quickly and purposefully when new and relevant information becomes known, this property is called flexibility. (Scholl 2001, pp. 94–95)

It should be noted that, as in the case of flexibility, a distinction must be made between the property of a plan regarding a production system and the property of the production system itself. This is without prejudice to the fact that these properties can be interrelated. For example, it can be assumed that flexibility (as well as adaptability) in the production system has a positive effect on the flexibility of the production plan. (Scholl 2001, p. 98)

In the literature, the concept of robustness is usually further differentiated. Mulvey, Vanderbei & Zenios (1995, p. 265) only distinguish between two types of robustness. In Scholl's work, for example, a distinction is made between six different criteria of robustness (Scholl 2001, pp. 99–101). Since the latter authors' classification of robustness is extended by the previously mentioned approach, this more comprehensive approach to the classification of robustness will be taken up and explained below.

The robustness of results refers to the level of results of the planning and compares several possible scenarios. The smaller the scenario-dependent deviations of the planning result are, the more result-robust the plan is (Scholl 2001, p. 99). The robustness of results does not consider the extent to which a robust plan for a specific scenario deviates from the optimal plan for that scenario. However, this is considered by the criterion of optimality robustness. The smaller the difference between scenario-specific optimal planning and robust planning, the more optimally robust a plan is to be assessed (Scholl 2001, p. 102; Mulvey, Vanderbei & Zenios 1995, p. 265).

The reliability robustness of a plan describes the extent to which a plan is permissible for multiple scenarios. A plan is totally reliability robust if it is applicable to all scenarios considered without modification. If this is not the case, a relatively reliability, robust plan may exist. (Mulvey, Vanderbei & Zenios 1995, p. 265; Scholl 2001, p. 104)

Furthermore, information about certain environmental situations could theoretically be obtained during planning, but this is not considered further for other reasons. Suppose a plan based on a set of environmental situations is also robust against unplanned environmental conditions in the sense of the above three sections. In that case, it is called information robust in the literature. (Scholl 2001, pp. 105–106)

If planning is carried out several times or if a plan is revised later, previous planning decisions may have to be revised. The smaller the number of revised decisions, the higher the planning robustness. (Scholl 2001, p. 108)

The evaluation robustness of a plan does not refer to the various possible environmental situations that enter the planning as in the other cases. Instead, it considers the problem that there may be a certain degree of fuzziness in determining the planning outcome. The less critical the exact way of calculating the planning outcome is for the selection of a plan, the higher the evaluation robustness of the plan. (Scholl 2001, p. 110)

Following Teich, Brodhun & Claus (2021, p. 84), robust planning exists when, firstly, uncertainty is considered in the planning by including several futures in the form of scenarios. Secondly, the risk aversion assumed by the planner should be considered by evaluating plans against one or more of the robustness criteria explained above.

This thesis combines various aspects of the aforementioned definitions of robustness to define the term "robust solution". To this end, solutions of the own approach must be result and optimality robust for the entire planning horizon. In addition, they must be reliability and planning robust for a shorter time horizon, as decisions must be fixed there. The plans may be adjusted for later periods. Planning robustness, according to Teich, Brodhun & Claus (2021, p. 84), which also takes risk aversion into account, is also necessary for this thesis. Finally, in Section 6.1.4, whether the approach also indirectly leads to information robustness is analysed.

In principle, a variety of methods can be used to create robust solutions. However, operations research methods, such as those in the field of optimisation, are suitable. (Scholl 2001, p. 173)

2.3 Decision Support Systems

This thesis discusses a digital assistance system (see Appendix E) categorised within this framework as a high-level and ability-extending cognitive support system or, more specifically, a decision support system (DSS).

DSS are interactive computer-based tools designed to aid decision-makers. They employ communication technologies, data, documents, knowledge, and models to identify and implement optimal solutions (Power 2002, p. 157). Another perspective characterises DSS as systems identifying solutions, evaluating alternatives, and acting autonomously (Blutner et al. 2007).

The decision-making process involves several steps where DSS play a crucial role. Firstly, in generating and processing information, DSS analyse, integrate, and filter data, mainly assisting users. Next, these systems transform data into decision alternatives, offering multiple choices for human selection. DSS can also evaluate these alternatives based on predefined criteria. Once a decision is made, DSS monitor its execution, ensuring alignment with set goals. Furthermore, these systems provide feedback, recommend revisions, and even prevent the execution of intended decisions, thus exerting control over the decision-making process. (Blutner et al. 2007)

A widely accepted DSS structure comprises four integral subsystems, as depicted in Figure 2-8 (Mir & Quadri 2009, p. 380).

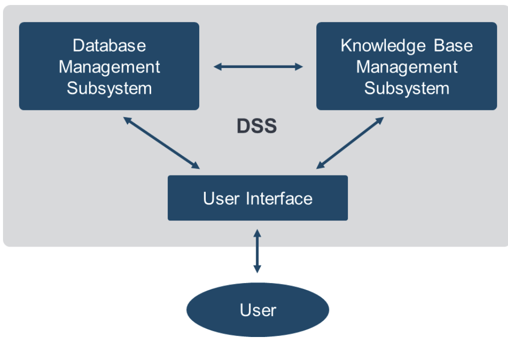


Figure 2-8: Main components of a DSS (own representation cf. (Mir & Quadri 2009, p. 380))

- Database Management Subsystem (DBMS): At the core of the DSS, the DBMS organises, retrieves, and manages data. It creates and maintains databases containing relevant information, controlling access to ensure only authorised users can interact with the data. Utilising tools such as data directories and query sites, it forms the system's backbone, facilitating efficient data handling. (Mir & Quadri 2009, p. 380)
- Knowledge Base Management Subsystem (KBMS): Building upon the DBMS, the KBMS serves as the analytical heart of the DSS. It applies pre-set logic, rules, and

methods to analyse data. Whether through scenario simulations or predictive insights, this subsystem leverages the organisation's collective knowledge to enable informed decision-making. (Mir & Quadri 2009, p. 380)

- User Interface Subsystem (Human-Machine Interface): This subsystem acts as the crucial bridge between the DSS and the user. Its design and capabilities are pivotal for the DSS's accessibility to non-technical specialists. It encompasses the design and functionality of screens, devices, and interface elements, offering an intuitive and user-friendly platform for inputting data, running queries, and interpreting results also for non-technical users (Power & Sharda 2007, p. 1046). Visualisations, reports, and other tools enhance comprehension, rendering complex data accessible and actionable. (Mir & Quadri 2009, p. 380)
- User: The final component is not a subsystem but represents the individuals who actively engage with the DSS. Users can include managers, analysts, staff, or other stakeholders. Their role is vital as they input data, interpret results, and apply insights to real-world problems. Their expertise and feedback often influence the design of other subsystems, ensuring that the DSS aligns with their needs and preferences. (Mir & Quadri 2009, p. 380)

Harjunkoski et al. (2014, p. 189) highlight the significance of consensus regarding approach and user acceptance as pivotal lessons for achieving successful model implementation. This notion stems from the essential understanding that a DSS utility only manifests when it is wielded correctly and aligned with its intended purpose. Moreover, Williams (2013, p. 40) posits that for modern DSS, the interface between user and model serves as a principal bottleneck in the efficacious implementation of DSS based on optimisation models, overshadowing the optimisation process itself.

Leveraging spreadsheets for data provision can thus greatly assist planners in familiarising themselves with the system, thus mitigating the risk of information loss. However, it's essential to acknowledge that while spreadsheets offer familiarity, they also bring about concerns like inconsistency and limited integration standards (Stadtler, Kilger & Meyr 2015, p. 504). Consequently, a comprehensive implementation should integrate a graphical interface within the company's information systems. Nonetheless, adopting a flexible approach during development confers the advantage of adaptability and the potential to define functionalities.

During the development, it is advisable for a user interface to elucidate the planning methodology and foster user engagement with the DSS. O'Hara & Fleger (2020) provide valuable recommendations, with particular importance given to the following for this thesis:

- Establishment of a standardised format
- Incorporation of internally recognised terminology to enhance traceability
- Migration of data structure from sources
- Segmentation onto distinct pages
- Clear differentiation of input fields, such as through a color-coding scheme
- Provision of illustrative examples and elucidations
- Delimitation of visible areas to pertinent user-input fields.

All of these strategies contribute to facilitating data input and curbing errors. Internal terminology adoption and data structure retention foster familiarity with the framework, including established approaches to data handling within the company. Lastly, the final four concepts collectively mitigate error susceptibility by guiding users through data input.

2.3.1 Data Visualisation

Data visualisation, often referred to as information visualisation, involves using visual elements such as charts and graphs to explore, understand, and communicate complex data. While the terms 'data visualisation' and 'information visualisation' are used interchangeably, they primarily deal with aggregated, summarised, and contextualised data rather than raw facts. In the realm of business intelligence, data visualisation encompasses various visual elements like charts, graphs, scorecards, and dashboards, which are crucial for creating and sharing business information effectively. (Turban 2015, pp. 145–146)

The power of a well-crafted visual representation in data analysis cannot be overstated. Simplifying complex datasets into understandable, insightful, and actionable insights is fundamental. Simplicity, avoiding unnecessary complexity, is vital in a data-overloaded world. Moreover, understanding the user's needs is crucial; visualisations must cater to varying expertise levels, interests, and the questions users aim to answer. The choice of chart type is equally pivotal; the appropriate visualisation method, considering factors such as time-series data or part-to-whole relationships, ensures clarity. Readability is enhanced through clear fonts, contrasting colours, and thoughtful colour choices, accommodating diverse viewers, including those with colour blindness. (Few 2009)

Well-designed dashboards operate on three layers: the monitoring layer, displaying graphical data for key performance metrics; the analysis layer, summarising dimensional data for root cause analysis; and the management layer, offering detailed operational data to identify necessary actions. Contextualisation, often achieved by comparing data against baseline or target values, is crucial. Effective dashboards not only present data but also tell a compelling story, guiding users through trends, anomalies, and areas of interest. Applied design principles, such as simplicity, clear hierarchies, and strategic use of colours, enhance the effectiveness of the narrative. Interactive features allow users to drill down or filter views and empower users, giving them control over the data narrative and facilitating deeper insights. (Turban 2015, pp. 162–163)

2.3.2 Maturity Models

A maturity model measures how advanced certain activities are in a specific area of interest. It includes research objectives, a scale to measure maturity, and areas of interest. Different models can vary in how they're structured and what they emphasise. Most maturity models focus on software development and maintenance (van Steenbergen et al. 2010, p. 317).

As mentioned, most maturity models in software modelling have five levels, each adding a unique piece to the software process and making an organisation's abilities better (van Steenbergen et al. 2010, p. 317). These levels match up with the primary Capability Maturity Model Integration (CMMI) Institute's model for improving processes (CMMI 2002). Each level builds on the one before it:

- Level 1: Initial: This is the beginning, where creating and maintaining software is unstable. People might not be committed, leading to problems. Projects often go off track during crises. The focus is more on individuals than the whole organisation.
- Level 2: Managed: Management policies and how they're carried out are defined. What was learned from past projects helps with new ones. Standards for projects are set and followed strictly.
- Level 3: Defined: Processes for software creation and management are documented across the organisation. A set process includes stable, repeatable, connected software creation and management steps. Everyone in the organisation knows their roles and responsibilities.

- Level 4: Quantitatively Managed: Organisations set clear goals for quality, with specific measurements for both products and processes. Data from projects is gathered and analysed in a central database.
- Level 5: Optimising: The main goal is to keep improving the organisation. Tools are used to find problems early and strengthen processes to prevent mistakes.

For this dissertation, a maturity model will be designed and used in Section 6.3 to evaluate the maturity regarding the implementation of the proposed DSS at different GPNs.

2.4 Data Integration

Databases serve as repositories for data storage, manipulation, and retrieval. Within well-structured organisational frameworks, clients not only access these systems but also actively contribute new data and modify existing data within them. However, a significant challenge faced by many companies is the presence of incompatible databases that have arisen from urgent needs rather than deliberate strategic planning or controlled evolution. (Hoffer, Scott & Topi 2009)

Hoffer, Scott & Topi (2009) also underscore the prevalence of data trapped within legacy systems, often suffering from subpar quality. They define a database as an organised collection of data varying in complexity and scale. Data represents meaningful objects and events within the environment, while information arises from processed data that enhances user knowledge. This transformation from data to information is frequently facilitated through the creation of reports. (Hoffer, Scott & Topi 2009)

Contextualisation is pivotal in rendering data meaningful, and metadata serves as the bedrock for imparting context. Metadata encapsulates attributes and contextual information for end-user data, encompassing data names, definitions, sizes, and permissible values. Through metadata, both database designers and users gain a deeper understanding of data types, their implications, and how to differentiate apparently similar data elements (Hoffer, Scott & Topi 2009). Effectively managing both metadata and data is imperative, as undefined data meanings can lead to confusion, errors, or misinterpretations. Metadata, such as creation dates or document ownership, can also be applied to documents and databases. Data can generally be categorised based on its structural degree. Unstructured data lacks any discernible structure, as found in raw text or photos. Semi-structured data follows a self-descriptive structure, as seen in CSV or XML files, but lacks the formal structure of a relational database. Structured data adheres to a predetermined and well-defined format and is commonly stored in relational databases like SQL databases, enabling systematic querying. Effectively managing these diverse data types is essential for robust production network planning. (Salam & Stevens 2006)

A Database Management System (DBMS) facilitates the creation, updating, storage, retrieval, and access management of user databases. While a DBMS enables users and programmers to share data across various applications, it is crucial that the applications inherently support data sharing for seamless integration. This becomes particularly significant when designing databases tailored to specific user requirements. Data models capture the essence and relationships of data. The structural arrangement of a database significantly impacts its efficiency and effectiveness. The data model comprises entities or objects, such as customers, invoices, cases, and orders. Information about each instance of an entity, such as a customer's name or ID, is an integral part of this model. Relational databases establish connections between entities through shared fields, such as order IDs or client IDs, facilitating the establishment of relationships between different entities. (Hoffer, Scott & Topi 2009)

Non-relational databases encompass a wide range of systems that diverge from the traditional approach of storing data in distributed tables. These alternative models, such as hierarchical or network-like structures, were prevalent before the advent of relational databases and continue to find utility in specific applications like CAD programs. However, with the emergence of the internet, web applications, and the exponential growth of Big Data, non-relational database systems have experienced a significant boom in popularity and adoption. (Meier & Kaufmann 2016, p. 18)

In conclusion, effective database management, including addressing compatibility challenges, harnessing metadata for contextualisation, and choosing appropriate data models, is essential for organisations to unlock the full potential of streamlined operations, enhanced data consistency, and improved decision support, ultimately contributing to the overall success and efficiency of their information systems.

2.4.1 Production Data Generation and Collection

In the digitalisation of GPNs, computer systems typically adopt a hierarchical structure resembling a pyramid (see Figure 2-9), characterised by distinct levels and nomenclature. Although Siepmann & Graef (2016) offer a prominent definition, alternative conceptualisations exist. For GPN planning, the two systems at the top of the pyramid are crucial and thus will be explained in detail.

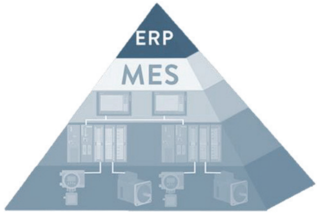


Figure 2-9 The automation pyramid based on (Siepmann & Graef 2016, pp. 49–51)

Enterprise Resource Planning (ERP) systems have a pivotal role in material and product flow management across the supply chain. Their scope spans inventory tracking, production schedule monitoring, resource management, optimising machinery, and labour allocation. Integrating ERP into GPN planning enhances overall efficiency, reduces lead times, and ensures precise production scheduling. Moreover, ERP provides real-time visibility into inventory levels and production processes, enabling swift responses to demand fluctuations and external influences.

Manufacturing Execution Systems (MES) play a critical role in orchestrating GPN planning. They design and optimise material and product flow, spanning production sites and logistical operations. Serving as data hubs, MES collect and process information from sensors and other sources, offering real-time insights into production processes. These insights inform production workflow optimisation, enabling adaptability in response to shift demand and other factors. Integrating MES into GPN planning empowers companies to enhance manufacturing efficiency, control costs, and elevate quality standards.

2.4.2 Digital Twins

According to the International Organization of Standardization (ISO), digital twins are defined as digital representations of observable manufacturing elements that are tailored to specific purposes. These representations are synchronised with their corresponding physical components. This broad definition, outlined in ISO 23247, serves as a common ground for various stakeholders, as it does not require the presence of a data link or the capability to predict future states.

In a widely adopted framework proposed by Stark, Kind & Neumeyer (2017), the concept of a digital twin is divided into two distinct components: the digital master and the digital shadow. The digital master serves as a generalised and abstract representation of a group or class of entities. In contrast, the digital shadow encompasses all the data associated with a specific entity throughout its entire life cycle. When the abstract digital master is logically connected to the digital shadow of a specific instance, a digital twin is formed, as depicted in Figure 2-10.

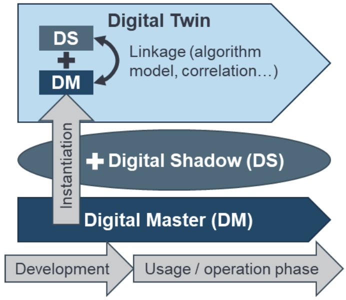


Figure 2-10: Digital twin, digital shadow and digital master based on (Stark, Kind & Neumeyer 2017)

The existing literature is mainly comprised of conceptual papers that need concrete case studies. Nevertheless, some practical applications exist at lower integration levels. Current research in manufacturing primarily focuses on production planning and control, where the DT serves as a central data hub. Despite these advancements, more in-depth case studies in industrial environments are needed to assess the tangible benefits of DT implementation. (Kritzinger et al. 2018)

Jones et al. (2020) analysed 92 Digital Twin-related papers from various sources and identified 13 key characteristics and processes of Digital Twins. These characteristics encompass both physical and virtual entities, connections, processes, and environments. The research also highlighted seven themes indicating gaps in existing literature and future research directions, including perceived benefits, integration, use cases, technical implementations, and data ownership. This thesis aims to be a fraction of closing this gap in the domain of GPN digital twins.

3 State of Research

To perform a literature review on frameworks for the optimisation of GPN, specific targets and requirements must be set. These requirements are based on the already presented research objectives in Figure 1-3. The robust solution, as defined in Section 2.2.4, must consider internal and external uncertainties by forecasting comprehensive demand scenarios and accommodating different types of flexibility within the solution space in case, for example, capacities fall out due to machine failures or trading restrictions. The approach should then lead to robust decisions regarding the network configuration that work well across different demand scenarios.

3.1 Existing Approaches

In this chapter, approaches for different requirements according to the described research objectives in 1.3 regarding the network configuration and network model, solution robustness, implementation of the planning process, and data integration are presented and discussed. Considered approaches should therefore:

1.1. account for flexibilities within the GPN, addressing the simultaneous consideration of different kinds of flexibilities,

2.1. developing effective methods to condense uncertainty within a reasonable number of scenarios in stochastic models,

2.2. provide mechanisms to condense information from multiple scenarios for robust solutions as defined in Section 2.2.4,

3.1. address the integration of DSS within the production planning process, exploring practical steps, challenges, and best practices for successful adoption and integration of DSS in GPNs, and show the practical application in actual use cases,

4.1. and focus on data-based Decision Support Systems, addressing the challenge of integrating data from diverse sources within organisations to construct effective digital twins for GPNs as well as provide methodologies and strategies for data acquisition and integration in GPN decision-making contexts.

Later, the research gap is summarised, and the research questions are derived (see Chapter 3.2).

3.1.1 Modelling of Flexibility in GPN

The consideration of flexibilities within the network model is necessary to broaden the solution space and find robust solutions. Sethi and Sethi (1990) provide an overview of the concept of production flexibility by reviewing relevant literature. Different types of flexibilities have been defined in the literature, and the article offers careful definitions of some of these flexibilities, especially for volume- and product mix flexibility, which is important for this thesis. The article describes operational and financial measures of flexibility that can be used to help production managers understand the extent of flexibility in their production process and make informed decisions on new equipment.

Numerous specific DSS for GPN configurations typically focus on one type of decision at a particular company. Comprehensive overviews are given by Lanza et al. (2019) and Govindan & Fattahi (2017). The utilised models are often mixed integer linear programming models focusing on costs or net present value. However, some also include additional objectives.

Existing literature hardly finds appropriate solutions for a combined consideration of volume and product mix flexibility. This means they mainly consider if a site could handle more volume but do not recognise if there is more volume within the type spectrum of the lines currently produced at other sites to take over potentially. One approach that had already tackled this problem early was Friese 2008. He develops a methodology for strategic GPN planning with a particular focus on developing an optimal flexibility strategy. Within the model, capacity adjustments over time are considered, as well as decisions on product allocations and transport programmes. A two-stage stochastic program is used for this purpose. In the first stage, strategic decisions must be made under uncertainty. In the second stage, operational and tactical decisions can be revised on a rolling basis when demand is known. Demand uncertainty is mapped by scenarios that are generated with the help of a Monte Carlo simulation. The basis for this is formed by scenario forecasts per product variant and the underlying statistical parameters, such as variances and correlations to other product demands. A limited number of simulations achieves a limitation to a manageable number of scenarios.

Instead of spending time forecasting future events and attempting to identify the amount of flexibility and changeability needed, some authors consider flexibility in the objective function and thus consider a multi-criteria objective function. One such approach is by Bachlaus et al. (2008). They outline a supply chain network that integrates production, distribution, and logistics at the strategic decision-making level. The design problem optimises cost, site flexibility, and volume flexibility while considering an agility performance index as a critical design criterion. The proposed solution methodology employs a hybrid Taguchi particle swarm optimisation (HTPSO) algorithm that combines the statistical design of experiments and random search techniques to identify the best suppliers, sites, distribution centres, and cross-docks.

In addition to an objective function cost component, factors such as delivery time, quality and flexibility are considered by Lanza & Moser (2014). Their model can simulate unpredictable changes in drivers of change and generate relationships between these drivers within an uncertain business environment. Additionally, the model evaluates the impact of the environment on the network based on the mentioned change drivers. Using an optimisation module, the model determines the optimal configuration of GPNs, including suppliers, sites, technologies, and logistics, at various points in time during the planning horizon. The approach was tested in the industry and was successful in identifying the optimal strategy based on the dynamic business environment.

Hochdörffer et al. (2022) consider flexibility in the constraint and add a cost value in the objective function to quantify the flexibility costs. They present a model for decision support involving customers in the design, planning and controlling of GPNs. In the three areas considered, the tasks include the configuration of the network, the allocation of customer orders to sites and the sequence planning in production. The overall objective is to minimise the costs for production, flexibility, and reconfiguration of the network, considered overall planning periods. No uncertainty is considered in the input data of the problem, but a sensitivity analysis is provided for in a later step of the procedure. The model is applied to a case study in the aviation industry to illustrate the process and the interdependencies considered.

3.1.2 Robust Solutions

This chapter delves into the realm of robust decisions within the context of GPN planning, focusing on approaches that address uncertainties. The exploration primarily centres on stochastic approaches, particularly techniques for scenario building. These methods are employed to manage influential factors effectively, such as demand uncertainty and changes in configuration. Furthermore, the chapter introduces pertinent literature concerning the concept of robust optimisation.

3.1.2.1 Forecasting Representative Demand Scenarios

When designing the GPN structure and building an allocation strategy, the uncertainty of influencing factors has to be considered (Lanza et al. 2019). Uncertain influencing factors that trigger changes within the GPN are referred to as change drivers (Wiendahl et al. 2007).

Most approaches use stochastic models, such as a Monte Carlo simulation, to consider change drivers in a variety of quantitative scenarios and representatively map the scenario funnel (Bihlmaier, Koberstein & Obst 2009; Stähr, Englisch & Lanza 2018). Bihlmaier, Koberstein & Obst (2009) describe a model for strategic and tactical production planning of GPNs in the automotive industry. Here, more than a hundred scenarios are formed to depict demand uncertainty. These are generated based on demand scenario forecasts for various products using a Monte Carlo simulation and estimating multiple statistical parameters. A further reduction of the generated scenarios does not take place since, instead, a heuristic approach using the "accelerated Benders' decomposition" is applied, which allows the high number of scenarios to be processed. Stähr, Englisch & Lanza (2018) use scenario analysis as the first step in creating configurations for scalable assembly systems in uncertain environments. During several individual interviews and expert workshops, they identify volatile receptors that influence production as well as conversion drivers that affect the individual receptors. The identified receptors include the number of units and the number of variants. In addition, key figures are defined for each receptor with which the changes can be quantified. Within the workshops, probabilities of occurrence and possible times of occurrence of the change drivers are also estimated. Modelling of the process follows this through the stochastic change drivers, project phases and waiting states. They then use a Monte Carlo analysis to simulate the occurrence of the conversion drivers and create possible quantitative development trajectories for each receptor. From this, a confidence interval is determined per period for the expected value of each receptor. This result is used to account for uncertainty in the configuration of a scalable assembly system. The methodology is tested using a production system for a mobile fuel cell system.

Other approaches try to condense the amount of information from many scenarios into fewer ones. As part of the dissertation by Stähr (2020), the methodology of Stähr, Englisch & Lanza (2018) is applied and expanded in the planning of scalable assembly systems. However, in the case of constant receptor values, the results are then divided into classes, which results in so-called aggregated scenarios and reduces the number of possible states. By combining the possible future states of each receptor, the stochastic state space is mapped, for which a scaling strategy for an assembly system is created using a Markov model. For validation, an application takes place at a manufacturer of high-pressure valves.

Santoso et al. (2005) and Azaron, Venkatadri & Farhang Doost (2021) reduce the number by the application of a sample average approximation approach. Santoso et al. (2005) develop a two-stage stochastic model similar to Friese (2008), which is designed for various planning tasks along the value chain. Here, site, capacity and allocation decisions are made on the first level and decisions regarding production and transport volumes are made on the second level. Uncertainty is, e.g., considered in the demand quantities and transport costs and represented by statistical parameters. By considering these distributions, scenarios are generated in a Monte Carlo simulation. To be able to include many scenarios, groups of scenarios are approximated by their sample mean. This is called "Sample Average Approximation". The concrete scenarios are solved by an "accelerated Benders' decomposition" in a multi-step approach, whereby the problem is divided, and the solution time is reduced.

Azaron, Venkatadri & Farhang Doost (2021) present a multi-objective, two-stage stochastic programming model for supply chain optimisation. The model incorporates decisions on warehouse and retailer site selection, production levels, inventory levels, and shipping quantities. Two conflicting objective functions aim to maximise the chain's total profit and minimise travel times for unsatisfied customers across multiple periods. Uncertain parameters such as demands, selling prices, and production times are considered. The ϵ-constraint method is utilised to generate a set of Pareto optimal solutions for the multi-objective problem. The study is further generalised to handle continuously distributed uncertain parameters using a simulation approach called the sample average approximation (SAA) scheme. Computational experiments involving hypothetical and real supply chain networks demonstrate the efficiency of the proposed solution methodology.

To be applicable for robust cost-minimal optimisation of the medium-term order allocation, (Buergin et al. 2019) reduce the number of scenarios through clustering. They explain an approach for the robust assignment of customer orders to periods and sites in a multi-variant series production. Various variants are considered here, which can also be configured by the customer after the order has been completed. However, it is not the quantity of the demand that is explicitly uncertain but only the configuration of the variants. The scenarios result from the possible configuration combinations of the individual orders. Due to the extremely high number of possible scenarios, the unsafe configurations per order are first summarised. For this purpose, the K-Means algorithm, which clusters configurations with a similar workload, is used. The scenarios are then combined to form stratified random samples from the clusters, considering the cluster probability. In addition, a worst-case scenario with the highest possible workload is selected. These scenarios are used in the methodology for the robust optimisation of medium-term planning with the aim of minimising costs. Validation is based on an application from aircraft construction.

Beyond the production scope, there are further approaches in the literature that address similar problems and also identify strategies to reduce a high number of scenarios. Khatami, Mahootchi & Farahani (2015) introduce a supply chain network design (SCND) methodology featuring a closed-loop, two-stage structure incorporating scenario generation. Initially, 1000 scenarios are created based on the demand probability distribution, incorporating demand correlations through Cholesky's factorisation method. The K-means algorithm is then employed to decrease the initial scenario count, determining the optimal number of representative scenarios by balancing computation time with the optimal objective value. Following this reduction, Benders' decomposition is applied to solve the modified problem.

Baringo & Conejo (2013) build scenarios for investment decisions. To do so, two approaches are applied. In the first procedure, intervals are formed with respect to both uncertainties and the frequency of occurrence of certain demand intervals. Combining these intervals results in a limited number of scenarios. In the second approach, hourly historical combinations of both uncertain parameters are taken as scenarios and clustered by a K-Means algorithm. The clusters are then characterised by their geometric centre of gravity, and the number of scenarios in the cluster defines the cluster probability.

This thesis aims to consider production needs and thereby advance state-of-the-art scenario techniques to plan only for relevant demand scenarios to be able to handle and solve them later on.

3.1.2.2 Identifying Robust Decisions within GPNs

Operations research applications often involve mathematical programming models that have noisy, erroneous, or incomplete data. To address the difficulties associated with such data, researchers typically use sensitivity analysis or stochastic programming formulations.

Mulvey, Vanderbei & Zenios (1995) were one of the founders of an approach called robust optimisation that characterises desirable properties of a solution to models when the data is described by a set of scenarios instead of point estimates. Specifically, a solution is defined as a robust solution if it remains close to optimal for all scenarios of the input data, and a model is robust if it remains almost feasible for all data scenarios. Both are essential criteria for this thesis, too. They develop a general model formulation that explicitly incorporates the conflicting objectives of solution and model robustness and compare robust optimisation with traditional approaches like sensitivity analysis and stochastic linear programming. They illustrate the issues with the classical diet problem and apply robust optimisation to several real-world applications, such as power capacity expansion, matrix balancing and image reconstruction, air-force airline scheduling, scenario immunisation for financial planning, and minimum-weight structural design.

Approaches such as the one presented by Khatami, Mahootchi & Farahani (2015) or Fattahi (2020) subsequently use Benders' decomposition to solve their problem. According to Fattahi (2020), the distributions in real-world scenarios may not be clearly defined, and only some historical data may be available. To address this issue, this study suggests a data-driven approach that uses a two-stage stochastic programming model to make robust decisions based on the moments of the available data within a defined ambiguity set. The proposed model is applied to the design of a recovery network that uses various technologies to generate power from municipal solid waste.

Robust optimisation problems with multiple objectives are consistently solved by applying a variant of the ϵ-constraint method to reduce the problem to a single-objective problem (Lotfi et al. 2021; Azaron, Venkatadri & Farhang Doost 2021; Lanza & Moser 2014). Lotfi et al. (2021) present an approach to designing a Closed-Loop Supply Chain Network that is Robust, Risk-aware, Resilient, and Sustainable (3RSCLSCND) to handle demand fluctuations caused by events such as the COVID-19 pandemic. To address this issue, they propose a two-stage robust stochastic multi-objective programming model, which includes objective functions such as cost minimisation, CO_2 emissions reduction, energy consumption reduction, and employment maximisation, with the application of Conditional Value at Risk to ensure reliability by reducing risk. The proposed model is compared to the Entropic Value at Risk and Minimax methods, and the Linear Programming (LP)-Metric method is used to solve the multi-objective problem. Due to the complexity of the model, the Lagrange relaxation and Fix-and-Optimise algorithm are utilised to find lower and upper bounds, respectively, in large-scale problems.

A lot of robust optimisation models combine their approach with the aspect of risk aversion. Many models employ a minimax approach, where only the worst-case scenario is considered. As pointed out by Mulvey, Vanderbei & Zenios (1995), modelling stochastic environments while only accounting for the worst-case outcome has been standardised in the literature despite them being exceptional cases of robust optimisation.

An entirely risk-averse model will consider equal scenario probabilities, as shown by Bertsimas & Sim (2003). Their study presents an approach to deal with data uncertainty in discrete optimisation and network flow problems. The proposed approach allows for controlling the level of conservatism in the solution and is both computationally feasible and theoretically sound. Specifically, when both the cost coefficients and the constraint data in an integer programming problem are uncertain, they suggest a robust integer problem of a slightly larger size that enables the control of conservatism in terms of probabilistic constraints.

Instead, Govindan & Fattahi (2017) investigate the deviation in model performance and outcome for such risk-averse and neutral robust objectives for all scenarios. They present a multi-stage and multi-period supply chain network design problem, where multiple commodities are produced through various production processes. The stochastic and highly variable demands are dealt with using a two-stage stochastic program. To address the stochastic demands, a Latin Hypercube Sampling (LHS) method is utilised to generate a range of scenarios, and then, a backward scenario reduction technique is used to reduce the number of scenarios. To obtain robust and risk-averse solutions, weighted mean-risk objectives using different risk measures and minimax objectives are investigated. The model's first stage decisions include determining the locations of new production sites, capacitated warehouses, and capacity levels of production processes at new production sites. The second stage, with multiple tactical periods, is considered to capture high time-variable demands in the model. Both LHS and the backward scenario reduction technique are applied to construct an efficient fan of scenarios. The proposed model's applicability is evaluated using a real-life glass supply chain.

Overall, investigating how to effectively incorporate multiple stages of decision-making and uncertainty handling within optimisation frameworks while considering the unique challenges of GPN planning presents a promising area of research.

3.1.3 Integration with the Planning Process

Designing and introducing DSS structured frameworks are crucial for assessing and enhancing organisational processes and capabilities. Further targeting at DSS in GPN planning, software tools like PSIglobal (Prestifilippo 2020), DPMN (Mourtzis, Doukas & Psarommatis 2015), OTD-NET (Liebler et al. 2013) and OptiWo (Schuh et al. 2012) highlight their capabilities in strategic planning and optimisation of GPNs. Lastly, company-specific planning tools and processes, e.g., at Daimler AG (Friese 2008) and Robert Bosch GmbH (Heinz 2006), get analysed, emphasising their roles in flexibility strategies and network planning.

One problem during the literature review was that neither of this software is open source, nor is most of it commercial software. Thus, only literature can explain their work and the methods used.

PSIglobal, published by Prestifilippo (2020), stands out as an exception because it is an advanced commercial software solution tailored for companies aiming to plan and optimise their Global Supply Chain strategically. This tool proves appropriate for organisations seeking effective management of their supply chain and GPNs, aiding in decisions like choosing new factory locations, shutting down existing warehouses, and streamlining supply chains. What sets PSIglobal apart is its ability to handle vast amounts of data and visualise future scenarios, enabling companies to make informed decisions. Technically, PSIglobal excels in integrating data from diverse sources, including ERP systems and warehouse management platforms. Its mathematical models and algorithms continually work to solve complex tasks, such as minimising transportation costs by incorporating geographical information systems (GIS). Newer algorithms that are under development are now also focusing on optimal production capacity. The software offers simulation capabilities, allowing users to dynamically assess the impact of changes in the network through "what-if" scenarios. Furthermore, PSIglobal's cloud-based infrastructure ensures seamless data processing, making it ideal for multinational corporations with extensive GPNs. This approach also facilitates effortless updates and enhancements, keeping the system technologically advanced. The software offers an interface that combines advanced features with user-friendly navigation. Users benefit from various visual representations, including interactive maps, detailed graphs, and comprehensive charts, enabling in-depth analysis of their GPN (see Figure 3-1). PSIglobal claims to be more than just a passive tool; it actively assists users in making optimal decisions through its alerting and recommendation systems. Its adaptability allows users to customise dashboards according to their specific needs. At the same time, the open architecture ensures smooth integration with other enterprise software, ensuring a seamless flow of data across platforms.

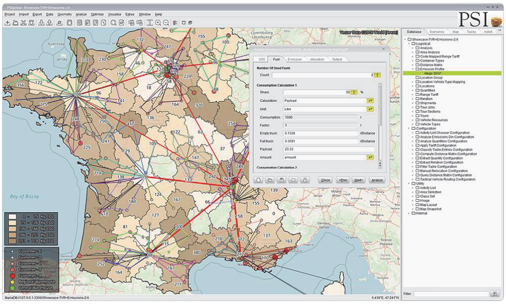


Figure 3-1: Exemplary dashboard in PSIglobal (PSIglobal 2023)

The **Design and Planning of Manufacturing Networks (DPMN)** software by Mourtzis, Doukas & Psarommatis (2015) represents a software solution consisting of various tools with the aim of determining the optimal design of GPNs capable of manufacturing individual products according to customer requirements. DPMN employs sophisticated algorithms implemented using the JAVA^{TM} framework, following the established software-as-a-service architectural pattern. The software tool is highly modular and flexible as it can be used as a standalone desktop-based module or over the web, either as a library or through web-services-based communication.

Figure 3-2: Exemplary dashboard in DPMN (Mourtzis, Doukas & Psarommatis 2015)

The software utilises tabu search, simulated annealing and intelligent search algorithms, allowing for in-depth analysis and evaluation of various manufacturing configurations. Its ability to generate and assess alternative manufacturing network setups is rooted in quantitative analysis, ensuring a systematic and data-driven decision-making process. Furthermore, DPMN incorporates geographical information systems (GIS) and employs the Google Maps API for accurate distance calculations between manufacturing plants. The software utilises coordinate-based distance calculation algorithms, especially for transatlantic transportation scenarios. These algorithms consider correction factors based on specific geographical locations, ensuring precise estimations in accordance with scientific principles. In terms of data management, DPMN relies on the MySQL relational database, an established and widely used database management system, ensuring efficient storage, retrieval, and manipulation of data. The software's use of customised XML files for data exchange follows industry standards, ensuring compatibility and reliability in scientific data communication.

The **Order-To-Delivery-NETwork Simulator (OTD-NET)** simulation tool is used by Liebler et al. (2013) to address challenges in managing complex supply chains, particularly in the automotive industry. This involves creating virtual models of real-world elements using object-oriented modelling and analysing the behaviour of these networks. The OTD-NET simulation tool includes a core simulation engine and an analysis component (OTD-Analyser) to evaluate performance metrics and cost factors. The approach helps to optimise decision-making for industries with intricate network structures and varied demands, such as the automotive sector. What is interesting here for this thesis is the object-oriented modelling, which opens up the opportunity to connect data sources smoothly.

PSIglobal's, DPMN's, and OTD-Net's focus is on the digitalisation of the supply chain and is specially designed to track the delivery of a product. As such, they offer a wide range of functions but do offer limited analysis of individual sites and their utilisation. Although they are offering algorithms for optimisation of production allocation, these functions need to be expanded. OptiWo and NetworkCapaPlanner/-Analyzer, on the other hand, focus precisely on this, and the utilisation of individual lines or stations can be analysed.

OptiWo, developed by the Laboratory for Machine Tools and Production Engineering (WZL) from RWTH Aachen, is a software tool designed for data-driven GPN evaluation as a consultancy. This advanced solution empowers production planners by integrating user-entered and operational IT system-derived data, enabling the design of cost-optimal GPNs. (Schuh et al. 2012)

The tool combines data-based analyses with expert knowledge, allowing for the simulation of the production process and transportation routes. It calculates total landed costs for configurations based on data provided about existing and potential new sites, sales regions, demand quantities, production resources, and transport routes. OptiWo's capabilities extend to detailed visualisations through a web-based data viewer developed with Java, JavaScript, and HTML (see Figure 3-3). (Schuh et al. 2014)

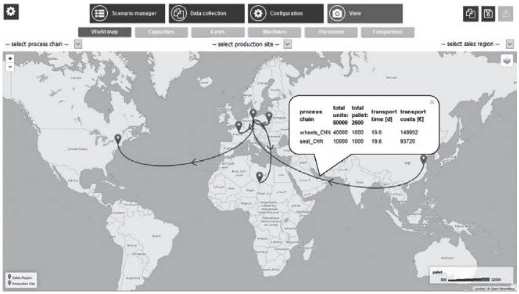


Figure 3-3: World Map visualising volumes and transportation (Schuh et al. 2019)

The data viewer offers comprehensive insights, including the 'World Map' visualisation, which illustrates financial aspects and transportation volumes between sites. Additionally, OptiWo provides a treemap display for in-depth production site details and cost breakdowns, aiding in the identification of potential savings. Users can conduct real-time sensitivity analyses, adjusting factors such as labour costs and material expenses. The tool also features a manual configurator, enabling modifications without initiating a new optimisation process. (Schuh et al. 2019)The aforementioned work by Friese (2008) made a significant impact through the creation and validation of two essential planning tools at Daimler AG: The **NetworkCapaPlanner**, designed for optimising flexibility strategies, and the **NetworkAnalyzer**, tailored for in-depth evaluations of GPNs.

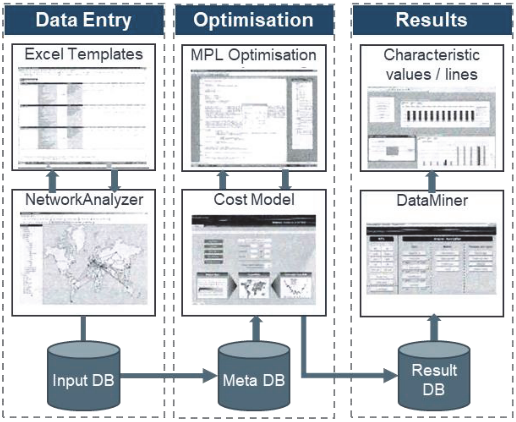


Figure 3-4: Data management and process implementation based on Friese (2008)

In the context of implementing the presented planning methodology, these two tools were developed to complement each other in functionality. They underwent validation in multiple strategic projects at Daimler AG (Friese 2008). The NetworkCapaPlanner facilitates the decision-making process for formulating flexibility strategies. The approach of flexible planning, based on a condensed state tree, is implemented using a stochastic mixed-integer optimisation model with recursion. While the NetworkCapaPlanner meets the requirements from a decision-theoretical perspective, it falls short of fulfilling all the needs of a strategic project. Specifically, operational planning areas and controlling demand a detailed breakdown of cost structures that goes beyond mere optimisation, along with the presentation of additional metrics.

Lastly, the **supported network planning process at the Robert Bosch GmbH,** as published by Heinz (2006), is described. During the data collection and preparation phase, production planners from individual plants submit data to the Network Coordination Unit (NCU), primarily through Excel files. This data includes production line capacities, measured in end-item quantities, and other information like customer releases for new part numbers, which are actively collected by the NCU. The NCU pre-processes total sales planning figures received from Market and Sales Planning (MSP). The NCU then conducts the product-mix-allocation process called the Plant Volume Allocation (PVA), representing allocated production quantities, which can be further broken down into site-specific figures. Feasibility checks for the entire network and specific geographical regions are performed. Depending on the outcomes, strategic decisions may be made, such as initiating new resources or discontinuing existing ones. The delicate planning stage incorporates data from the preceding collection and preparation activities. Planning constraints arise from system parameters, external factors, and strategic decisions. Thereby, they follow the process shown in Figure 3-5.

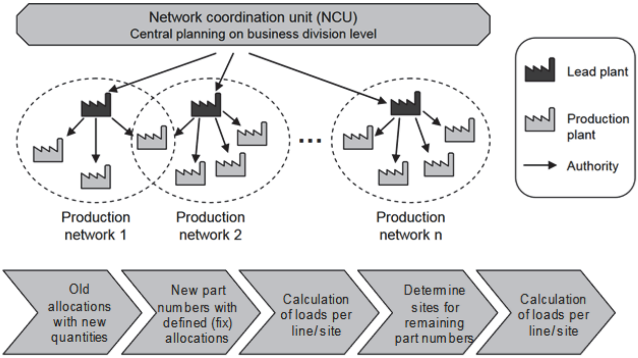


Figure 3-5: Presented PVA process by Heinz (2006)

After the PVA, the plans get visualised by the **TEK-Chart**. TEK stands for technical capacity, and it is a diagram in which the capacities of all lines of a GPN can be summarised and displayed (see Figure 3-6). It is based on spreadsheet calculations in Excel and shows, besides the standard capacities of individual lines, the accumulated reserve capacity for a defined period as stacked bars. The diagram is supplemented by lines showing the already planned demand from the last PVA process, the confirmed orders, and the actual demand containing possible orders MSP is anticipating.

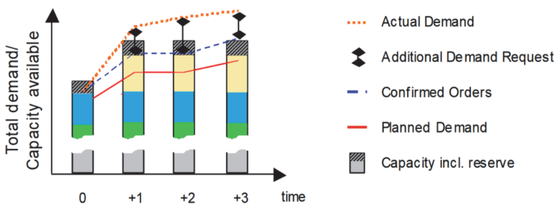


Figure 3-6: TEK-charts and tables in Excel. Coloured bars show the standard capacity of each production line based on Heinz (2006)

While most of the presented tools can cover GPNs holistically, the TEK chart has only limited functions. But, due to its simplicity and low requirement regarding the amount of data, it can be quickly and easily adapted to other networks, while for the other solutions, higher effort is to be expected. For this thesis, it is exciting, as it marks essential requirements and an initial status to ease adaption at Bosch, which will be the company under consideration later.

While the provided literature shows the application and, thus, the significance of DSS, various maturity models exist (see Appendix H) targeting topics like implementation state or data governance. A multifaceted research gap still exists in exploring comprehensive strategies for the effective introduction of DSS within an enterprise, particularly within GPN environments. This research delves into the practical steps, challenges, and best practices involved in successfully adopting and integrating DSS in GPNs, taking into consideration the design and functions of the tool itself, but also of the user experiences and training requirements.

3.1.4 Data Integration

Finally, research is first presented and, later on, analysed, which establishes interfaces to actual data sources in order to improve and support decision-making at the GPN stage.

As an often cited research, Stark, Kind & Neumeyer's (2017) conceptualisation of digital twins, characterised by digital masters and shadows, illuminates a path toward more sophisticated decision-making frameworks. This theory offers an intriguing perspective, promising a deeper understanding of complex systems. However, practical implementation encounters formidable challenges, especially when managing vast volumes of data from diverse sources and ensuring seamless alignment with the digital twin concept.

Navigating this landscape, the existing literature diverges into two fundamental trajectories: the establishment of foundational decision-making frameworks and the structuring of essential data sources. In the quest to establish these frameworks, scholars have diligently explored nuanced avenues. Schuh, Prote & Dany (2017) laid the groundwork with a foundational framework for the Internet of Production. However, questions persist regarding its real-world applicability due to its lack of specificity in models and data processing methods. This critical gap highlights the pressing need to explore the practical application of such frameworks within contemporary decision-making contexts.

Simultaneously, researchers have explored diverse methods to structure data for effective decision-making in GPNs. Gölzer et al. (2015) pioneered a significant stride by adopting a big-data approach for network configuration tasks, emphasising the intricate challenge of integrating ERP data into NoSQL databases seamlessly. They introduce an approach to improve decision-making in the design and operation of GPNs. Current methods often overlook network-wide dependencies, leading to suboptimal designs and risks. The proposed solution suggests using Big Data techniques to enable comprehensive decision-making across the entire network.

Furthermore, there is a growing emphasis on automating the generation of decision-making models. Bergmann, Straßburger & Schulze (2013) showcased the potential of automatic generation of discrete event simulation models, indicating a transformative shift toward automation and data-driven modelling in decision-making processes. They address the significance of precise simulation model initialisation in online and symbiotic simulation. These simulations serve as essential DSS, relying on accurate initial conditions for dependable predictions. Although existing literature acknowledges the importance of linking simulations with the physical system, more details are needed. A proposed solution includes utilising core manufacturing simulation data (CMSD) with required extensions and showcasing a prototype implementation.

In the domain of supply chain management, scholars have made commendable progress in disruption management. Ivanov & Dolgui (2021) harnessed information systems, optimisation, and simulation techniques to craft digital supply chain twins. They introduce the concept of a digital supply chain (SC) twin, a real-time computerised model representing network states. It investigates the design and implementation conditions of these twins in managing disruption risks within SC. Through a blend of model-based and data-driven methods, it uncovers the connections between risk data, disruption modelling, and performance evaluation. The undeniable impact of SC shocks and adaptations during the COVID-19 pandemic, as well as post-pandemic recoveries, underscores the urgent necessity of digital twins for mapping SC and ensuring visibility. The study's outcomes enhance predictive and reactive decisions in SC risk management by leveraging SC visualisation, historical disruption data analysis, and real-time disruption data and promoting end-to-end visibility and business continuity across global companies.

Simultaneously, Park, Son & Noh (2021) pioneered direct communication between network resources and products using the asset administration shell. They explore the challenges of personalised production within a make-to-order (MTO) supply chain (SC) environment. Personalised production involves dynamic fluctuations in SC operations. Such an SC requires a robust system due to redundant inventory and capacity.

However, standalone cyber-physical systems (CPS) have limitations for MTO SC control. To address this, the study proposes a coordinated cyber-physical logistics system (CPLS), integrating agent-based CPS in a multi-level architecture. This approach offers technical functionalities for robust SC control. The study introduces a distributed digital twin (DT) simulation for service composition and operation to mitigate SC-related problems like the bullwhip and ripple effects. An early CPLS case minimises asset differences via distributed DT simulation and establishes SC and production plans based on simulation outcomes.

Milde & Reinhart (2022) outline a concept designed to streamline the development of simulation models for order processing in GPN. The approach aims to optimise efficiency by allowing users to concentrate on the crucial tasks of executing and analysing simulation studies. The concept's core principles involve precisely defining, tracking, and tracing data as the primary raw input and automating data preparation, model creation, and parameterisation using dedicated algorithms. Currently, in the development stage, this approach is set to be implemented within a German car manufacturer's GPN for engine production. Future papers will detail the progress of individual module development, process implementation, and evaluation, shedding light on the practical effectiveness of this approach in real-world production scenarios.

A significant gap arises when integrating data from diverse sources within organisations to construct effective digital twins for production systems, keeping in mind that this data belongs to different areas and might be sensitive. Addressing this gap demands the development of simultaneous data acquisition from various systems into digital twins for production systems and networks. These advancements not only promise a more integrated and effective approach to decision-making in the intricate world of GPNs but also empower decision-makers with precise modelling, in-depth analysis, and informed decision-making across the entire life cycle of production systems and networks. The red thread tying these diverse threads together lies in the exploration of different data sources, understanding diverse stakeholders' perspectives, and navigating varying levels of data quality, each requiring a level of abstraction. This comprehensive exploration serves as the foundation for a unified and advanced framework, which will be explored in this thesis.

3.2 Research Deficit

	Modelling of Flexibility in GPNs	Forecasting Representative Demand Scenarios	Identifying Robust Decisions within GPNs	Solution Approach	Integration within Planning Process	Use Case	Data Integration
Section 3.1. Modeling of Flexibility in GPNs							
Hochdörffer et al. (2022)	●	◕	◑	Flexibility Constraints and Solver	◔	Aviation Industry	○
Bachlaus et al. (2008)	◕	◕	◑	Hybrid Taguchi Particle Swarm Optimization	◔	Steel Manufacturing Company	○
Lanza and Moser (2014)	●	◑	◑	Dynamic Multi-Objective Optimization	◔	Railway Industry	○
Friese (2008)	◕	◕	◑	Monte Carlo Simulation and Solver	◕	German Automobile Manufacturer	◑
Sethi and Sethi (1990)	◕	○	○	-	○	-	○
Section 3.2.1. Forecasting Representative Demand Scenarios							
Bihlmaier, Koberstein, & Obst (2009)	◑	◕	◑	Monte Carlo Simulation and Benders Decomposition	◔	Abstract Strategic Network Design Problem	○
Stähr, Englisch, & Lanza (2018)	◑	●	◑	Monte Carlo Decision Problem and Backward Induction	◔	Fuel Cell Production	○
Santoso et al. (2005)	◕	●	◑	Sample Average Approximation and Benders Decomposition	◔	Cardboard Packages Supplier	○
Khatami, Mahootchi, and Farahani (2015)	◑	●	◔	K-Means and Benders Decomposition	◔	Cell Phone Supply Chain	○
Buergin et al. (2019)	◑	●	◑	K-Means	◔	German Automobile Manufacturer	○
Baringo and Conejo (2013)	◑	●	◑	K-Means	◔	Wind-Power Production	○
Section 3.2.2. Identifying Robust Decisions within GPNs							
Mulvey et al. (1995)	◑	◔	◕	ϵ-Constraint Method and Solver		Power Capacity Expansion	○
Fattahi (2020)	◑	◕	◕	Benders Decomposition and Solver	◔	Waste Supply Chain	○
Lotfi et al. (2021)	◑	◕	◕	ϵ-Constraint Method, Lagrangian Relaxation, and Solver	◔	Automotive OEM Supply Chain	○
Govindan et al. (2017)	◑	◑	◕	Latin Hypercube Sampling and Solver	◔	Glass Supply Chain	○
Bertsimas & Sim (2003)	◑	◕	◕	Multi-Policy Approximation Scheme	○	-	○
Azaron, Venkatadri, and Farhang Doost (2021)	◑	◑	◕	Sample Average Approximation and ϵ-Constraint Method	◔	Industrial Supply Chain (unspecified)	○

	Modeling of Flexibility in GPNs	Forecasting Representative Demand Scenarios	Identifying Robust Decisions within GPNs	Solution Approach	Integration within Planning Process	Use Case	Data Integration
Section 3.3. Integration within Planning Processs							
Prestifilippo (2020)	◔	◔	◔	Solver	◕	Commercial Software	◕
Mourtzis et al. (2015)	◑	◔	◔	Tabu Search, Simulated Annealing and Intelligent Search Algorithms	◕	CNC Machine Building Sector	◑
Liebler et al. (2013)	◑	◑	◑	Heuristic Optimisation Method and Solver	◑	Automotive Sector	◕
Schuh et al. (2014)	◕	◑	◑	Genetic Algorithm / Evolutionary Algorithm	◕	Medium-Sized Company	◑
Heinz (2006)	◑	○	○	-	●	Automotive Supplier	◔
Section 3.4. Data Integration							
Schuh, Prote & Dany (2017)	○	○	○	Framework Internet of Production	◔	-	◕
Gölzer et al. (2015)	◔	◔	◔	Core Manufacturing Simulation Data Standard	◔	-	◕
Bergman et al. (2011)	◔	○	○	Automatic Generation of Event Discrete Simulation	◔	-	◕
Ivanov and Dolgui (2021)	◔	◑	◑	Digital Supply Chain Twin	○	Fictive GPN exiting COVID-19 Pandemic	◕
Park et al. (2021)	◔	○	○	Asset Administration Shell	◔	Personalised Production	◕
Milde and Reinhardt 2022	◔	◑	◑	Automatic Generation of Event Discrete Simulation	◔	German Automobile Manufacturer	◕

Table 3-1: Summary of discussed literature

The provided literature review identifies several research gaps across different aspects of production systems, decision support systems, and data-based decision-making in the context of Global Production Networks (GPNs).

Flexibilities within the Network Model: The research gap here refers to the insufficient attention in the literature to find appropriate solutions that simultaneously consider both volume and product-mix flexibility in production systems.

Solution Robustness: The research gap involves the difficulty in deciding the number of scenarios in stochastic models and the need for effective methods to condense information from multiple scenarios into fewer ones for robust, cost-minimal decisions.

Integration of Decision Support Systems in the Planning Process: The research gap pertains to the insufficient in-depth exploration into practical steps, challenges, and best practices for successfully adopting and integrating DSS in GPNs, considering various aspects such as design, user experiences, training, data governance, and organisational change management.

Data Integration: The research gap involves the challenge of integrating data from diverse sources within organisations to construct effective digital twins for GPNs, emphasising the need for methodologies and strategies for data acquisition and integration in GPN decision-making contexts.

The following research questions match these research gaps and will be focussed on this thesis.

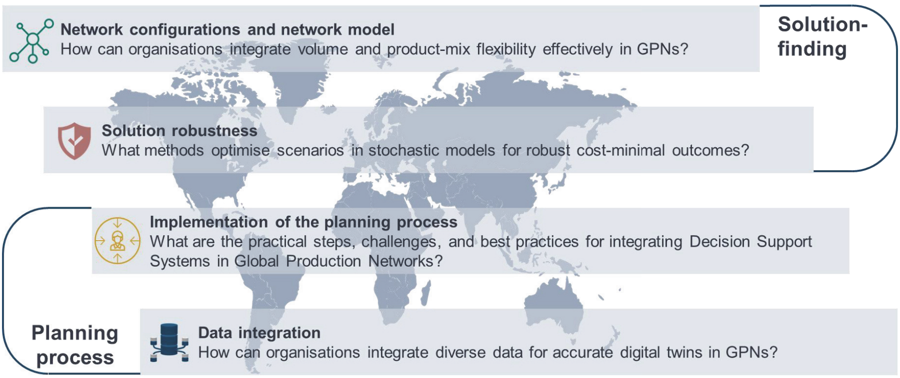


Figure 3-7: Derived research questions

4 Framework for DSS to Identify Robust Decisions in GPN

The following approach is structured into a generalised optimisation framework in Chapter 4, which is independent of the actual use case and the company-specific implementation in Chapter 5 following Figure 4-1. The colours highlight that while the first two research questions concerning the flexibilities within the network model and the identification of robust solutions will be targeted mainly by the framework, the second two research questions concerning the integration of the DSS in the planning process as well as the data integration will be tackled during the concrete implementation in an actual use case at Bosch.

On the other hand, Figure 4-1 also shows the implementation of the digital twin following the definition of Stark, Kind & Neumeyer (2017). First, in Section 4.1, a generalised model is designed as a digital master, which is an abstract description of a GPN. Then, the semi-automated robust feedback is first designed and then implemented in Sections 4.2.2-5.1. The digital shadow, representing all data related to a concrete GPN over its entire life cycle, gets logically linked with the digital master by developing a data model and implementing its connection to the related databases in Section 5.4 as well as cross-functional interfaces, e.g. to logistics in Section 5.6. The remaining Sections 5.2-5.3 regarding the organisational concept and the development of a user interface, as well as the result presentation in Section 5.5, advance this digital twin to a decision support system for the optimisation of GPN.

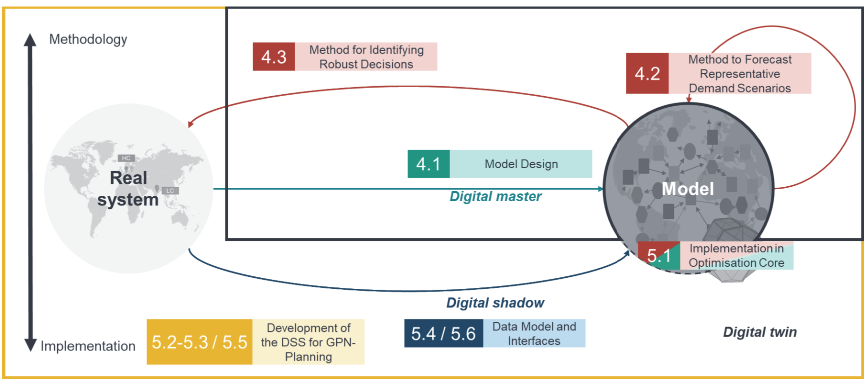


Figure 4-1: Steps of the framework for DSS to identify robust decisions in GPN

4.1 Model Design

To offer a complete framework for DSS to identify robust decisions in GPN as described above, first, the model design, second, the method to forecast representative production demand scenarios, and third, the method to find robust decisions depending on the risk aversion of the decision maker are presented. Involved in the model development were the student projects (A_Foran 2023; A_Hartmann 2021; A_Hemeury 2021; A_Rädler 2020; A_Bouzidi 2022; A_Delkof 2021; A_Voelkle 2020; A_Sachsenweger 2022; A_Küppers 2020) which the author of this thesis supervised.

Each site in the GPN of a particular product consists of several production lines. Each line has a nominal capacity boundary corresponding to regular working shifts. By utilising additional shifts and incurring corresponding costs, line capacity can be extended up to an absolute capacity boundary. Product variants require specific technical production capabilities called features. Each line has specific existing features as well as the possibility to purchase additional features through upgrades. The upgradeability differs for each line since not all technical specifications can be installed and combined on every line. Customer orders may be produced on any line that possesses the necessary set of features. A production line may be shut down to save fixed costs. Similarly, new production lines may be constructed if utilisation exceeds capacity on existing lines to a certain degree. In addition to line features that are technically required for production, production can only take place if the product customer has inspected the line for the fulfilment of quality requirements and issues a line release. This release mechanism applies to entire production sites as well, necessitating both line and site releases to enable production. Any release can be initiated by purchasing the release for a specified price.

After production, finished goods are packaged and shipped either directly to the customer or to an intermediate warehouse to fulfil the specific order issued by the customer, incurring outbound logistics costs. To incorporate volume and product-mix flexibility, sites possess outbound and inbound flexibility metrics. Outbound flexibility is defined as the production volume that is anticipated to be produced at the site under consideration but could also be produced at another site. Inbound flexibility is defined by the production volume that the site under consideration would be able to take over from another site. For applicability in real GPNs, hard strategic constraints need to be considered, e.g., site contracts assuring a specific volume of produced products at a site.

As these constraints are non-negotiable, techniques that find near-optimal solutions while considering consistently changing hard constraints were focused on. Exact models have a distinct advantage over heuristics in terms of applicability. They possess the ability to automatically adapt to diverse decision variables and accommodate changing goals, constraints, and complexities prevalent in changing settings. The aspects considered allow for a linear mapping of the optimisation problem. Facing a complex combinatorial problem with numerous discrete decisions, the model is constructed as a Mixed-Integer Linear Programming (MILP), accepting a near-optimal solution gap of 1%. The model was published by Brützel et al. (2021), although the current model is subject to further development.

4.1.1 Sets

The following will introduce the most important sets regarding the formulation of the model. A list of all sets can be found in the Abbreviations and Symbols.

Table 4-1: Excerpt of most important sets

Sets	Index	Description	Unit
F	f	Set of possible line features	
L	l	Set of production lines (existing & new)	
O	o	Set of orders	
$\tilde{O}$	$\tilde{o}$	Set of sister orders	
S	s	Set of manufacturing sites	
$\tilde{S}$	$\tilde{s}$	Set of preprocessing sites	
T	t	Set of time periods	Half Year
V	v	Set of preprocesses	
Γ	γ	Set of triads	
Ω	ω	Set of demand scenarios	

Formally, production sites $s \in S$ are composed of production lines $l \in L$ that receive and produce orders $o \in O$ over discrete time periods in a planning horizon $t \in T$ and are located in a triad $\gamma \in \Gamma$. Note that a single order may span multiple periods, incurring different production volumes in each period. Production lines may possess or be upgraded to possess features $f \in F$. Pre-processing sites $\tilde{s} \in \tilde{S}$ and the pre-processing orders $v \in V$ that are required to fulfil orders to enable the modelling of inbound logistics costs. Every order entails an explicit set of 'sister orders' $\tilde{o} \in \tilde{O}_o$. The sister orders are those produced for the same customer and product, corresponding to these orders sharing the same required customer release. The joint optimisation respecting different demand scenarios is introduced by denoting these as $\omega \in \Omega$.

4.1.2 Parameters

The parameters that capture the characteristics of the GPNs are described in Abbreviations and Symbols. Those parameters requiring a more detailed description are presented next. Individual realisations of the uncertain parameter of demand are represented for each order o in period t of scenario ω with volume $\eta_{o,t,\omega}$. Scenario probability weights $p_{\omega}^{ScenarioAd}$ are introduced to account for the likelihood of a demand scenario occurring. Capacities are modelled as production time $k_{l,t}^{standard,existing}$ on line *l* in period *t*. The production cycle time (CT) parameter $\varrho_{o,l,t}$ adjusts the nominal CT $\zeta_{o,l,t}$ by the relative decrease through learning effects for later periods $\psi_{o,l,t}$ in 3:

$$\varrho_{o,l,t} = \zeta_{o,l,t} \cdot \prod_{t \in T} \left(1 - \frac{\psi_{o,l,t}}{100}\right) \qquad 3$$

4.1.3 Variables

The following will introduce the most important variables to be optimised. A list of all variables can be found in the Abbreviations and Symbols. In the context of order fulfilment, $q_{o,l,t,\omega}$ denotes the allocated production volume in pieces of an order *o* to a line *l* in period *t* and scenario ω, which is transformed as the corresponding utilised capacity $\upsilon_{o,l,t,\omega}$ measured in time units, which are described by constraint 15 and 16. Binary variables get used for investment decisions, such as $e_{l,t,\omega}$ for constructing new lines, $u_{l,f,t,\omega}^{receiving}$ for lines that acquire features *f,* or $z_{l,t,\omega}$ for considering whether line *l* in period *t* and scenario ω is active for production. Furthermore, customer releases on lines $y_{o,l,\omega}^{line}$ and sites $y_{o,s,\omega}^{facility}$ can be acquired. Based on the defined minimum values for inbound and outbound flexibility, the solver invests in certain order groups to introduce the shipment through warehouses, making them flex types $y_{o,\omega}^{flex}$, which means these orders are servable from different sites. The produced volume of these flex types is declared as the flexible volume $q_{o,s_1,s_2,t,\omega}^{flex}$, where s_1 denotes the nominal site and s_2 the available alternative. If an order cannot be produced at $s_2 \in S$, the flexible volume is automatically zero. From the variable describing the produced volume $q^{flex}_{o,s_1,s_2,t,\omega}$, the inbound and outbound flexibility are calculated. This is described in the formulas 33-40.

4.1.4 Objective Function

The MILP model entails a minimisation objective function consisting of individual cost components where c denotes the accordingly defined cost factor and p'_ω the weight for scenario probability. The model rewards delayed monetary flows by multiplying the incurred upgrading costs with the internal interest rate i^r_l.

$$min \sum_{\omega \in \Omega} p^{ScenarioAd}_{\omega} \cdot \left(\sum_{t \in T} \frac{1}{(1+i^r_l)^t} \cdot \left(\sum_{o \in O} \sum_{l \in L} v_{o,l,t,\omega} \cdot c^{variable}_l \cdot \left(1+i^{wage}_l\right)^t \right.\right. \quad 4$$

$$+ \sum_{l \in L} \delta^{overutilization}_{l,t,\omega} \cdot c^{overutilization}_l \cdot \left(1+i^{wage}_l\right)^t \quad 5$$

$$+ \sum_{l \in L} \delta^{underutilization}_{l,t,\omega} \cdot c^{underutilization}_l \cdot \left(1+i^{wage}_l\right)^t \quad 6$$

$$+ \sum_{l \in L} z_{l,t,\omega} \cdot c^{fixed}_l \quad 7$$

$$+ \sum_{v \in V} \sum_{\tilde{s} \in \tilde{S}} \sum_{s \in S} \rho_{v,\tilde{s},s,t,\omega} \cdot c^{inbound}_{\tilde{s},s,v,t} \quad 8$$

$$+ \sum_{o \in O} \sum_{l \in L} q_{o,l,t,\omega} \cdot c^{outbound}_{o,l,t} \quad 9$$

$$+ \sum_{l \in L} \sum_{f \in F} u^{receiving}_{l,f,t,\omega} \cdot c^{feature,existing}_{l,f} \quad 10$$

$$\left. \sum_{l \in L} e_{l,t,\omega} \cdot \left(c^{build} + c^{feature,new}_l\right) \right) \quad 11$$

$$+ \sum_{o \in O} \sum_{l \in L} y^{line}_{o,l,\omega} \cdot c^{releaseline}_{o,l} + \sum_{o \in O} \sum_{s \in S} y^{facility}_{o,s,\omega} \cdot c^{releasefacility}_{o,s} \quad 12$$

$$\left. + \sum_{o \in O} y^{flex}_{o,\omega} \cdot c^{flexible}_o \right) \quad 13$$

In 4, variable costs of lines $c_l^{variable}$ are considered for the required production duration of orders $v_{o,l,t,\omega}$ and multiplied by the annual expected cost increase for production. This is mostly dependent on the wage increase parameter i_l^{wage}.

In 5, the summation involves the costs $c_l^{overutilization}$ incurred from capacity utilisation exceeding the available standard capacity $\delta_{l,t,\omega}^{overutilization}$ for each line in each period.

In 6, the summation involves the costs $c_l^{underutilization}$ incurred from available standard capacity exceeding the utilised capacity $\delta_{l,t,\omega}^{underutilization}$ for each line in each period.

For active lines $z_{l,t,\omega}$, fixed costs specific to that line c_l^{fixed} are incurred in 7. These costs are applied period-wise and are not dependent on the amount of production.

In 8, inbound logistics costs $c_{\tilde{s},s,v,t}^{inbound}$ are considered for the sites s receiving semi-finished goods v that have been produced in a pre-processing site $\tilde{s}$. The inbound logistics costs per unit are multiplied periodically by the volume $\rho_{v,\tilde{s},s,t,\omega}$ of pre-processing units shipped.

In 9, the summation involves the multiplication of production quantities $q_{o,l,t,\omega}$ with the individual outbound logistics costs $c_{o,l,t}^{outbound}$ depending on the line.

In 10, the summation involves upgrading costs $c_{l,f}^{feature,existing}$ for the period in which a feature upgrade is purchased $u_{l,f,t,\omega}^{receiving}$ for an existing line.

In 11, the summation involves costs for the decision of building a new line $e_{l,t,\omega}$. This includes general costs for the building project itself c^{build} and cost for installing the needed features during the building of the line $c_l^{feature,new}$.

In 12, the summation involves the release costs for lines $c_{o,l}^{releaseline}$ and sites $c_{o,s}^{releasefacility}$ for the respective orders. Since the effect of the releases on the total cost is considered low, but the number of individual binary variables is very high (since it depends on *o*), a period-specific consideration is dispensed in favour of shortening the calculation time for the purchase variables $y_{o,l,\omega}^{line}$ and $y_{o,s,\omega}^{facility}$.

In 13, the summation involves the decision of the implementation of flex types $y_{o,\omega}^{flex}$, which are planned to be served from different sites in parallel. Additional costs arise because if an order should be served from two sites in parallel, these must be served from a joint warehouse, which needs to be planned as an additional investment $c_o^{flexible}$.

4.1.5 Constraints

The model is subject to constraints, which constitute its solution space. The following subsection explains these constraints. Equation 14 guarantees that the production volume $q_{o,l,t,\omega}$ equals demand $\eta_{o,t,\omega}$, ensuring demand is always fulfilled.

$$\sum_{l \in L} q_{o,l,t,\omega} = \eta_{o,t,\omega} \qquad \forall o \in O, t \in T, \omega \in \Omega \tag{14}$$

In 15, the production duration for orders $\upsilon_{o,l,t,\omega}$ must match the production quantity $q_{o,l,t,\omega}$ multiplied by the CT $\varrho_{o,l,t}$ adjusted by the equipment effectiveness of existing lines $\theta_{l,t}^{existing}$. Big-M is utilised to set this constraint inactive for new lines, where $e_{l,t,\omega} = 1$, since it ensures the right-hand side term to become negative, if the line was newly built in any period *t*. Note that $\theta_{l,t}^{existing}$ is the individual utility rate of the specific line.

$$\upsilon_{o,l,t,\omega} \geq q_{o,l,t,\omega} \cdot \frac{\varrho_{o,l,t}}{\theta_{l,t}^{existing}} - M \cdot \sum_{t \in T} e_{l,t,\omega} \qquad \forall o \in O, l \in L, \omega \in \Omega \tag{15}$$

In 16, the production duration for orders $\upsilon_{o,l,t_1,\omega}$ is set to match the CT ϱ_{o,l,t_1} of production volumes $q_{o,l,t_1,\omega}$ adjusted by the equipment effectiveness of new lines θ_{l,t_2}^{new}. Big-M guarantees this constraint becomes active only when considering lines that are built in period t_1-t_2.

$$\upsilon_{o,l,t_1,\omega} \geq q_{o,l,t_1,\omega} \cdot \frac{\varrho_{o,l,t_1}}{\theta_{l,t_2}^{new}} - M \cdot \left(1 - e_{l,t_1-t_2,\omega}\right) \\ \forall t_1, t_2 \in T, o \in O, l \in L, t_1 \geq t_2, \omega \in \Omega \tag{16}$$

In 17 it is incurred, that production requires an active line $z_{l,t,\omega}$, where the right-hand side becomes 0, if $z_{l,t,\omega} = 0$, correspondingly setting $q_{o,l,t,\omega}$ to 0.

$$q_{o,l,t,\omega} \leq z_{l,t,\omega} \cdot \eta_{o,t,\omega} \qquad \forall o \in O, l \in L, t \in T, \omega \in \Omega \tag{17}$$

In 18, lines remain inactive $z_{l,t,\omega}$ if the line was inactive in the preceding period $z_{l,t-1,\omega}$ and the line is not being opened in the current period $e_{l,t,\omega}$. A line cannot be re-activated since a shutdown often results in deconstruction to utilise the space for other production lines.

$$z_{l,t,\omega} \leq z_{l,t-1,\omega} + e_{l,t,\omega} \qquad \forall l \in L, t \in T, t > 0, \omega \in \Omega \tag{18}$$

In 19 it is ensured, that allocating production volume $q_{o,l,t,\omega}$ is only possible if all required features for the order $\iota_{o,f}$ are available at the line $u^{existing}_{l,f,t,\omega}$.

$$q_{o,l,t,\omega} \cdot \iota_{o,f} \leq u^{existing}_{l,f,t,\omega} \cdot \eta_{o,t,\omega} \qquad \forall o \in O, l \in L, t \in T, f \in F, \omega \in \Omega \qquad 19$$

In 20, $u^{existing}_{l,f,t,\omega}$ can only become 1 if either the feature was initially available at a line $d_{l,f}$, the feature upgrade had been available in the previous period $u^{existing}_{l,f,t-1,\omega}$ or the feature upgrade was purchased in the current period $u^{receiving}_{l,f,t,\omega}$. For the initial period of $t = 0$, prior periods are not considerable.

$$u^{existing}_{l,f,t,\omega} \leq \begin{cases} d_{l,f} + u^{existing}_{l,f,t-1,\omega} + u^{receiving}_{l,f,t,\omega}, & \text{if } t > 0 \\ d_{l,f} + u^{receiving}_{l,f,t,\omega}, & \text{if } t = 0 \end{cases} \qquad 20$$
$$\forall l \in L, f \in F, t \in T, \omega \in \Omega$$

In 21, a line release is ensured to be available for production. Parameter μ enables or disables the consideration of sister orders in this constraint. Existing releases for an order and its sister orders are taken into consideration with $r^{line}_{o,l}$ and $r^{line}_{\tilde{o},l}$, respectively. If a release for the order is already available, the right-hand side of the inequation becomes 0, based on the minimisation in the goal function. If there is no release for the order available yet, a release is purchased $y^{line}_{\tilde{o},l,\omega}$ if there is also neither an existing release $r^{line}_{\tilde{o},l}$ nor a purchased release $y^{line}_{\tilde{o},l,\omega}$ for any sister order.

$$\left(y^{line}_{\tilde{o},l,\omega} + \mu \cdot \sum_{\tilde{o} \in \tilde{O}_o} r^{line}_{\tilde{o},l} + y^{line}_{\tilde{o},l,\omega} \right) \cdot \eta_{o,t,\omega} \geq \left(1 - r^{line}_{o,l}\right) \cdot q_{o,l,t,\omega} \qquad 21$$
$$\forall o \in O, l \in L, t \in T, \omega \in \Omega$$

In 22 it is ensured, that the customer release for a line $r_{o,l}^{line}$ requires the customer release for the site $r_{o,s}^{facility}$. Again, releases for sister orders are considered with $r_{\tilde{o},l}^{line}$ and $y_{\tilde{o},l,\omega}^{line}$ as well as $r_{\tilde{o},s}^{facility}$ and $y_{\tilde{o},s,\omega}^{facility}$. Whether a line belongs to a site is indicated by $b_{l,s}$. Parameter μ is applied to disable redundant release purchasing for sister orders. Big- M is used to ensure that only one site release is necessary for multiple lines at one site, which are released.

$$\left(y_{o,l,\omega}^{line} + r_{o,l}^{line} + \mu \sum_{\tilde{o} \in \tilde{O}_o} \left(r_{\tilde{o},l}^{line} + y_{\tilde{o},l,\omega}^{line} \right) \right) \cdot b_{l,s} \leq \left(y_{o,s,\omega}^{facility} + r_{o,s}^{facility} + \mu \sum_{\tilde{o} \in \tilde{O}_o} \left(r_{\tilde{o},s}^{facility} + y_{\tilde{o},s,\omega}^{facility} \right) \right) \cdot M$$ 22

$$\forall o \in O, l \in L, s \in S, \omega \in \Omega$$

In 23, it is ensured that capacities are available when allocating production volumes. Therefore, the sum of production quantities of a period $q_{o,l,t_1,\omega}$ multiplied by the respective CT ϱ_{o,l,t_1} must be less or equal to the corresponding available maximum line capacity in this period. When allocating production volumes to an existing line, the maximum capacity of this line $k_{l,t_1}^{maximum,existing}$, adjusted by the overall equipment effectiveness for existing lines $\theta_{l,t_1}^{existing}$, can not be exceeded. Once production volumes are allocated to a newly built line, θ_{l,t_2}^{new} must be employed to the maximum capacity of the new line $k_{l,t_2}^{maximum,new}$, since new lines exhibit much lower operational efficiency as existing lines. This means for any period t_1, where t_2 indicates the distance to the period $t_1 - t_2$ in which the new line is opened, the capacity of this line adheres to the operational efficiency of new lines θ_{l,t_2}^{new}. The model is confronted with a dynamically shifting variable θ_{l,t_2}^{new} that is directly dependent on the manifestation of $e_{l,t,\omega}$.

$$\sum_{o \in O} q_{o,l,t_1,\omega} \cdot \varrho_{o,l,t_1} \leq \sum_{t_2 \in T} k_{l,t_2}^{max,new} \cdot \theta_{l,t_2}^{new} \cdot e_{l,t_1-t_2,\omega} + k_{l,t_1}^{max} \cdot \theta_{l,t_1}^{existing}$$ 23

$$\forall l \in L, t_1 \in T, t_2 \in T, t_1 \geq t_2, \omega \in \Omega$$

Closely following the logic of 23, where the capacity and equipment effectiveness of new and existing lines are considered separately, the required production duration of an order on a line gets subtracted from the capacity of the line to determine the underutilisation $\delta_{l,t_1,\omega}^{underutilization}$ in 24 and the overutilisation of a line $\delta_{l,t_1,\omega}^{overutilization}$ in 25.

$$\delta_{l,t_1,\omega}^{underutilization} \geq k_{l,t_1}^{standard,existing} \cdot \theta_{l,t_1}^{existing} \cdot z_{l,t_1,\omega} + \sum_{t_2 \in T} k_{l,t_2}^{standard,new} \cdot \theta_{l,t_2}^{new} \cdot e_{l,t_1-t_2,\omega} - \sum_{o \in O} q_{o,l,t_1,\omega} \cdot \varrho_{o,l,t_1} \quad \forall l \in L, t_1 \in T, t_2 \in T, t_1 \geq t_2, \omega \in \Omega \qquad 24$$

$$\delta_{l,t_1,\omega}^{overutilization} \geq \sum_{o \in O} q_{o,l,t_1,\omega} \cdot \varrho_{o,l,t_1} - (k_{l,t_1}^{standard,existing} \cdot \theta_{l,t_1}^{existing} \cdot z_{l,t_1,\omega} + \sum_{t_2 \in T} k_{l,t_2}^{standard,new} \cdot \theta_{l,t_2}^{new} \cdot e_{l,t_1-t_2,\omega}) \quad \forall l \in L, t_1 \in T, t_2 \in T, t_1 \geq t_2, \omega \in \Omega \qquad 25$$

In 26, it is ensured that pre-process volumes $\rho_{v,\tilde{s},s,t,\omega}$ equal the order volumes $q_{o,l,t,\omega}$ if a pre-process is required. $\chi_{o,v}$ is 1 if a preprocess v is required for an order o, and 0 otherwise.

$$\sum_{\tilde{s} \in \tilde{S}} \rho_{v,\tilde{s},s,t,\omega} = \sum_{o \in O} \sum_{l \in L} q_{o,l,t,\omega} \cdot \chi_{o,v} \cdot b_{l,s} \quad \forall v \in V, s \in S, t \in T, \omega \in \Omega \qquad 26$$

In 27, it is ensured that the required pre-process volume $\rho_{v,\tilde{s},s,t,\omega}$ does not exceed the available production capacity of the pre-processing site $k_{v,\tilde{s},t}^{preprocess}$.

$$\sum_{s \in S} \rho_{v,\tilde{s},s,t,\omega} \leq k_{v,\tilde{s},t}^{preprocess} \quad \forall v \in V, \tilde{s} \in \tilde{S}, t \in T, \omega \in \Omega \qquad 27$$

In 28, the decision maker gets enabled to neglect the assignment of orders to specific sites for all periods by setting the binary variable $m_{o,s,t} = 0$.

$$\sum_{l \in L} q_{o,l,t,\omega} \cdot b_{l,s} \leq \eta_{o,t,\omega} \cdot m_{o,s,t} \quad \forall o \in O, s \in S, t \in T, \omega \in \Omega \qquad 28$$

In 29, $x_{o,s,t}$ enables the definition of a minimum volume of orders and corresponding sister orders to specific location.

$$\sum_{\tilde{o} \in \tilde{O}} \sum_{l \in L} q_{\tilde{o},l,t,\omega} \cdot b_{l,s} + \sum_{l \in L} q_{o,l,t,\omega} \cdot b_{l,s} \geq \sum_{\tilde{o} \in \tilde{O}} x_{\tilde{o},s,t} + x_{o,s,t} \quad \forall o \in O, s \in S, t \in T, \omega \in \Omega \qquad 29$$

In addition, 30 and 31 implement that the model can ensure that a facility receives a minimum production volume $w_{s,t}^{facility}$ and that a triad is served by a minimum share $w_{\gamma,t}^{triad}$ locally within the triad.

$$\sum_{o\in O}\sum_{l\in L} q_{o,l,t,\omega}\cdot b_{l,s} \geq w_{s,t}^{facility} \quad \forall o\in O, s\in S, t\in T, \omega\in\Omega \tag{30}$$

$$\sum_{o\in O}\sum_{l\in L}\sum_{s\in S} q_{o,l,t,\omega}\cdot b_{l,s}\cdot \kappa_{s,\gamma}\cdot \varsigma_{o,\gamma} \geq w_{\gamma,t}^{triad}\cdot\sum_{o\in O}\eta_{o,t,\omega}\cdot \varsigma_{o,\gamma} \quad \forall\gamma\in\Gamma, t\in T, \omega\in\Omega \tag{31}$$

In 32, it is ensured that an order can only be declared as a flex type $y_{o,\omega}^{flex}$ if releases for two different locations are existing $r_{o,s}^{facility}$ or purchased $y_{o,s,\omega}^{facility}$.

$$2\cdot y_{o,\omega}^{flex} \leq \sum_{s\in S} r_{o,s}^{facility} + \sum_{s\in S} y_{o,s,\omega}^{facility} \quad \forall\, o\in O, \omega\in\Omega \tag{32}$$

Volume and product-mix flexibility are combined at the site level by implementing KPIs for outbound and inbound flexibility. Three constraints determine the flexible production volume $q_{o,s_1,s_2,t,\omega}^{flex}$. Formula 33 specifies that the flexible production volume of an order must not be greater than the volume produced at that location. In 34-36, the parameter M is used to specify that the volume produced is deemed flexible if the corresponding order is declared as a flextype and the corresponding releases are available.

$$q_{o,s_1,s_2,t,\omega}^{flex} \leq \sum_{l\in L} q_{o,l,t,\omega}\cdot b_{l,s_1} \quad \forall\, o\in O, s_1, s_2\in S, \mathrm{t}\in T, \omega\in\Omega \tag{33}$$

$$q_{o,s_1,s_2,t,\omega}^{flex} \geq \sum_{l\in L} q_{o,l,t,\omega}\cdot b_{l,s_1} - M\cdot\left(2-\left(y_{o,s_2,\omega}^{facility} + r_{o,s_2}^{facility}\right) - y_{o,\omega}^{flex}\right) \tag{34}$$

$$\forall\, s_1, s_2\in S, t\in T, o\in O, \omega\in\Omega$$

$$q_{o,s_1,s_2,t,\omega}^{flex} \leq M\cdot y_{o,\omega}^{flex} \;\forall\, s_1, s_2\in S, \mathrm{t}\in T, o\in O, \omega\in\Omega \tag{35}$$

$$q_{o,s_1,s_2,t,\omega}^{flex} \leq M\cdot\left(y_{o,s_2,\omega}^{facility} + r_{o,s_2}^{facility}\right) \forall\, s_1, s_2\in S, \mathrm{t}\in T, o\in O, \omega\in\Omega \tag{36}$$

In 37 and 38, the inbound flexibility $f_{s_1,t,\omega}^{inbound}$ and the outbound flexibility $f_{s_1,t,\omega}^{outbound}$ are calculated. In 39 and 40, the lower bounds $f_s^{mininbound}$ and $f_s^{minoutbound}$, which the planner can define, is applied for the existing in- and outbound flexibility.

$$f_{s_1,t,\omega}^{outbound} = \sum_{s_2\in S}\sum_{o\in O} q_{o,s_1,s_2,t,\omega}^{flex} - \sum_{o\in O} q_{o,s_1,s_1,t,\omega}^{flex} \;\forall\, s_1\in S, t\in T, \omega\in\Omega \tag{37}$$

$$f_{s_1,t,\omega}^{inbound} = \sum_{s2\in S}\sum_{o\in O} q_{o,s_2,s_1,t,\omega}^{flex} - \sum_{o\in O} q_{o,s_1,s_1,t,\omega}^{flex} \quad \forall\, s_1\in S, t\in T, \omega\in\Omega \tag{38}$$

$$f_{s,t,\omega}^{inbound} \geq f_s^{mininbound}\cdot\sum_{o\in O}\sum_{l\in L} q_{o,l,t,\omega}\cdot b_{l,s} \quad \forall\, s\in S, t\in T \tag{39}$$

$$f_{s,t,\omega}^{outbound} \geq f_s^{minoutbound}\cdot\sum_{o\in O}\sum_{l\in L} q_{o,l,t,\omega}\cdot b_{l,s} \quad \forall\, s\in S, t\in T \tag{40}$$

4.2 Method to Forecast Representative Production Demand Scenarios

To obtain qualitative scenarios, the approach described in Bruetzel et al. (2022) is applied, where a scenario generation methodology has been developed specifically for the optimisation model. The approach entails three core operations:

- Identify demand change drivers and their individual effects on demand volumes.
- Generate many demand scenarios by applying a Monte-Carlo simulation, which simulates the occurrences of change drivers.
- Reduce the number of scenarios with the principle component analysis and the K-Means algorithm to obtain a manageable scenario set.

4.2.1 Identifying Change Drivers

Scenario generation relies on the predictions of market researchers. First, the expected demand volumes for individual products are estimated. Additionally, individual corporate and market developments are predicted, and their expected effect on the existing demand forecast for individual products or product groups is estimated. These market effects are referred to as demand change drivers. A change driver consists of the information listed in Table 4-2. Each data point listed is included in the provided change driver forecast.

Table 4-2: Explanation of change drivers

Change Parameter	Indication
Reference	Defines the affected category and instance. Possible categories are order, customer, region, or variant, whereas instance defines the manifestation.
Probability (p_c^{Change})	The occurrence probability of the change driver.
Influence (I_c)	The percentage by which demand is increased or decreased, should the change driver occur.
Earliest period of entry (T_c^{Low})	The lower bound of the affected period range.
Latest period of end (T_c^{Up})	The upper bound of the affected period range.
Dependency	Describes how change drivers affect each other up to mutual exclusivity or condition. Therefore, keys must be defined and set for dependent orders.

4.2.2 Monte Carlo Simulation

A Monte Carlo simulation is applied to simulate the effects of change drivers on the forecasted demand volumes. For generating a particular demand scenario $\tilde{\omega}$, the simulation process randomly iterates through the list of change drivers and generates random values within the defined bounds of the following three stochastic parameters for each change driver C. The realisation of the first stochastic parameter $X_{\widetilde{\omega},C} \in \mathbb{R}|0 \leq X_{\widetilde{\omega},c} \leq 1$ determines whether the change driver occurs. If the stochastic parameter is within the probability space p_c of the change driver, $X_{\widetilde{\omega},c} \leq p_c$, the change driver occurs. In this case two further stochastic parameters $Y_{\widetilde{\omega},c}$ and $Z_{\widetilde{\omega},c}$ are generated, to determine the period of entry and the period of end in which the change driver takes effect. The period of entry is defined by the realisation of $Y_{\widetilde{\omega},c}$, within bounds $Y_{\widetilde{\omega},c} \in \left[T_c^{Low}, T_c^{Up}\right]$. Y is then set as the new lower bound for the realisation of the stochastic parameter that determines the period of end $Z_{\widetilde{\omega},c}$, where $Z_{\widetilde{\omega},c} \in \left[Y_{\widetilde{\omega},c}, T_c^{Up}\right]$. The demand volumes of the orders affected by the change driver are adjusted by the influence of the change driver I within the generated period bounds accordingly, where $(I_c \in [-1, \infty]$. Mutual exclusivity or condition of a change driver is enabled through the dependency parameter, once one of these change drivers occurs. The process is repeated 100,000 times leading to as many scenarios $\overline{\Omega}$ before the scenario reduction method is applied.

4.2.3 Scenario Reduction

Finally, the large set of scenarios $\overline{\Omega}$ is reduced to a manageable set of representative scenarios Ω equal to the amount of desired clusters K, which may be decided upon by the decision maker. Differing demand volumes directly influence the decision variables of the model. Moreover, demand reductions may change capacity utilisation. This means the cumulation of scenarios in the large scenario set entails specific characteristics before optimisation. Some relatively intuitive characteristics include periodic demand, product-specific demand, customer-specific demand, and country-specific demand. These must be respected and maintained when performing scenario reduction. Therefore, finding a reduced set of scenarios that resembles the diverging characteristics of the individual scenarios within the large scenario set is a non-trivial task. These characteristics can be described as a feature vector for each scenario, with the vector dimension equalling the number of possible linear combinations of decision variable parameters. Since this results in a very high-dimensional vector, the approach applies a principal component analysis (PCA) to reduce the dimensionality while minimising the loss of information[1]. To do so, a singular value decomposition gets applied to find several unit vectors that minimise the sum of squared distances of data points while being orthogonal to other unit vectors. These vectors are representative of those correlated data points, enabling dimensionality reduction, which takes place until a specified 'elbow' is reached, where further reduction would compromise the informational value.

With the reduced feature vectors of scenarios, the K-Means algorithm[2] gets applied. The newly generated set of feature vectors Ψ of $\bar{\Omega}$ initial scenarios in which K clusters must be found. To initiate the clustering algorithm, C_k random cluster centroids are chosen in the space. To avoid local minima, adequate distancing of initial centroids is given. Then, each scenario vector ψ_ω is appointed the cluster where the squared Euclidian distance from ψ_ω to C_k is minimal. The algorithm iteratively optimises the cluster centroids by minimising the sum of squared Euclidean distances W in function 41, where $J_{\omega,k} = 1$ if the feature vector belongs to the cluster $\psi_\omega \in k$. Otherwise, $J_{\omega,k}$ becomes 0. Once minimisation has been achieved, the nearest point ψ_ω to a cluster centroid C_k constitutes the representative scenario (since C_k may not be a scenario, but just an empty point in the space). These points construct the set of representative scenarios Ω. The size of a cluster is defined by the number of points in the cluster $\psi_\omega \in k$. The relative size of clusters corresponds to the scenario probabilities $p_\omega^{Scenario}$.

$$W = \sum_{\omega=1}^{\bar{\Omega}} \sum_{k=1}^{K} J_{\omega,k} | \psi_\omega - C_k |^2 \quad (41)$$

[1] The *scikit-learn* package provides us the PCA calculation functionality.

[2] The *scikit-learn* package provides us the K-means algorithm functionality.

4.3 Method for Identifying Robust Decisions

The approach is based on the student project A_Foran 2023, which the author supervised. First, the generalised framework following the approach of Mulvey, Vanderbei & Zenios (1995) is used, where the realisations of the uncertain parameters are represented by individual scenarios. Further, variables are classified into recourse and non-recourse variables. Accordingly, an optimisation model of the following two stage structure is considered

$$\begin{aligned} &Minimise \quad && c^T x + d^T y, \quad x \in R^{n_1}, y \in R^{n_2} \\ &s.t. && Ax \geq b, \\ & && Bx + Cy = e, \\ & && x, y \geq 0 \end{aligned} \qquad 42$$

where $x \in R^{n_1}$ and $y \in R^{n_2}$ constitute the non-recourse and recourse variable vectors, respectively (Mulvey, Vanderbei & Zenios 1995). The first constraint in 42 represents those constraints unaffected by uncertainty, where A is a $m\ x\ n_1$ coefficient matrix and b represents a variable $m-$vector. The second constraint represents all those constraints containing coefficients subject to uncertainty. This general optimisation model can be extended to include the individual realisations of the uncertain parameter, which are characterised by individual representative scenarios $\omega \in \Omega$ with occurrence probability $p_\omega^{Scenario}$, given $\sum_{\omega \in \Omega} p_\omega^{Scenario} = 1$.

The values for variables are determined by the model to minimise costs in each scenario ω. The decision-maker can define variables $e_{l,t,\omega}$, $u_{l,f,t,\omega}^{receiving}$, and $z_{l,t,\omega}$ to be non-recourse for specific periods, constructing the sets Φ^e, $\Phi^{u^{receiving}}$, and Φ^z. To ensure consistency, the sets $\Phi^{y^{line}}$ and $\Phi^{y^{facility}}$ get constructed for the period-independent variables $y_{o,l,\omega}^{line}$ and $y_{o,s,\omega}^{facility}$. Variables deemed non-recourse in specific periods must be the same across all scenarios $\omega \in \Omega$. The variables $\delta_{l,t,\omega}^{overutilization}$, $\delta_{l,t,\omega}^{underutilization}$, $v_{o,l,t,\omega}$, $q_{o,l,t,\omega}$, $\rho_{v,\tilde{s},s,t,\omega}$ and $u_{l,f,t,\omega}^{existing}$ always remain recourse, assuming that the final allocation of volumes can be decided reactively depending on the realised scenario.

The equations 43, 44, 45, 46 and 47 define the decision variables that may be deemed non-recourse. Equation 42 forces the model to jointly activate or deactivate lines in certain periods in all scenarios, while Equation 44 and 45 force the model to make joint investment decisions for entire lines or only individual features. Equations 46 and 47 enable joint decisions regarding line and site releases. To ensure that each variable is non-recourse in the specific periods indicated by the decision maker, the respective sets of time periods for non-recourse variables $\Phi^{(\cdot)}$ in each constraint get utilised. Equating the decision variables for all scenarios in the periods of $\Phi^{(\cdot)}$ guarantees them becoming non-recourse for the indicated periods.

$$z_{l,t,\omega_1} = z_{l,t,\omega_2} \quad \forall l \in L, \omega_1, \omega_2 \in \Omega, t \in T, t \in \Phi^z \tag{43}$$

$$e_{l,t,\omega_1} = e_{l,t,\omega_2} \quad \forall l \in L, \omega_1, \omega_2 \in \Omega, t \in T, t \in \Phi^e \tag{44}$$

$$u_{l,t,\omega_1}^{receiving} = u_{l,t,\omega_2}^{receiving} \quad \forall l \in L, \omega_1, \omega_2 \in \Omega, t \in T, t \in \Phi^{u^{receiving}} \tag{45}$$

$$y_{o,l,\omega_1}^{line} = y_{o,l,\omega_2}^{line} \quad \forall l \in L, \omega_1, \omega_2 \in \Omega, \Phi^{y^{line}} \neq \varnothing \tag{46}$$

$$y_{o,s,\omega_1}^{facility} = y_{o,s,\omega_2}^{facility} \quad \forall l \in L, \omega_1, \omega_2 \in \Omega, \Phi^{y^{facility}} \neq \varnothing \tag{47}$$

Second, the principles for modelling robustness from Bertsimas & Sim (2003) are introduced, who consider a risk-aversion parameter λ_i of the $i-$th constraint under symmetrically bounded uncertainty for discrete linear optimisation problems. The approach enables the decision maker to directly state the desired level of aversion by setting the non-integer risk-aversion parameter in the range $\lambda \in [0,1]$. Based on λ adapted probability weights $p_\omega^{ScenarioAd}$, can be defined 48:

$$p_\omega^{ScenarioAd} = \begin{cases} (\frac{1}{|\Omega|} - p_\omega^{Scenario}) \cdot \lambda + p_\omega^{Scenario}, & if\ \lambda > 0 \\ p_\omega^{Scenario}, & otherwise \end{cases} \tag{48}$$

The risk-aversion parameter increases the weight of unlikely scenarios while decreasing the weight of likely scenarios. Setting $\lambda = 1$ will weigh all scenarios equally.

5 Implementation

In this chapter, a proposed implementation during the introduction phase of a DSS called Automated Plant Volume Allocation (APVA) within the planning process and system framework of Bosch is presented, aimed at enhancing the decision support process for PVA presented in Section 3.1.3.

The Plant Volume Allocation (PVA) process at Bosch is a crucial component of their network planning process. It involves the Network Coordination Unit (NCU) collecting data from individual plants, primarily through Excel files. This data includes information on production line capacities measured in end-item quantities and other relevant details, such as customer releases for new part numbers. The NCU actively gathers this data and preprocesses total sales planning figures received from Market and Sales Planning (MSP).

Once the data is collected and prepared, the NCU carries out the PVA process. The PVA represents allocated production quantities, which are determined through the still time-consuming product-mix-allocation process. One weakness is that due to the still manual process, the consideration of uncertainties remains dispensed. The whole process will be automated through the presented framework for DSS to identify robust decisions in GPN trying to solve both issues.

These allocated quantities can then be broken down into site-specific figures. The NCU also performs feasibility checks for the entire network and specific geographical regions, which may lead to strategic decisions such as initiating new resources or discontinuing existing ones. After the PVA, the plans are visualised using the TEK-Chart, which stands for technical capacity. The TEK-Chart is a diagram that summarises and displays the capacities of all production lines within a Global Production Network (GPN) as stacked bars. It is currently based on spreadsheet calculations in Excel and includes standard capacities of individual lines and accumulated reserve capacity for a defined period. It shows planned demand from the last PVA process, confirmed orders, and actual demand anticipated by MSP. During the implementation of APVA, these TEK-Chart should be included in the visuals designed in Section 5.5 to use familiar charts planners already know.

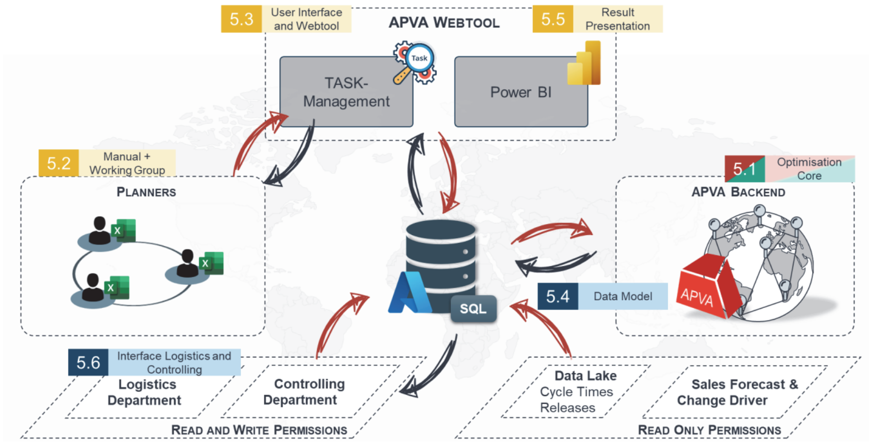


Figure 5-1: Proposed holistic implementation of the APVA Tool

The proposed implementation of the APVA tool was developed, incorporating the robust optimisation core, a user-friendly interface, an easily accessible web tool application, an extendable database with various interfaces and connections, and intuitive visualisations through PowerBI (see Figure 5-1).

The optimisation core of APVA employs advanced optimisation algorithms to analyse vast datasets and determine optimal Plant Volume Allocation scenarios, including robust line configurations. The regarding software implementation of the MILP model presented in Chapter 4 is described in Section 5.1.

In addition to the technical implementation, the organisational integration of APVA within Bosch's existing processes played a pivotal role in optimising Plant Volume Allocation strategies. An efficient organisational concept (see Section 5.2) is proposed to integrate the DSS seamlessly into the company's workflow. This involved collaborative efforts between data scientists, IT specialists, and decision-makers, ensuring alignment within a real-world application's overarching objectives. Furthermore, the implementation team conducted thorough training sessions for employees, ensuring they were proficient in using the APVA tool. User manuals and documentation were provided, aiding users in effectively navigating the frontend, interpreting optimisation results, and understanding the visualisations generated by PowerBI.

The APVA tool’s frontend was designed with a focus on simplicity and user experience. Section 5.5 presents the development of a streamlined interface, which was created through extensive user feedback and an iterative design processes. The frontend provides an intuitive platform for inputting parameters. The proposed Webtool offers the planner an easy-to-use web application for uploading the problem sheets and downloading results with necessary privacy management of data, the scheduling of problems and later interesting visualisation regarding their results.

Another key aspect is the establishment of a robust database connection through the usage of a standardised data model for GPNs presented in Section 5.4. APVA was prototypically integrated with Bosch’s existing databases, enabling data synchronisation. This integration allowed the DSS to access up-to-date CTs, releases, and market demand. Import functions are proposed to efficiently import relevant data sets into the APVA system, ensuring that decision-makers have access to comprehensive and current datasets.

To enhance data comprehension and facilitate real-time decision-making, APVA integrates seamlessly with a visualisation software, which in this case was chosen to be PowerBI. The tool generates dynamic visualisations, presenting complex data in an easily digestible format presented in Section 5.5. Interactive dashboards and graphical representations enable stakeholders to gain insights into allocation trends, production capacities, and market demands, thereby empowering them to make strategic decisions promptly.

Lastly, Bosch's supply chain relies on the Supply Chain Network Design (SCND) model. The SCND model is integral to Bosch's strategy, providing real-time transparency and enhancing stability and reliability in product delivery. The networking of both tools is prototypically made possible by a cross-functional interface, which is explained in Section 5.6.

5.1 Software Implementation to Solve the Proposed MILP

Beyond formulating the mathematical problem (see Chapter 4), a key objective of this thesis is to create a software tool capable of extracting raw data from the multi-sheet workbook provided by the company. The subsequent is formally based on a master's thesis at Bosch by Lotze (2018), which was already finished when the research of this thesis started. The steps involve constructing objects for the Mixed Integer Linear Programming (MILP) formulations, invoking a solver on these objects containing parsed input data, and generating a processable solution if one exists. The Code is implemented in Python, and the source code is commented.

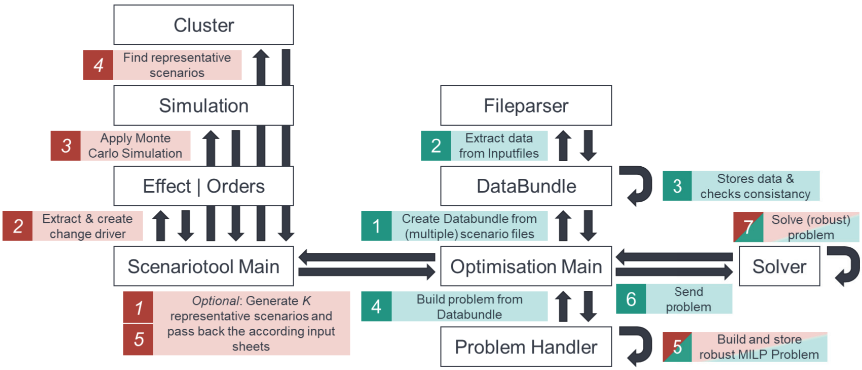


Figure 5-2: Architecture of the Optimisation Core

The software architecture consists of two main components. The Optimisation Main is the superior one, responsible for orchestrating the entire process. On the other hand, the Scenariotool Main orchestrates the optional generation of representative scenarios. Figure 5-2 provides an abstract overview of the control flow during a typical software run. The main module is initiated with specified options, including the path of the file required for processing the problem.

Initially, the user has to decide if scenarios are to be generated or not. If this is the case, the Optimisation Main calls the Scenariotool Main to generate the desired amount K of representative scenarios *(1)*. Therefore, the additional sheet containing the change driver gets extracted, and effects, as well as the orders, get generated *(2)*. Then, the Effects and the Orders are passed to the Monte Carlo simulation to generate the set of initial scenarios $\overline{\Omega}$ *(3)*. After finalisation, these scenarios get reduced to the representative set of scenarios Ω *(4)* and the according input sheets get passed back to the Optimisation Main *(5)*.

A DataBundle object is then created for all scenario files, which are stored in the folder (1), triggering a call to the parser on the given files. The Fileparser extracts necessary data from the input files and passes them back to the DataBundle object (2). Subsequently, the DataBundle object assesses the extracted data for general consistency, including non-empty data fields, correct typing, and inconsistencies (3).

After the DataBundle object is returned, the main module engages a problem handler (4) to generate a mathematical problem in the required format, as described in Chapter 4. All relevant parameters get stored in a csv. file called '*all_parameter_values*' and a problem file in the mps. format is generated, offering the option to use a wide range of solvers later on (5). Depending on the decision of using the robust optimisation approach, here, the different scenarios get merged, and variables are set to be recourse or non-recourse, as described in Section 4.3. Finally, the main method calls the solver specified by the user via the initial options (6). If a solution is found, it is written out as 'solution.csv', and post-processing starts for user inspection (7).

5.2 Organisational Concept

Implementing a Decision Support System (DSS) within an organisation's production processes entails a comprehensive assessment that encompasses a broad spectrum of critical dimensions. This evaluation ranges from process documentation to strategic alignment and maturity.

As described in Section 3.1.3, the Plant Volume Allocation (PVA) at Bosch is a key component of their network planning process. Currently, the Network Coordination Unit (NCU) collects data from individual plants, primarily through Excel files, including production line capacities and customer releases for new part numbers. This data is preprocessed with total sales planning figures from Market and Sales Planning (MSP). The NCU then carries out the PVA process to determine allocated production quantities, but this process is still manual and does not consider uncertainties. The NCU also conducts feasibility checks for the entire network and specific regions, which may result in strategic decisions like acquiring new resources or discontinuing existing ones. After the PVA, the plans are visualised and reported to upper management.

The targeted APVA process at the introduction stage operationalising the presented DSS based on the existing PVA process is described as follows. The process integrates various stages shown in Figure 5-3, ensuring accurate data input, in-depth analysis, and efficient communication of results.

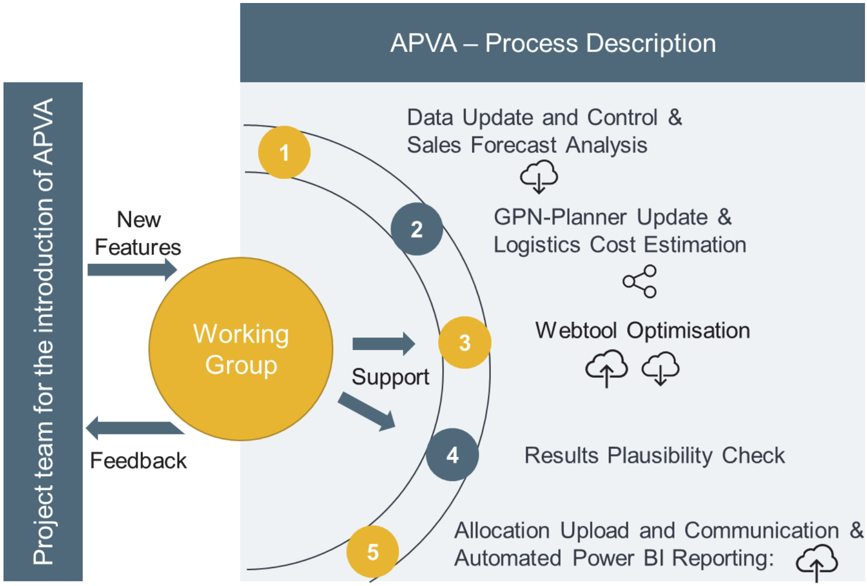


Figure 5-3: Process description at the introduction stage

1 – Volume preparation: In the beginning, as a preparation before the final volumes are released, **regular updates of data are** crucial for accurate decision-making. As described, the PVA foresees collecting data from individual plants, primarily through Excel files, and preprocessing this data. A DSS can support the acquisition of the latest information related to production configurations and costs, as well as logistics and other relevant parameters if data exists in a standardised way. This automation ensures that the decision-making process is based on the most current data, thereby improving the accuracy of decisions. The DSS can be integrated with financial systems and external data sources to streamline this process. At the same time, the Market and Sales Planning (MSP) performs the **sales forecast analysis,** which ends up in the official update of the estimated demand in an existing sales tool. For preprocessing, the DSS can employ data transformation techniques to ensure data quality and readiness for further analysis. Here, robustness plays an important role. While currently, only one volume scenario later gets passed to the planners, with the implementation of APVA, in the future, the MSP will also be enabled to mention critical uncertainties within these plannings as change drivers and pass them, too. This automation can significantly speed up the process and later improve the robustness of the results. The downloadable sheet itself containing all orders is called ‘Current PVA'.

2 – Volumes are released: After receiving the market forecast, the planner's role within the PVA process continues with **strategic premises updates** to ensure that the allocation aligns with overarching business goals, which get released together with the sales forecast. Therefore, the DSS can provide a user-friendly interface for planners to input and update data efficiently. A step which is entirely new for the PVA process is the **consideration of actual logistics cost estimates**. In the targeted process, the logistics department simultaneously receives the order volumes and starts to review and update the cost estimations for all potential deliveries, accounting for various factors such as routes, transportation modes, and regulatory considerations. It ends up calculating the full factorial of outbound and inbound logistic costs from every site for each order. This computation is performed using the PSI Global Tool, overseen by the logistics department.

3 – Webtool Optimisation: The updated data is fed into a webtool that performs the optimisation core. By applying mathematical modelling and optimisation algorithms, the DSS can support by quickly analysing various product-mix scenarios to determine the optimal allocation of production quantities. This optimisation can consider multiple constraints and objectives, such as conforming with the mentioned strategic constraints, assuring flexibility, or minimising costs. The DSS can also incorporate stochastic models to account for uncertainties in demand, supply, and production capacities, making the allocation decisions more robust. This step seeks to identify the most cost-effective and operationally efficient network configuration.

4 – Results Plausibility Check: Ensuring the plausibility of optimisation results is essential for their real-world applicability. A DSS can employ algorithms to perform plausibility checks by comparing optimisation results against historical data. This step verifies that the derived solutions are realistic and achievable.

5 – Allocation Upload and Communication: Once the optimal allocation is determined, it is essential to communicate these changes effectively. A DSS can automate the upload of allocation data back into the sales tool and facilitate seamless communication with relevant stakeholders. This ensures that all parties are informed of the allocation changes, promoting transparency and collaboration across the organisation. The APVA automatically provides visuals for the optimisation results using automated

Power BI reports. These reports provide informative insights into the cost-saving potential and network enhancements achieved through the optimisation process.

In the ever-evolving landscape of modern business, the successful development and implementation of a DSS demands the orchestration of a project team. Such a team, comprising diverse roles and expertise, is crucial to ensure the seamless integration and efficient functioning of the DSS across the organisation.

Appendix G presents the composition of the **project team** for implementing APVA at the network level, considering various stakeholders and steering committee involvement. One piece of the project team is the working group, which acts as an interface between the project team for the APVA introduction and the network planners themselves.

Working Group Collaboration: During the targeted process for the introduction stage, a founded working group serves to provide valuable support. Experts from various departments contribute insights and expertise to refine the optimisation strategy and support beginners with the usage of APVA. If necessary, direct contact with subject matter experts is initiated to address complex challenges or to seek specialised input. This ensures the optimisation process benefits from diverse perspectives. On the other hand, the project team of the tool introduction gets valuable feedback from end-users who are directly interacting with the DSS. The working group comprising digitally motivated end-users provides real-world context, identifies pain points, and offers suggestions for user-centred improvements.

5.3 Development of a User Interface

Spreadsheets function as a widely utilised and inclusive tool, offering a common ground for various users to collaborate, conduct statistical analyses, and visualise data. Noteworthy is their versatility in accommodating users of varying proficiency levels, from beginners to experts, facilitated by a user-friendly direct manipulation interface. (Litt et al. 2020)

Through their intuitive design and powerful features, spreadsheets continue to play a vital role in shaping how one interacts with and understands data in the modern age. Thus, at the current stage, they will also serve as a frontend for the database.

To improve legibility, an Excel file is divided into multiple sheets, each dedicated to distinct data elements. This completion of all necessary input data is followed by accessing the optimisation core by a web tool with an interface to upload the sheet, schedule the optimisations, and download their results.

5.3.1 Input Sheet

In the first stage, the applied approach focused on a specific use case, which limited the investment in a practical user interface due to the familiarity of all involved parties with the approach and model properties. However, as the project evolved and aimed to extend its application within the organisation, it necessitated the engagement of users not previously involved. This expansion prompted the need for a universally applicable interface developed in the student's project A_Hartmann 2021.

The following objectives stem from expert workshops as well as literature mentioned in Section 2.3 and guide the introduced input sheet:

- Introduce a colour code to distinguish user input fields, explanations, and non-input areas.
- Clearly differentiate between mandatory and optional inputs.
- Non-input areas should maintain a consistent structure across sheets, serving purposes such as denoting header rows or displaying values derived from other sheets.
- Ensure all sheets adhere to a consistent pattern.
- Place input instructions at the top, followed by an illustrative example and associated input fields.
- Maintain a uniform header row for input sections across all sheets, simplifying data parsing by providing consistent reference points for explanations and examples.

- Streamline input efforts and reduce errors by requiring a single entry for static elements like line names, sites, or technical features and use formulas to propagate these static elements across relevant sheets, minimising manual input.
- Facilitate user input by aligning the spreadsheet with existing company data structures.
- Enable users to add meta-information to multiple orders simultaneously by implementing keys, such as article numbers, for associating meta-information.
- Streamline data entry and reduce errors by allowing users to input critical information once for each key. This information is automatically propagated to all linked orders when the relevant parameter is generated.

Figure 5-4 exemplifies the input sheet structure. The colour code is indicated at the top, followed by explanatory sections. The left box describes the data type and purpose required on the sheet, while the right box describes detailed instructions on completing the sheet, including data formats. Subsequently, an illustrative example follows, structured identically to the subsequent input fields, which are highlighted in their respective colours. Keys are used to facilitating the input of metadata for logistics, releases, CTs, fixations, and features on order characteristics instead of doing it for each order.

Automatically filled / no Input	Input fields	Explanations

Sheet description
This sheet should contain the already existing and via technical upgrades achievable line features.
The shown line features are identical to the product characteristics in sheet "1 Current TPZ" and automatically taken from the inputs there
During the allocation run it is checked and ensured that the lines, a product is allocated to, have the necessary technical features.

How to fill out?
- Fill in line names of already existing lines in fields B15:B34
-> The required format for line names is: 'Product Site Line Name' (see example)
- Fill in line names of potential lines to be installed in the future in fields B36:B58
- Fill in "yes" if a line has already installed the technical feature
- Fill in the costs in [€] if you want to enable the possibility of a line upgrade regarding the technical feature.
-> Potential upgrades will exponentially impact the calculation time, so try to keep to a minimum

Example

Yes = line can manufacture products with the feature "2 Zyl (120)"

Name of existing line

Upgrade to enable line to produce products with the feature "Gen 2" costs 225.000 Euro

Example	Line name	2 Zyl (120)	Drossel (Station 05)	Cross Coupling (Station 530)	Z ring (Station 525)	Meteri... (Statio...	Leakage ... R	RP7 (Stat... 2)		
	Example BarP SL1	Yes		Yes			Yes			
	Beispiel FeP SL2	Yes				Yes	Yes	225000		

Existing and potential technical line features

	Line name	Lefts	Right	Small Gear	Big Gear	Housing 1	Housing 2	Housing 3		
Existing lines in IPN	Servomotor KA SL1	Yes	1000000	800000	Yes	Yes	Yes	725000		
	Servomotor KA SL2	Yes	1000000	Yes	1000000	725000	Yes	Yes		
	Servomotor KA SL3	Yes	1000000	Yes	1000000	Yes	Yes	Yes		
	Servomotor KA SL5	1000000	Yes	Yes	1000000	Yes	Yes	Yes		
	Servomotor KA SL6	Yes	Yes	Yes	1000000	725000	Yes	Yes		
	Servomotor KA SL7	Yes	Yes	Yes	1000000	725000	Yes	Yes		
	Servomotor KA SL8	Yes	Yes	Yes	1000000	Yes	Yes	Yes		
	Servomotor KA SL9	Yes	Yes	800000	Yes	Yes	725000	725000		
	Servomotor KA SL10	1000000	Yes	800000	Yes	Yes	Yes	725000		
	Servomotor KA SL11	1000000	Yes	800000	Yes	Yes	Yes	Yes		
	Servomotor CN SL13	Yes	Yes	800000	Yes	725000	Yes	Yes		
	Servomotor CN SL14	Yes	1000000	800000	Yes	Yes	Yes	Yes		
	Servomotor CN SL15	Yes	1000000	Yes	1000000	725000	Yes	725000		

Figure 5-4: Exemplary sheet structure for line features

Table 5-1 provides a list of all currently required Excel sheets and briefly describes their contents. Each sheet contains the described explanation and guided Input.

Table 5-1: Data basis in Excel

No.	Excel Sheet	Explanation
1	Information about all orders	Contains various information about customers and their orders. Crucial details include ordered quantities per period and product features associated with the ordered products.
2	Line features	Contains information about existing line features and the costs of features to be purchased.
3	Customer releases for lines	Contains information about which customer has approved for a production line, enabling the production of the order on that line.
4	Customer releases for sites	This section contains information about which customer has approved a site, enabling the production of the order at that site.
5	Capacity-related data of lines	Contains four capacity-related parameters for each line and each period: Overall Equipment Effectiveness (OEE), regular workdays per half-year, maximum workdays per half-year, and production hours per day.
6	Capacity-related data of planned lines	Contains four capacity-related parameters for each planned line and each period: Overall Equipment Effectiveness (OEE), regular workdays per half-year, maximum workdays per half-year, and production hours per day.
7	Fixed order allocations to sites	Contains fixed allocations of orders to sites for all periods.
8	Costs and information on utilisation	It contains four utilisation-related parameters for each line: costs for underutilisation, costs for overutilisation, the standard shift model, and the maximum possible shift model.
9	Costs for customer releases of lines	Contains the costs incurred when a customer releases a line. There is a default value applicable to all lines unless explicitly defined otherwise.
10	Costs for customer releases of sites	This section contains the costs incurred when a customer releases a site. Unless explicitly defined otherwise, the default value applies to all sites.
11	Logistic costs	Contains general logistics costs as well as unit costs associated with the production of a product at a specific location.
12	General parameters for the tool	Contains scaling measures for adjusting variables in the tool and the assignment of sites to regions.

13	Fixed and variable production costs	This section contains fixed and variable costs associated with production on a line. Additionally, the annual change rate of variable costs is recorded here.
14	Allocation of a portion of the order volume to sites	Contains the allocation specifying which portions or total quantities need to be produced at which site during a specific period.
15	Allocation of a portion of the order volume to regions	Contains the allocation specifying which portions or total quantities need to be produced in which region during a specific period.
16	Cycle times of the lines	Contains information about the cycle times of different products on various production lines.
17	Special reductions in Cycle time	Contains information about future reductions in cycle times.

5.3.2 Webtool for Optimisation

Webtool design is a dynamic process aiming to create user-friendly online tools. Accessibility and responsiveness across devices are crucial considerations. Continuous testing and user feedback guide iterative improvements, ensuring a refined user experience. For the implementation of the Webtool, the corporate research department of the company Bosch, which will be in charge of the whole software solution, was supported.

Upon entering the first page, users are prompted to register. Following registration, they can create product groups, allowing them to upload and version their input sheets. Optionally, users can share their progress with others by inviting them to join their product group. Access to the data is restricted to members of the respective product group.

Moving to the second page, users upload their sheets and initiate the optimisation process. Here, users have the flexibility to set a time limit. If the time limit is reached, the optimisation core returns the best solution found. Alternatively, it continues the search until a specified gap to optimality is achieved. The user can define this gap, which thus serves as an opportunity to accelerate the process at the cost of solution quality. Users can monitor the progress & check the success of the problem calculation. In the event of optimisation failure, users can download log files for further analysis and share them with expert support.

The visualisation of the results with Power BI will be shown in Section 5.5.

5.4 Data Model of the Digital Twin of GPNs

The holistic implementation of the DSS involves addressing the challenge of constructing digital twins for production networks, given the wide distribution of relevant data sources within an organisation. Unlike digital twins for individual products or resources that can be integrated via sensors, applying this approach to GPN becomes unfeasible due to the infrequent updates required for the models and the vast number of direct data sources that would need to be connected. To overcome this problem, the solution involves acquiring data from various information systems such as MES, ERP, SCM, and sometimes additional sources for master data.

As a basis, therefore, the data model discussed in Benfer et al. (2023) is used as a prototype matching strictly for the GPN tasks mentioned in the dissertation. The authors want to mention that other data models, like the Core Information Model for Manufacturing (CIMM), are well-established at the company, as well as at the GPN stage (Grangel-González et al. 2023). Thus, these were considered during the data model development process. Nevertheless, these models did not precisely match the requirements. The proposed data model represents GPNs and their attributes in an object-oriented format. A generic architecture is established, comprising four main object clusters: orders, products, production resources, and logistics. This architecture is designed to be versatile, allowing adaptation to suit the specific needs of an organisation and versioning of different scenarios.

5.4.1 Structure of the Data Model

The relevant data required for generating the mathematical optimisation problem using Automated Plant Volume Allocation is spread across multiple sheets in the Excel file, as explained in Section 5.3.1. Due to ongoing developments and adjustments to the planning base at the different GPNs, the data basis undergoes regular modifications. Therefore, within the student project A_Orhan 2022, a universally applicable object-oriented data model for modelling global production networks was formulated. This model was implemented in MS SQL and tailored to APVA, as presented in Figure 5-5.

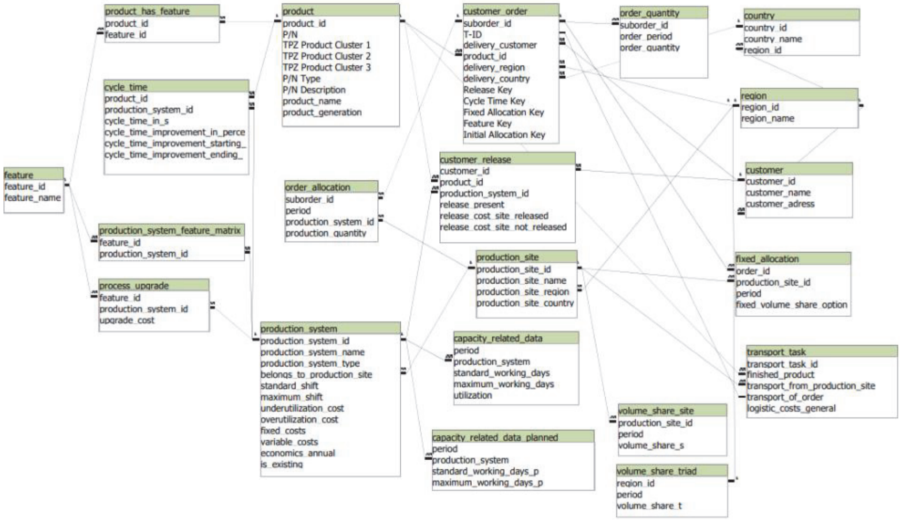


Figure 5-5: Database tables with relationships based on Orhan (A_ 2022)

Versioning data aims to display data that varies over time. Versioning is intended to provide additional information (Date, Lorentzos & Darwen 2014). To maintain the different applications of APVA in distinct versions, the following approach was prototypically implemented by A_Feldinger 2023, illustrated in Figure 5-6.

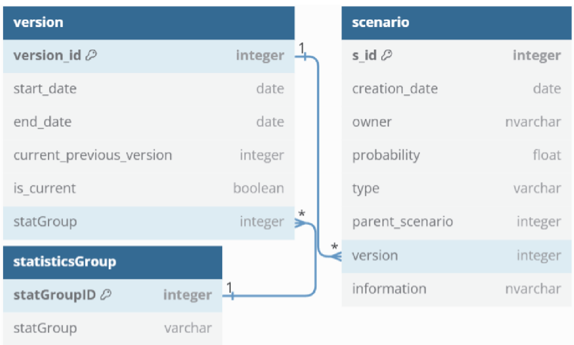


Figure 5-6: Versions and scenarios in SQL by A_Feldinger 2023

The versioning paradigm is instrumental in maintaining historical data integrity. Each GPN may have multiple versions, each possessing a unique identity that increments with each new version. The *current_previous_version* attribute maintains links between versions, especially when obsolete versions are removed. Deletion policies can be tailored based on application-specific or enterprise-wide criteria. The *is_current* flag indicates the current version status. Time validity is represented using the date data type, offering granularity suitable for higher planning frequencies.

The scenario class introduces new attributes, e.g. information (*nvarchar*) containing scenario details and type (*varchar*) indicating whether the scenario is nominal, alternative, or other. The type attribute informs the deletion policy, with nominal scenarios typically retained for a longer duration. Each scenario possesses a unique identity, creation date, owner information, entry probability and dependency on a parent scenario, all tied to a specific version.

Specific tables remain unconnected to the block version. For tables with infrequent changes, such as region and country, versioning is omitted. The data structure, as illustrated in Figure 5-7, demonstrates how the *capacity_related_data* class undergoes modifications to accommodate versioning. The inclusion of a new table facilitates version tracking, with arrays managing the association between data versions and corresponding block versions.

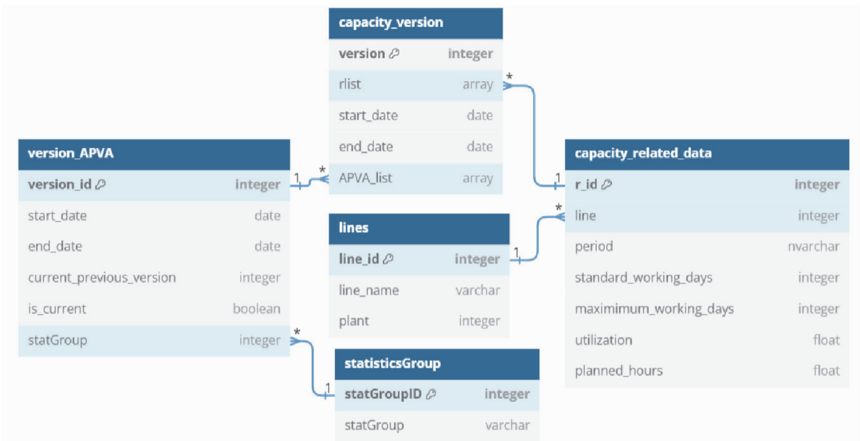


Figure 5-7: Versioning of data tables with split-by-rlist by A_Feldinger 2023

This approach aims for a natural and intuitive representation of separate data versioning at the table level, acknowledging the trade-offs in query complexity and data management overhead.

5.4.2 Database Connection

To establish data interconnections and optimise data collection efficiency, a comprehensive understanding of the origins of the required data is imperative. This exploration yields insights into the collected dataset, enabling the differentiation between elements that can be automated and those that remain reliant on manual intervention. Summarised in Table 5-2 is the depiction of the data source identification at a prototypical case, indicating areas where automation is applied via Python scripting.

Table 5-2: Input data and sources for the automated connection to APVA

Input Data	Source
Information about all orders	Automation from Sales – Salesforce
Product and Line Features, Upgrade Costs	Manual by GPN Planners
Customer Releases	Automation from MAS
Costs for Customer Releases	Manual by GPN Planners
Capacities Current & Planned	Standard Excel Document
Fixed order allocations to sites	Manual by GPN Planners
Costs and information on utilisation	Controlling
Logistic costs	Supported from SCND (LOG)
Fixed and variable production costs	Controlling Department
Allocation of a portion of the order volume to sites/ regions	Contractual Agreements with sites
GPN cycle times of the lines	Automation from MAS
Special reductions in cycle time	Manual by GPN planners

For instance, data concerning existing customer releases and cycle times can be inferred from the so-called data lake (MAS). A segment of the MES-generated data is transferred and mapped onto a Hadoop Cluster, a cloud-based data repository. This storage methodology offers robust security features due to its data lake architecture. The repository undergoes periodic updates, maintaining alignment with real-time data by a short time lag.

However, this raw data, in a prototypical case, lacked the desired format and quality necessary for accurate outcomes from the product-mix-allocation process, which entails volume allocation, customer release lists, upgrade lists, and cost term overviews. To enhance the quality of the input data, an automation process leveraging Python scripting for the aforementioned inferable data is proposed.

Figure 5-8 delineates the automated data acquisition process workflows for cycle times established by Maatoug (A_ 2021). The cornerstone of these processes comprises Python scripts that encompass automation logic and algorithms for transforming the data retrieved from the Hadoop Cluster into a format suitable for the object-oriented data model. These scripts establish a connection to the Hadoop cluster, extracting data and orchestrating functions for processing, formatting, and filtering.

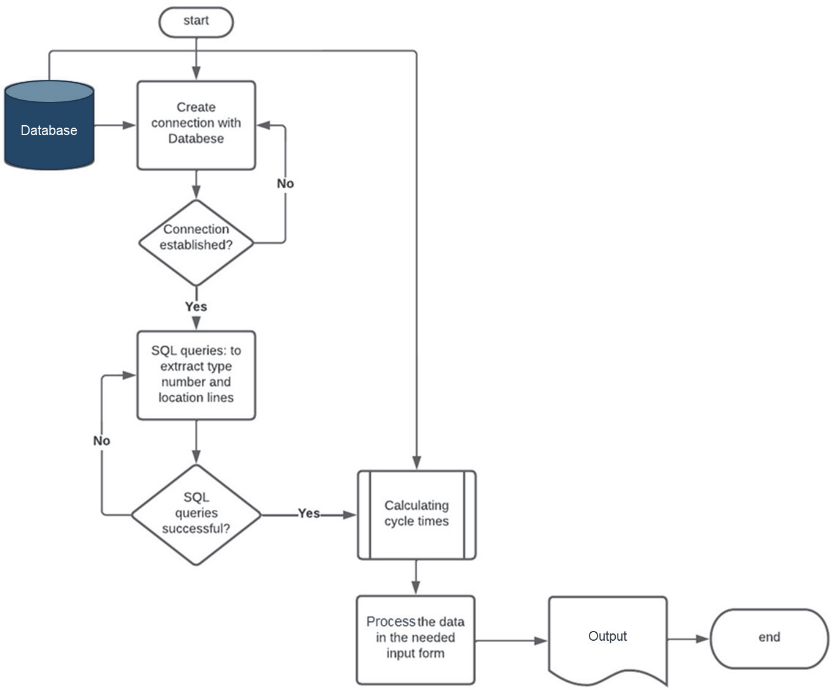


Figure 5-8: Example Python script for the workflow of the cycle times acquisition

These scripts bear a significant advantage in facilitating fundamental data manipulations, including data type conversions and transformations. The transformation is achieved, at times, through embedded SQL queries. In future, these scripts might get obsolete with the targeted introduction of the Bosch Data Market (Zhou et al. 2022). However, they can still be used during the effort of integrating data into the data market.

5.5 Results Presentation

This chapter delves into the landscape of APVA result analysis utilising advanced PowerBI techniques based on the student's project A_Schmidt 2023. With a keen focus on dynamic filtering, parameterisation, and interactive visualisations, insights into production capacities, line features, and cost structures are provided. Furthermore, multi-scenario comparisons, facilitated through clustered column charts and delta analyses, offer a profound understanding of diverse production landscapes. This analysis equips industry professionals with empirically grounded insights, fostering informed decision-making and strategic planning in industrial contexts.

5.5.1 Result Data Import

The implementation of data integration within the PowerBI environment plays a pivotal role in converting raw data into a cohesive and understandable format. PowerBI offers a diverse set of options for importing and connecting to data sources (see Appendix F). In the context of the APVA tool, two distinct options warrant consideration: direct CSV file imports and the potential connection to an existing database system. An implemented query serves with a file directory, presenting all available scenarios within the designated directory location. This approach empowers users to quickly select their desired scenarios through a filtering mechanism for downloaded and locally saved results. Only the initial queries, representing 'all_parameter_values,' 'solution,' and 'Current PVA' files, are required, regardless of the number of scenarios under examination. In situations where multiple scenarios are selected, the data is appended, with each data record clearly marked with its associated scenario (see Figure 5-9).

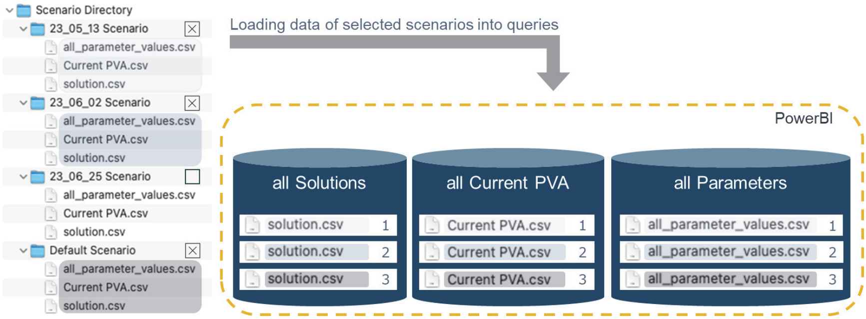


Figure 5-9: Appending data of selected scenarios in the relevant query

As an alternate strategy, the exploration of connecting results directly to the database system under development, where data is stored centrally, was considered. This approach holds the potential for even faster data loading and preserves the benefits of streamlined scenario management.

5.5.2 Summary of Data from Optimisation

The overview presented in Figure 5-10 provides an overview of all generated tables and their dependencies. Firstly, the 'Input Data' tables encompass all external information for the selected scenarios. The directory and scenario selection determine the specific names of each scenario, the number of scenarios, and the product name. These parameters are intermittently employed in subsequent processes. ' Supporting Lists' were introduced to streamline the transformation of added tables and fortify the model against errors during editing. Functioning as variables, these lists contain the names of information types to be considered by the relevant tables. The 'Tables for Visualization' play a pivotal role in report preparation, serving as sources for visuals and constituting the core element. Additionally, 'Relationship Tables' are employed to connect data from different tables. The table labelled 'prod' at the centre provides support to the 'all Solution' file, requiring further processing operations before its utilisation.

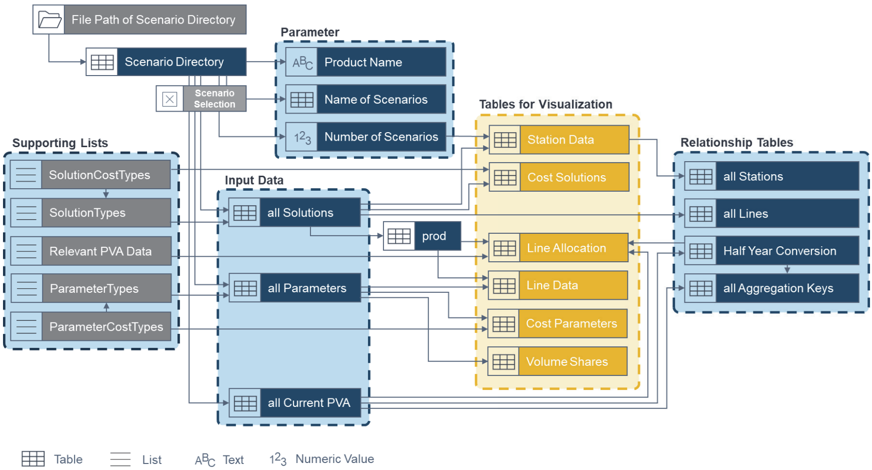


Figure 5-10: All data objects and their dependencies

Below, the various result types are introduced:

- Overutilisation: This metric signifies the total duration of used reserve capacity per line and half-year index.
- Activity: This parameter specifies whether a line is active or inactive during the specified half-year.
- New Line: Indicates whether the establishment of a new line is necessary in the specified half-year.
- Production Specification: This specification outlines, for each order defined by the aggregation key, the number of pieces produced per line and half-year.
- Time Specification: Specifies, for each order defined by the aggregation key, the total time required per line and half-year.
- Station Availability: Indicates whether the specified station is available at the line during the named half-year.
- Station Addition: Specifies if and in which half-year the corresponding station is added to the named line.
- Line and Site Release Requirement: Indicates whether the specified order, defined by the aggregation key, requires approval for the named line and site.

5.5.3 Filters

As the user seeks to view data in a default format and conduct customised data analysis, it is imperative to establish a concept that facilitates intuitive interaction. This involves, in addition to suggested charts and overview pages, providing the user with a reasonable selection of filter and display options.

The filter menu, illustrated in Figure 5-11, is prevalent on almost every page. These filters are synchronised, meaning that if a specific line is selected on one page and the page is subsequently changed, the same selection is applied to the new page. Key filter options identified for effective data analysis include scenario selection, the choice of individual or multiple sites or lines, and the restriction of the examined time period. Additionally, the implementation of the ability to view data at the line or site level enhances the existing TEK-Chart presented in Section 3.1.3. To facilitate switching, buttons are employed for scenario selection. Given the larger number of choices when filtering by sites or lines and time period, a dropdown menu with the option for multiple selections was deemed appropriate.

Figure 5-11: General filter menu

The submenu (see Figure 5-12) designed for filtering all orders based on specific attributes is implemented using dropdown menus. The most pertinent selection options include filtering by part number (P/N), TPZ product cluster 3 (which broadly describes a product variant), delivery customer, delivery customer group, and country of delivery.

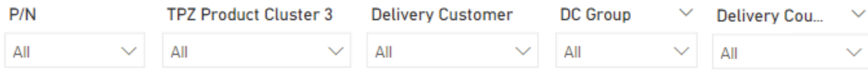


Figure 5-12: Submenu for filtering volumes

5.5.4 Single Scenario Visualisations

Visualisation methodologies were devised during collaborative user workshops, building upon existing visuals as a basis for extension and improvement. Subsequently, these refined visualisations were trialled in real-world use cases to validate their effectiveness and applicability. Various pages were created to analyse all data that resulted in the automated allocation process for a single scenario. The following subchapters go into the specific charts and explain how they work and which information can be taken from them. The example shown in the graphs is fictive. It is based on the production of servomotors of the Learning Factory Global Production of the wbk Institut of Production Science located in Germany and China.

The Learning Factory Global Production at the wbk Institute of Production Science (KIT) is an innovative educational platform designed to address the complexities of modern manufacturing. It provides a hands-on experience of Industry 4.0, allowing participants to engage with and understand the tangible effects of global production networks. The Learning Factory emphasises the importance of agile global production networks in the context of advancing globalisation. It serves as a research and training ground to assist in comprehending the interconnected nature of manufacturing across globally distributed sites. (Lanza et al. 2015)

Overall, the fictive production network contains 13 lines, while nine are located in Karlsruhe (KA SL1, KA SL3, KA SL4, KA SL5, KA SL6, KA SL7, KA SL8, KA SL10, KA SL11) four are located in China (CN SL12, CN SL13, CN SL14, CN SL15). Two lines have historically already been closed (KA SL2, KA SL9). For the seven delivery customers and their according delivery countries (VW-Germany, VW Brasil-Brasil, Cummins-USA, BYD-China, Seat-Spain, Renault-France, and Toyota-Japan), 15 different part numbers (P/N) exist (1, 2,…, 15).

5.5.4.1 Capacity-Chart & Line Utilisation

The initial section of the report is titled 'Capacity & UT,' an abbreviation for Capacity-Chart and Utilisation. The pivotal visual element within this section is the Capacity-Chart (Figure 5-13). This chart is of high importance as it is extensively utilised for production planning, and planners are accustomed to its structure. Hence, the decision was made to reconstruct this chart in PowerBI. The chart is a fusion of a stacked column chart and a line chart. The X-axis represents time periods in half-year increments, while the Y-axis quantifies the number of pieces. Each bar corresponds to the standard capacity per line, with distinct colours representing different lines. Additionally, the 'Reserve Capacity' is displayed at the top in a light grey shade for all lines combined.

In this chart, the line illustrates the actual allocated number of pieces (in black). This representation provides a swift overview of the overall utilisation and capacity of chosen lines within the GPN for upcoming periods. It facilitates prompt assessments of whether minimum production requirements are being met or if reserve capacity needs to be utilised.

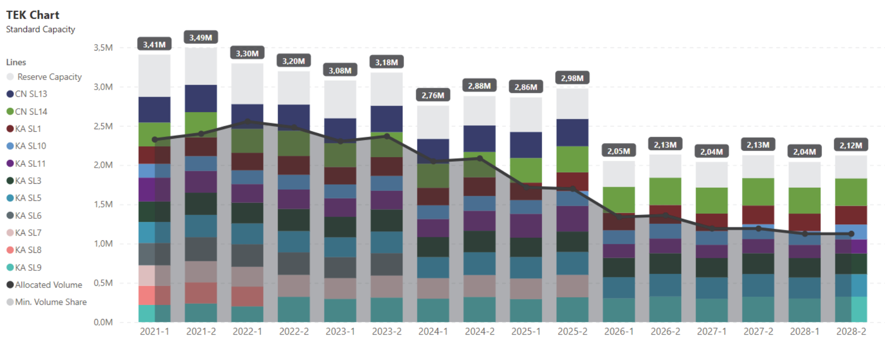


Figure 5-13: Capacity-Chart on line-level

Users can access more detailed information about the diagram through a feature known as a tooltip. This overview, depicted in Figure 5-14, becomes visible when the user hovers the mouse cursor over an element within the diagram.

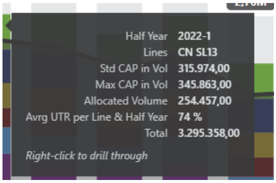
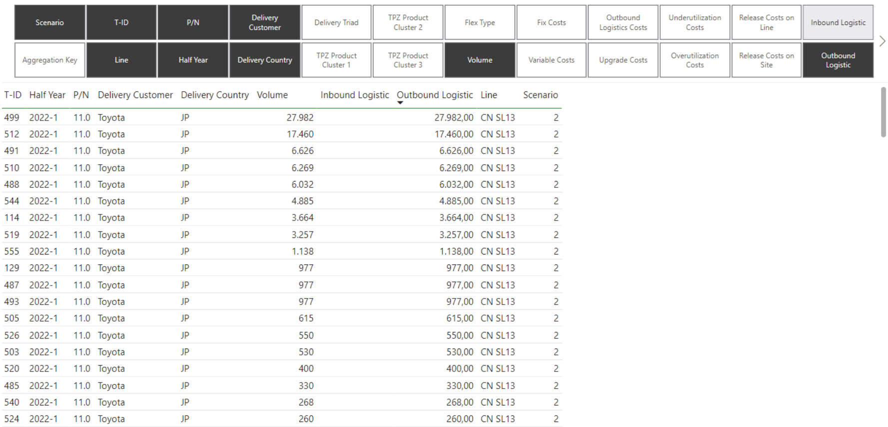


Figure 5-14: Tooltip of Capacity-Chart for the period 2022-1 regarding line CN SL13

The tooltip additionally provides an option for Drill Through upon right-clicking. This feature has been implemented to offer users a comprehensive understanding of the numerical breakdown within the diagram. Upon selecting Drill Through, a table is presented, listing all orders with their specific order ID (T-ID) corresponding to the specific line and half-year period from which the Drill Through was initiated. This function allows for a detailed exploration of the underlying data (see Figure 5-15).



T-ID	Half Year	P/N	Delivery Customer	Delivery Country	Volume	Inbound Logistic	Outbound Logistic	Line	Scenario
499	2022-1	11.0	Toyota	JP	27.982		27.982,00	CN SL13	2
512	2022-1	11.0	Toyota	JP	17.460		17.460,00	CN SL13	2
491	2022-1	11.0	Toyota	JP	6.626		6.626,00	CN SL13	2
510	2022-1	11.0	Toyota	JP	6.269		6.269,00	CN SL13	2
488	2022-1	11.0	Toyota	JP	6.032		6.032,00	CN SL13	2
544	2022-1	11.0	Toyota	JP	4.885		4.885,00	CN SL13	2
114	2022-1	11.0	Toyota	JP	3.664		3.664,00	CN SL13	2
519	2022-1	11.0	Toyota	JP	3.257		3.257,00	CN SL13	2
555	2022-1	11.0	Toyota	JP	1.138		1.138,00	CN SL13	2
129	2022-1	11.0	Toyota	JP	977		977,00	CN SL13	2
487	2022-1	11.0	Toyota	JP	977		977,00	CN SL13	2
493	2022-1	11.0	Toyota	JP	977		977,00	CN SL13	2
505	2022-1	11.0	Toyota	JP	615		615,00	CN SL13	2
526	2022-1	11.0	Toyota	JP	550		550,00	CN SL13	2
503	2022-1	11.0	Toyota	JP	530		530,00	CN SL13	2
520	2022-1	11.0	Toyota	JP	400		400,00	CN SL13	2
485	2022-1	11.0	Toyota	JP	330		330,00	CN SL13	2
540	2022-1	11.0	Toyota	JP	268		268,00	CN SL13	2
524	2022-1	11.0	Toyota	JP	260		260,00	CN SL13	2

Figure 5-15: Destination of a Drill Through for CN SL13 and 2022-1

Figure 5-16 displays the Capacity-Chart representing site-level data. This presentation is particularly valuable in GPNs with numerous sites, enhancing clarity by reducing the complexity of elements.

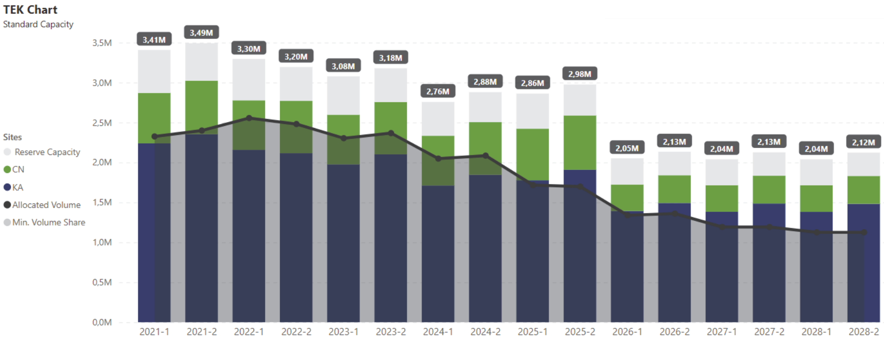


Figure 5-16: Capacity-Chart on site-level

The Capacity-Chart on the report page is accompanied by a highlight table that showcases the utilisation of each line during specific half-year periods. This table offers a detailed breakdown of each line's utilisation, enabling a quick assessment of profitability and potential bottlenecks in the future. It serves as a valuable tool for identifying lines that might need closure. High utilisation rates are colour-coded in green, while low utilisation rates are highlighted in red.

In Figure 5-17, a subset of lines from the use case is presented. It's important to note that empty fields signify line closures for the respective half-year. The percentage values are based on the maximum capacity, indicating that utilisation of 100% means that both standard and reserve capacities are fully utilised.

Utilization Rate based on Max. Capacity	2021-1	2021-2	2022-1	2022-2	2023-1	2023-2	2024-1	2024-2	2025-1	2025-2	2026-1	2026-2	2027-1	2027-2	2028-1	2028-2	**Average**
CN SL13	38 %	28 %	74 %	68 %	62 %	57 %	49 %	46 %	46 %	40 %							**51 %**
CN SL14	91 %	95 %	91 %	95 %	91 %	95 %	91 %	95 %	91 %	95 %	84 %	83 %	60 %	60 %	53 %	53 %	**83 %**
KA SL1	22 %	21 %	55 %	52 %	59 %	56 %	52 %	50 %	37 %	35 %	28 %	27 %	17 %	16 %	15 %	14 %	**35 %**
KA SL10	82 %	84 %	82 %	84 %	82 %	84 %	82 %	84 %	71 %	68 %	82 %	84 %	82 %	84 %	82 %	84 %	**82 %**
Average / HY	**69 %**	**69 %**	**77 %**	**77 %**	**75 %**	**75 %**	**74 %**	**72 %**	**60 %**	**57 %**	**63 %**	**62 %**	**57 %**	**55 %**	**54 %**	**52 %**	**66 %**

Figure 5-17: Highlight table indicating the utilisation rate of specific lines.

5.5.4.2 Line Configurations

The report's second page provides an overview of the line configurations and assesses the need for additional features during specific periods. Unlike the first page, this section does not offer the option to switch to a site-level view.

The lines presented in Figure 5-18 exemplify the representation capabilities. The first column indicates whether a line is active, e.g. (KA SL1) or closed, e.g. (CN SL15) during the considered period. It also allows for specifying if a line is active up to a certain half-year, as demonstrated by line CN SL13, which remains active until 2025-2. The report theoretically allows for indicating the date a line becomes operational; however, in the current use case, this information isn't applicable to any line. A similar approach is taken to indicate whether a line possesses a specific station; if a line lacks a particular feature, the corresponding field is left empty for clarity. For example, to install a small gear, an adaptation of the station is necessary to enable the feature that allows smaller components to be gripped. This update is performed at line CN SL14.

Show only lines with changes

Lines	Active	Big Gear	Housing 1	Housing 2	Housing 3	Lefts	Right	Small Gear
CN SL13	until 2025-2	Yes		Yes	Yes	Yes	Yes	
CN SL14	Yes	Yes	Yes	Yes	Yes	Yes	from 2021-1	from 2021-1
CN SL15	No			Yes		Yes		Yes
KA SL1	Yes	Yes	Yes	Yes		Yes		

Figure 5-18: Example of chart indicating line features

A button has been integrated that, upon activation, filters the table to display only the lines where changes have occurred during the preview. This action conceals all other lines, drawing attention specifically to the alterations made.

5.5.4.3 Detailed Allocation View

In this subsection, the three pages titled 'P/N on Line,' 'Delivery Customer,' and 'Delivery Country' are discussed collectively due to their similarity. All three pages utilise a multiple ribbon chart as their primary visual representation. The term 'multiple' in this context signifies that the chart provides one visual representation per line or site, which can be scrolled through.

For instance, diagrams for the line CN SL14 are illustrated in both Figure 5-19 and Figure 5-20. Within these diagrams, users can access additional information through tooltips and drill down to individual volumes summarised in the charts. Apart from standard filters, it is possible to filter data based on attributes listed on all three pages.

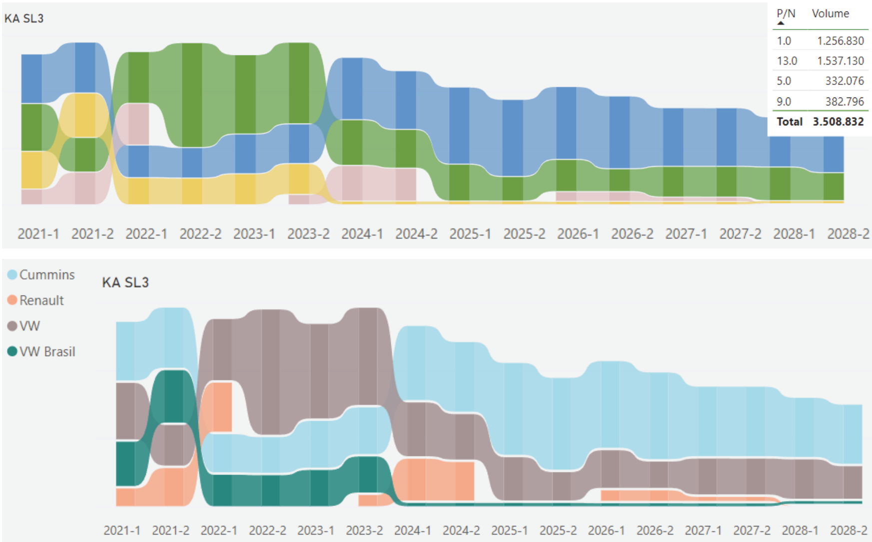


Figure 5-19: Ribbon Charts displaying volumes with the same part number (top) and delivery customer (bottom) for line KA SL3.

Apart from the ribbon chart, each page includes a compact table situated in the upper right corner, listing all groupings from the respective page along with their corresponding volume. In the case of the part number (P/N), a colour code legend is dispensed, as in real-world scenarios, about 50 different P/N can quickly run on the same line as one customer might order multiple slightly different variants. All tables and the ribbon charts are interconnected: selecting a specific customer, for instance, updates the ribbon chart, accordingly displaying only the orders associated with that customer.

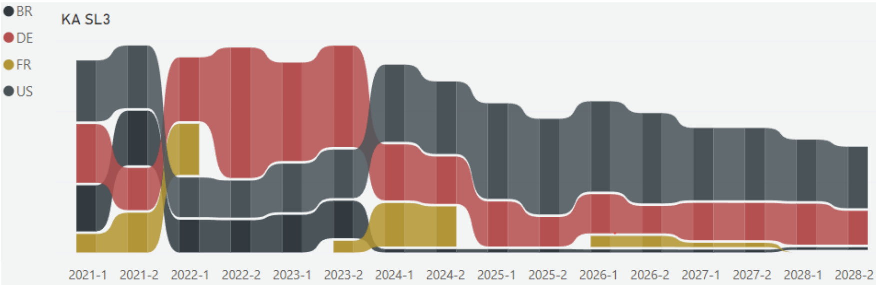


Figure 5-20: Ribbon Chart displaying volumes with the same delivery country for line KA SL3.

An extra feature of the 'Delivery Country' page includes an additional map displaying the distribution of orders to specific countries (see Figure 5-21).

Figure 5-21: Map indicating the distribution of volumes in delivery countries.

5.5.4.4 Detailed Line & Site View

The sixth page is called 'Line/Site Details' and is a dashboard for overviewing a line or site's activity. Unlike all other pages, only one line or site can be viewed at a time. However, several diagrams are available. For the example, line KA SL3 is used.

A special feature of PowerBI is the interactivity of the diagrams, which is particularly noticeable on this page. Thus, in almost every diagram, a display element can be selected, with the consequence that this element is highlighted. Since all visualisations are based on the same data model, the selection is transferred, and the corresponding data is highlighted in all affected charts. An example is shown in Figure 5-22.

Figure 5-22: Effect of the interactivity of charts in PowerBI

Starting at the top left, important key figures of the line are displayed (see Figure 5-23). These include the allocated volume, the average utilisation over the considered period and the average CT per piece. Right next to it, a combination of a doughnut chart and a column chart is placed. Via a selection bar with basic buttons, which work by using the parameter 'Filter Line/Site Details', the attribute by which the volumes should be grouped may be selected. In the example, 'Delivery Country' is chosen. In the doughnut diagram, it can be seen quickly how large the total share of the respective groups is. The column chart next to it breaks this information down into the half-year periods.

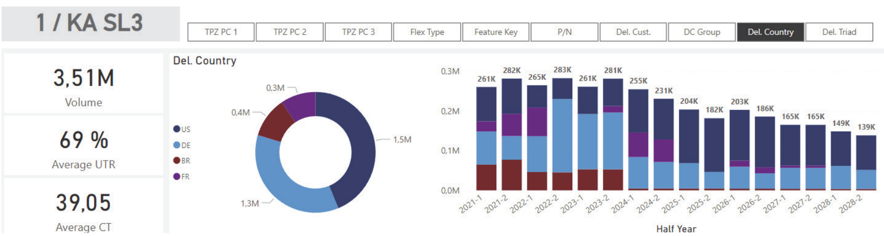


Figure 5-23: KPIs, Donut chart and column chart of a specific line or site

At the bottom of the page, there are two charts. The one on the left (Figure 5-24) reflects a miniature representation of the Capacity chart and shows the standard and reserve capacity as a stacked column chart, supplemented by a line representing the allocated volume. Below the chart, a single row is added indicating the Utilisation Rate per half year.

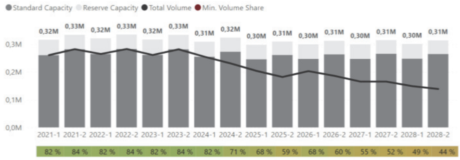


Figure 5-24: Miniature Capacity-Chart and utilisation rate

The last visualisation (Figure 5-25) is a line chart that shows both the development of the average CT and the development of the utilisation rate per half year. As can be seen in the figure, there is also a tooltip effect in this diagram, as in all diagrams on this page, as well as the possibility of performing a drill through the underlying data.

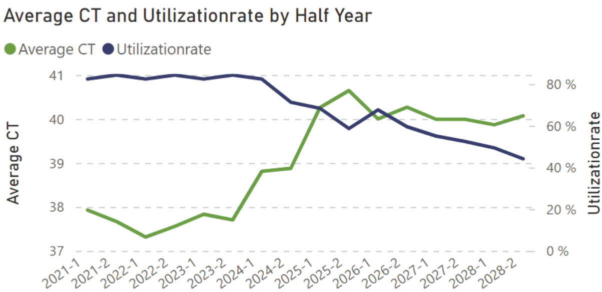


Figure 5-25: Line Chart indicating average CT and utilisation rate

5.5.4.5 Releases

Another page displays releases that require customer approval. It is important to note that orders can share their release, as explained in Chapter 4, with their sister orders, so also, if only one release was purchased, several part numbers can appear as released. To facilitate this, the filter allows the selection of purchased releases, providing an accurate count of necessary release processes instead of displaying all orders awaiting approval. The 'Initially Released' button shown in Figure 5-26 distinguishes between releases that can run in parallel, that enhance flexibility and those that are essential because they have not been approved elsewhere yet.

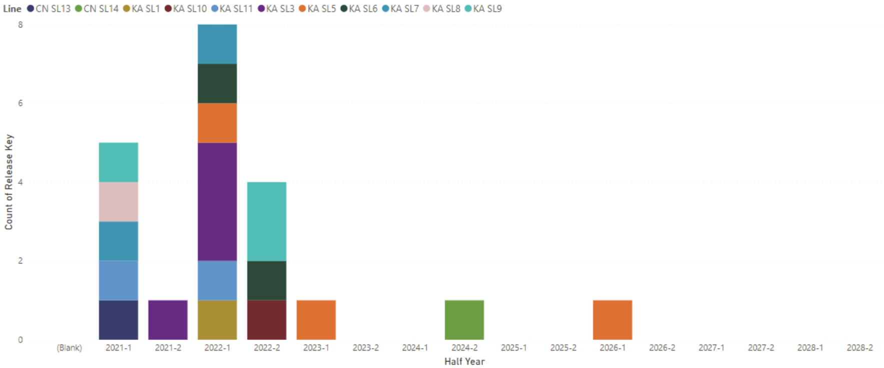


Figure 5-26: Chart representing the number of necessary releases.

5.5.4.6 Cost Overview

The last page of the report on the evaluation of individual scenarios is focused on the analysis of the costs, which APVA aims to minimise. On the one hand, it was decided to present the aggregated results clearly. For this purpose, a card visual was selected from PowerBI for each measure, and a colour was assigned to each category to ensure clear identification across the entire page (Figure 5-27). Below the cards, a legend was built using the treemap visualisation element, which also serves as a filter element by utilising the interactivity between the diagrams. This creates an intuitive way for the user to filter the corresponding chart by cost category.

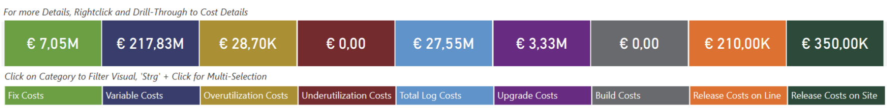


Figure 5-27: Card elements displaying the objective value per cost category

In addition to displaying results on card elements, the costs are plotted in a stacked column chart along the half-years (Figure 5-28). This makes it possible to see the expenses per half-year at first glance, the relation between each cost category, and the categories with the largest share of the costs.

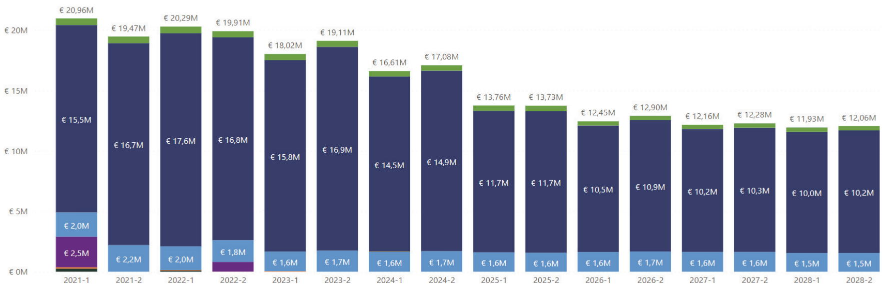


Figure 5-28: Stacked column chart displaying the costs of a single scenario

5.5.4.7 Detailed Logistic Costs Overview

Logistic costs are further differentiated into inbound and outbound logistic costs. A specific view of both can be taken from the Chart 'Log KPI' (see Figure 5-29).

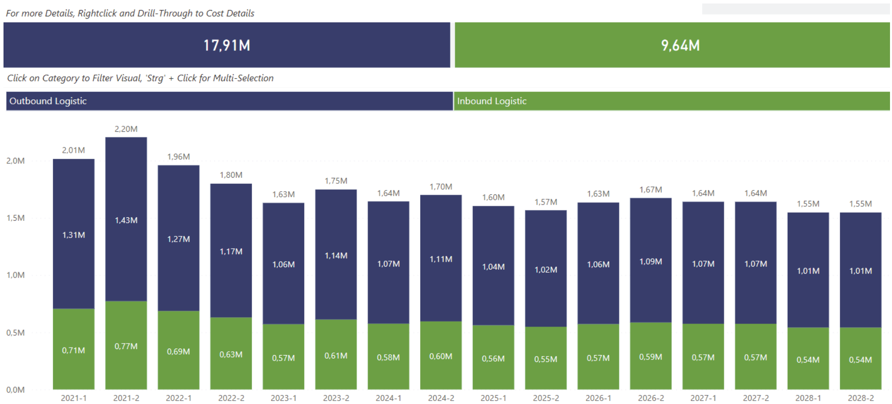


Figure 5-29: Stacked column chart displaying the logistic costs of a single scenario

Supply chain planning faces a myriad of costs that significantly impact their inbound and outbound logistic costs. Among these, freight costs, CO_2 costs, Free Trade Agreement (FTA) costs, inventory costs, and packaging costs stand out as crucial factors shaping the efficiency and sustainability of supply chains. Although the optimisation layer does not differentiate between freight costs or emission costs when it comes to logistic costs, the visuals can restore information related to the calculated allocation based on detailed information from the logistics department shown in Figure 5-30. This table is only generated when additional information is offered by the logistics, which is not necessarily the case.

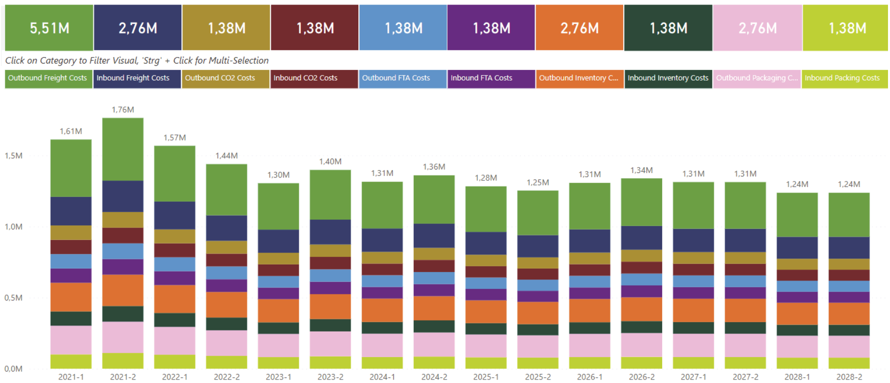


Figure 5-30: Stacked column chart displaying the logistic costs of a single scenario

5.5.5 Multi Scenario Visualisations

To facilitate the comparison of various scenarios, four further report pages were developed: a 'Capacity Comparison', a 'Line Feature Comparison', and a 'Cost Comparison' page. These pages can still be filtered for lines, sites, or half-year periods. A significant difference lies in the fact that multiple scenarios can now be selected in the filter context.

For the example shown, constraints, such as only China being allowed to serve China exclusively and all other countries not being allowed to be served by China, are suspended. This means China is allowed to serve the whole Asian and European continent now and vice versa.

5.5.5.1 Capacity Comparison

To cater to the crucial need of production planners for a comprehensive overview, a diagram was crafted, enabling the simultaneous display of up to four scenarios. At its foundation lies a clustered column diagram, displaying maximum capacity per scenario and half-year in a subdued grey hue. Layered atop this, another clustered column diagram with darker columns illustrates the standard capacity per scenario and half-year. Finally, a line chart is superimposed, representing allocated volumes per scenario. The resulting chart for the site in China is depicted in Figure 5-31. Notably, the chart avoids the division into lines and sites, for now overloading the user with too much information.

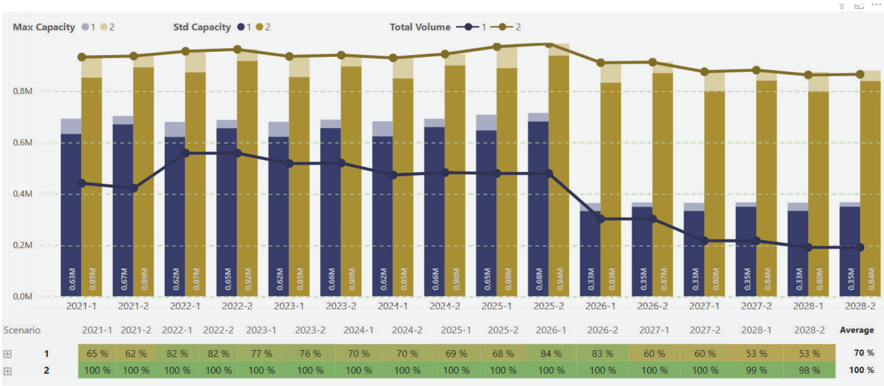


Figure 5-31: Multi-scenario Capacity-Chart for the site CN - the numbers 1 (“baseline”) and 2 (“All for all”) stand for the according scenario

5.5.5.2 Allocation Comparison

To meet the needs of GPN planners to understand which volumes have been reallocated starting from a basis he already knows, a further visualisation has been developed. This visualisation allows users to track changes in allocated volume based on different categories such as P/N, Delivery Country, and Delivery Customer. Users have the flexibility to choose categories to focus on and can also apply filters to analyse data by line and site. In the example of Figure 5-32, a strong drift in allocated volumes on this line, from China volumes to volumes in other countries, is noticeable, based on the changed constraint, that this is allowed within scenario 2 but not in scenario 1.

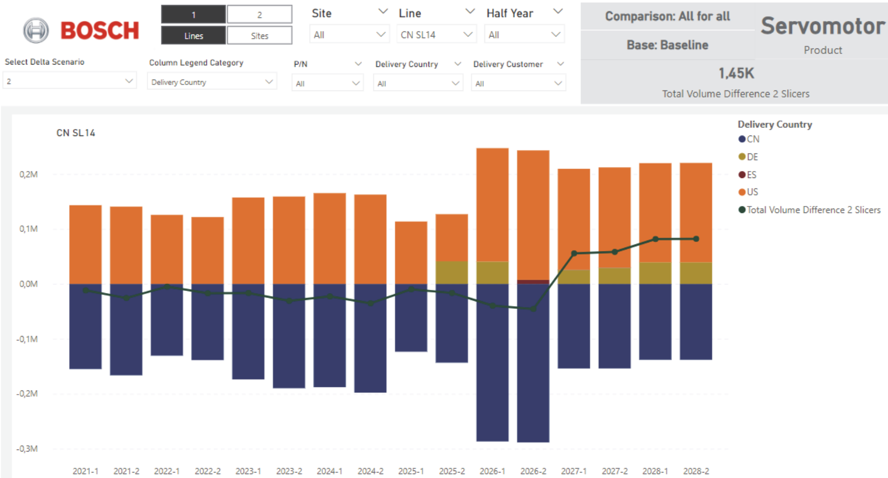


Figure 5-32: Multi-scenario Allocation-Chart for the line CN SL14 for the category Delivery Country

5.5.5.3 Station Comparison

A matrix was developed to facilitate comparing line features across various scenarios. The basic structure of the matrix is identical to a single-scenario representation. The key difference lies in the addition of the 'Scenario' attribute from the 'all Lines' table, creating nested rows. Each line within these rows showcases the data for the respective selected scenario. Figure 5-33 provides an illustrative example, with three lines selected, demonstrating distinct line features specific to each scenario.

Lines	Active	Big Gear	Housing 1	Housing 2	Housing 3	Lefts	Right	Small Gear
⊟ KA SL9								
2	Yes	Yes	Yes		from 2021-1	Yes	Yes	from 2021-1
1	Yes	Yes	Yes		from 2021-1	Yes	Yes	from 2022-2
⊟ KA SL8								
2	No		Yes	Yes	Yes	Yes	Yes	Yes
1	until 2022-1		Yes	Yes	Yes	Yes	Yes	Yes

Figure 5-33: Comparing features of lines between scenarios 1 and 2.

5.5.5.4 Cost Comparison

The cost comparison's delta analysis is patterned after the layout of the 'Cost Overview' page, employing a similar structure and colour scheme. In the top row, costs for the initially chosen scenario are displayed by category, following the same functional principles as the 'Cost Overview'. Directly below, the user can select the scenario for comparison, and the delta costs are calculated, appearing in the second coloured row.

To offer a quick overview of cost disparities within each category, a relative change is showcased and colour-coded based on the prefix. This information is presented using card elements, with data sourced from the '% Change' measure filtered by category. A colour-coded legend is included, serving as a filter menu for subsequent visuals. The upper half of the 'Cost Comparison' page is depicted in Figure 5-34.

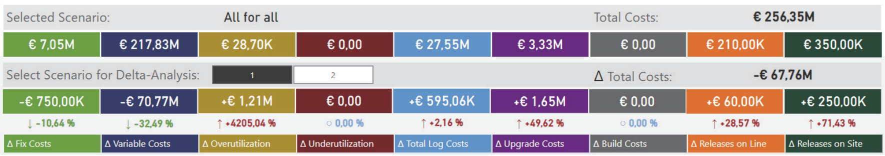


Figure 5-34: Cost comparison and delta Calculation between two Scenarios

Furthermore, a stacked column chart, like the one in 'Cost Overview,' displays delta costs per category and half-year. This chart, shown in Figure 5-35, swiftly indicates significant differences in various half-years per category. For instance, it illustrates that the comparison scenario necessitates significantly fewer variable costs, that more investments have to be made in the beginning (+1,7 Mio. €), or that logistics costs in later periods are a few higher for intercontinental shipments.

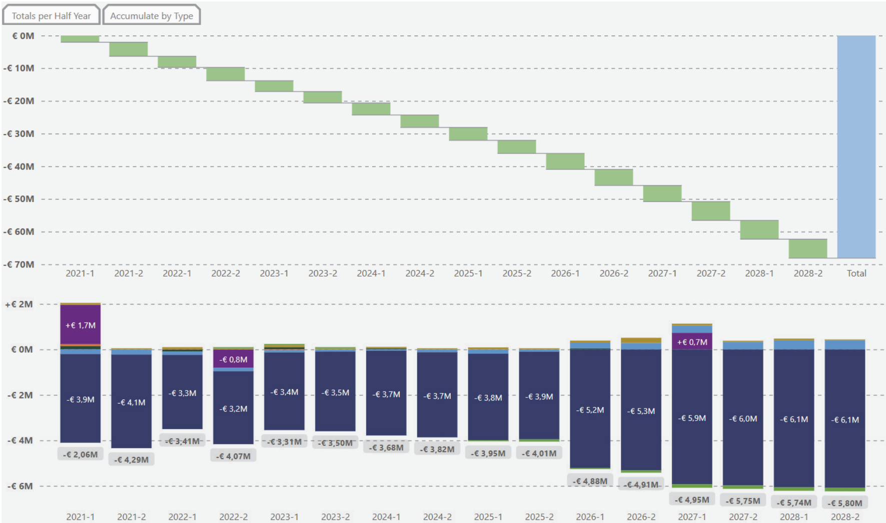


Figure 5-35: Delta costs accumulated (top) and per category (bottom) between scenarios 1 and 2

Lastly, a focus on logistic costs is also possible on a comparison level like section 5.5.4.7. Here, inbound and outbound logistic costs can be observed in detail.

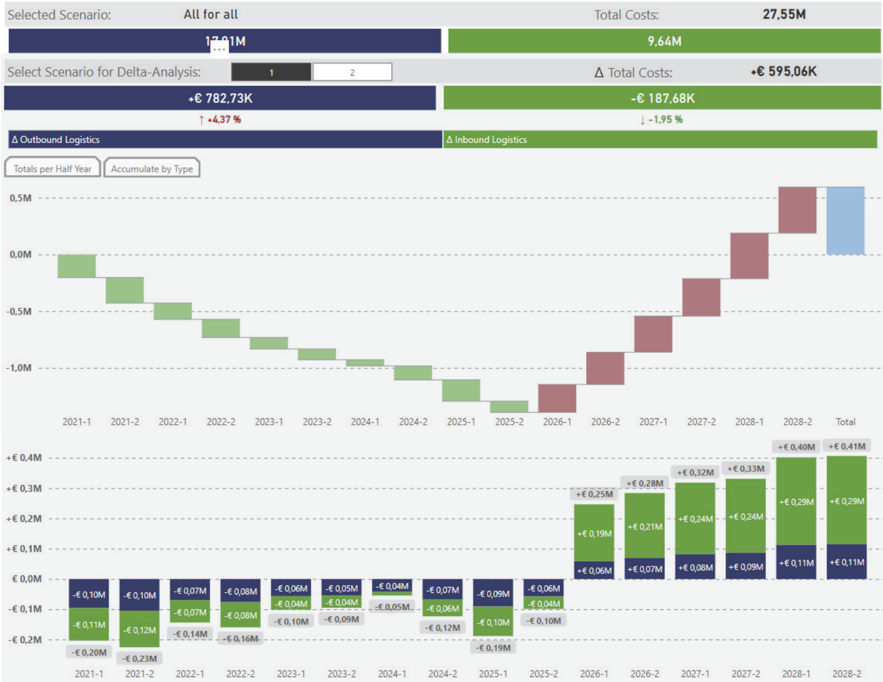


Figure 5-36: Delta logistic costs accumulated (top) and per category (bottom) between scenarios 1 and 2

5.6 Cross-functional Logistics Interface

The challenges in logistics are intimately connected to the production of goods and services, demanding spatial, temporal, and quantitative coordination before, during, and after production to address availability issues (Kiener et al. 2018, p. 4). Production and logistics are intricately linked in the operational service framework, where the establishment of fixed transport and logistics networks is essentially concentrated in densely populated, industrialised nations. Production planning faces individual complexities, hindering seamless coordination across the entire value chain caused by consideration of cost minimisation, logistic requirements, and availability of resources. (Albach 2002)

Optimising both production and logistics for companies operating globally necessitates integration. Lack of coordination leads to suboptimal network operation. Central planning units may synchronise supply chain levels to achieve common goals, considering coordination tasks such as procurement and information flow control. It also enhances synergy, scalability, overall planning quality, and control (Schuh & Stich 2012, p. 430; Rudberg & Olhager 2003, p. 3). Actual logistics cost data, when used in detailed planning, potentially lead to better local fulfilment, lower overall internal costs, reduced emissions, and minimised total internal and external costs (Schuh & Stich 2012, p. 423).

In this thesis, the costs for inbound from the supplier, intercompany, and outbound to the customer are optimised by the intended integration of the logistics department into the product-mix-allocation process.

When analysing and designing production and logistics networks, a holistic approach is at the top of the list of requirements. The processes and structures of the company's own production facilities, warehouse locations, procurement and distribution routes, transport and tariffs must be considered, as well as those of suppliers and customers. Even small companies find it challenging to maintain an overview. This is all the truer for large companies like Bosch. The company has 15 divisions with 60 product groups worldwide, 270 production plants, 800 logistics centres, 20,000 direct suppliers and 250,000 customers. When reviewing and optimising its logistics networks and designing new networks, Bosch pursues a holistic, cross-functional TCO (total cost of ownership) approach. The Supply Chain Network Design (SCND) model emerges as a critical tool in achieving this integration. (Barck 2018)

As a digital twin of the Bosch supply chain, the SCND includes a simulation model, which is implemented with the PSI Software presented in Section 3.1.3, mirroring the physical network using data primarily sourced from the Bosch logistics data pool. The model links and corroborates this data, providing a foundation for optimisation and simulation of the GPN, too. Thus, the transformative shift from manual to streamlined analysis, offering users an up-to-date overview of material movements, master data, packaging data, and the geographic locations of customers and suppliers, is enabled. (Barck 2018)

The SCND software finds primary application among Bosch supply chain designers, warehouse footprint optimisation associates, and risk management professionals. It aids in identifying dependencies, simulating the impacts of planned changes, and considering network structures, procurement, and distribution channels, as well as the means and costs of transport. (Barck 2018)

Current applications of the SCND software include simulation for assessing scenarios related to location decisions and evaluating cost impacts resulting from shifts in market demand. In the overall scope of this thesis, it gets used to calculate the full-opportunistic inbound and outbound logistic costs to produce each order from each site under consideration. The consideration of inter-company costs is already implemented for prototypical use but still needs to be in operative use.

Therefore, a process for the interaction of the SCND software and APVA is necessary. As overseas deliveries with air freight share are assumed, this also has a stock-reducing effect, as local deliveries are better valued.

- First, an allocation must be created in which all possible supply relations occur. This information is generated in a specified optimisation run, where the APVA tool identifies the technical ability of allocation for each order-to-site combination based on current technical features at the lines at the sites but also considers defined investment opportunities in updating or building lines.
- This result of the APVA tool is provided to the SCND software to calculate the resulting inbound and outbound logistics costs.
- The SCND software creates a detailed cost matrix for every order and potential manufacturing location as input for the APVA tool. Logistics costs include costs for emissions during transport, freight, and actual and simulated customs costs. Soft factors like lead times, inventory, and emissions in tons are also analysed but are still not being used for further processing.
- The result is analysed, transferred to the APVA tool as one cost factor, and finally used for a subsequent iteration.
- In the end, an output showing the exact logistics cost for the given allocation is generated. The SCND software can validate or compare these output logistics costs.

This interface allows for the order-related allocation of actual logistics costs. The iterative procedure involves creating an allocation with all possible supply relations, calculating detailed logistics costs for each order, and using this data to optimise the allocation in subsequent iterations.

6 Industrial Validation

Following the implementation of the Automated Plant Volume Allocation (APVA) using the developed concepts, a comprehensive analysis was carried out to assess the practical application of the Decision Support System (DSS) in real-world scenarios. This analysis serves as a validation of the methodology, addressing the challenges associated with handling large volumes of data and ensuring data quality in real-life situations. The analysis is divided into three main parts. Firstly, a scientific examination of the framework is conducted to identify robust decisions in the Global Production Network (GPN). Secondly, the level of usage and automation is evaluated to gauge the progress of implementation across different GPNs within the company being studied. Lastly, a utilisation concept is presented, along with examples showcasing successful applications, to demonstrate how the APVA can be effectively deployed and utilised. This aims to emphasise the potential of the APVA in GPN planning and improvement.

6.1 Application of the Framework to Identify Robust Decisions in GPN

This thesis focuses on examining GPNs for different products of Bosch Mobility, which is responsible for automotive components. The thesis was part of the partnership between the wbk Institute for Production Technology at the Karlsruhe Institute of Technology (KIT) and the central department of Connected Manufacturing of the Bosch Mobility division. Given the anticipated changes in the car engine market, including a decline in demand for combustion engines, the GPN will require frequent modifications in the coming years to accommodate an increasing number of product variants while overall production volume decreases. These changes must be made with limited funds to invest in a downscaled GPN. Although other GPNs in different companies may face completely different scenarios, they must still adapt frequently and under uncertain circumstances.

6.1.1 Network Design

The following application of the framework to identify robust decisions is based on a GPN, which comprises 1160 individual orders with about 200 part numbers (P/N), and its GPN comprises four production sites located in separate European and Asian countries. The four production sites accumulate a total of 15 existing production lines. The lines are at significantly different stages of expansion in terms of their capabilities and can, therefore, only produce specific variants. Moreover, operating costs, cycle times (CT), and capacities differ between the lines. Production is planned for 5 to 6 days a week in three 8-hour shifts, depending on the site. The distribution network includes 65 delivery customers located in 21 different delivery countries, all of whom are supplied by the four production sites. To incorporate logistics costs, the automotive supplier has established a separate department that can calculate the appropriate distribution costs given a source, sink, delivery period, and respective volumes.

6.1.2 Forecasting of Representative Demand Scenarios

Around 150 change drivers are specified during the phase of scenario building, which are uncertain and affect the demand for products. Therefore, existing data about the acquisition chance is used for each order that has not already been accepted. Furthermore, change drivers and their characteristics (e.g., probability, affected orders, etc.) are determined by expert interviews. Thereby, the connection between change drivers is specified, e.g., if A occurs, B does not.

Table 6 1 shows an exemplary excerpt of change drivers. Change driver W3 influences all products of the triad' EUR', whereas W7 influences all products with part number' 1'.

Table 6-1: Examples of change drivers

Change Driver	Cate-gory	In-stance	Probability ($P(C)$)	Influ-ence (I)	Earliest Period of Entry (T_1)	Latest Period of End (T_2)	Depend-ency
W3: New eFuel	Triad	EUR	0.1	0.2	7	16	-
W7: Quality problem	Part Number	1	0.05	-1	1	16	-

The approach was tested at different points in time with different resulting datasets and, thus, scenarios. The validation, as published in Bruetzel et al. (2022), uses an older dataset with less change driver of the same GPN as for the application of the method for identifying robust decisions. Thus, the following are distinct between two different datasets.

6.1.2.1 Pre-study – Validation of the Method to Forecast Representative Production Demand Scenarios

Based on the defined change drivers, 100.000 demand scenarios are simulated by a Monte Carlo analysis. To ensure applicability and manageability in optimisation, a limited number of representative scenarios are now created. To enable a comparison, different numbers of representatives (4, 8, 10, 12, and 15) are created by choosing the amount of scenarios as an input parameter in the beginning. Existing information is used to create possible clustering criteria. In the use case, the total number of parts, the number of parts per period, customer, and country of delivery, as well as the number of different variants in a scenario, is employed to create 106 different criteria.

By applying a PCA and the elbow criterion, the reduction to seven factors occurs in the use case. Based on these factors, clustering is now performed using the K-means algorithm. The resulting number of clusters corresponds to the number of desired representative scenarios. These are each chosen as the scenario closest to its centroid. Figure 6-1 shows the resulting scenario funnel of ten representative scenarios with respect to the criterion "number of pieces" and the probability of the occurrence of the underlying cluster (thickness of the line) in comparison to the scenario funnel of 1000 randomly simulated scenarios.

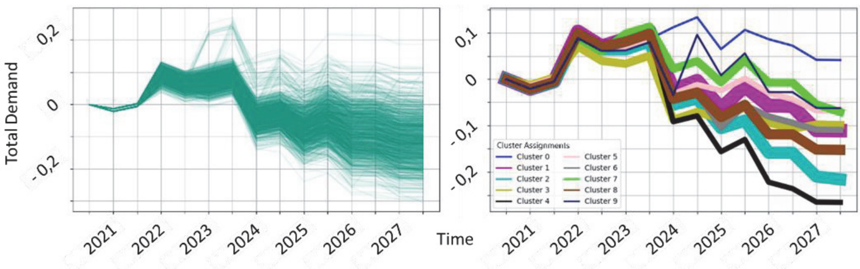


Figure 6-1: Scenario funnel for 1000 random (left) and ten representative (right) scenarios. The figure shows the periodic demand for 16 half-year demand periods. The line thickness indicates the probability weight p_ω of each scenario.

Now, the optimisation for the representative scenarios takes place using the deterministic model of Section 4.1, assuming each scenario gets solved independently (all recourse variables are set to 1). In addition to the representative scenarios, a reference of 100 random scenarios is optimised to evaluate the approach. While the optimisation of the representative scenarios can be done overnight, even for fifteen scenarios, the reference needs more than three days, which is inapplicable in a short-cycled planning process. To estimate the quality of the representative scenarios in the use case, a cost distribution is first created based on the reference. Then, the cost distribution is calculated using the representative scenarios and the overlap of these distributions with the reference is used as a measure of quality. The calculation also considers the weightings of the representatives. Figure 6-2 shows the results and, additionally, the distribution based on different samples of ten random scenarios each. The use of ten random scenarios leads to a large scatter and, on average, to significantly worse results even than four representative scenarios.

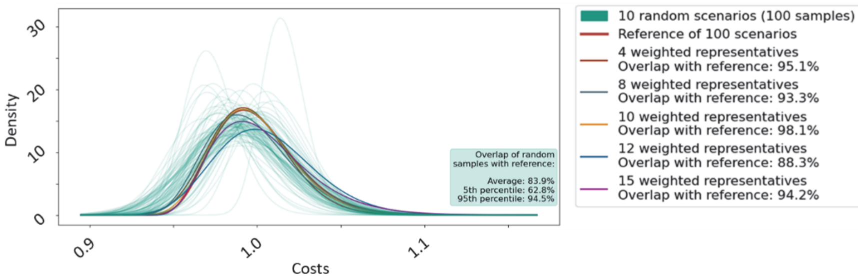


Figure 6-2: Comparison of cost distribution of weighted representatives and random samples

In the use case, ten representative scenarios lead to a significantly better result than 95% of the random samples.

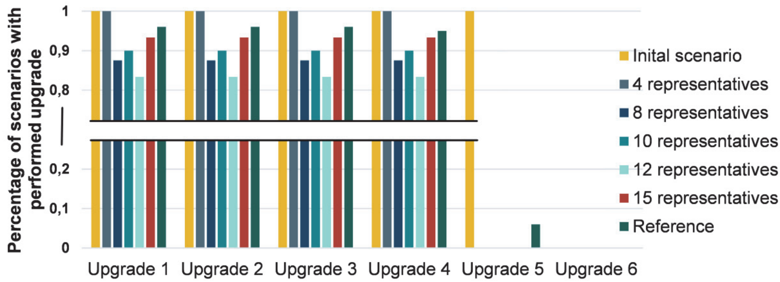


Figure 6-3: Comparison of upgrade decisions of initial, reference of 100 and representative scenarios

A second evaluation is done by comparing the line upgrade decisions, which would be done with the reference of 100 scenarios, the representative scenarios, and the current (initial) planning scenario. In the use case, these upgrades, e.g., buying a feature at a line, come with high investments. The result, which is displayed in Figure 6-3, shows that the representative scenarios would lead to the same decision as the reference. At the same time, the initial plan seems to be an edge scenario, which would differ here.

These evaluations show the representativeness of the scenarios in the described use case, leading to more robust decisions.

6.1.2.2 Main Study –Method for Identifying Robust Decisions

Based on the pre-study, ten scenarios with more change drivers are chosen for the updated dataset. A Monte Carlo simulation simulates another 100,000 demand scenarios. With the data provided, sets of representative scenarios for different K are generated. Figure 6-4 shows the periodic demand for $K = 10$ in 16 half-year demand periods.

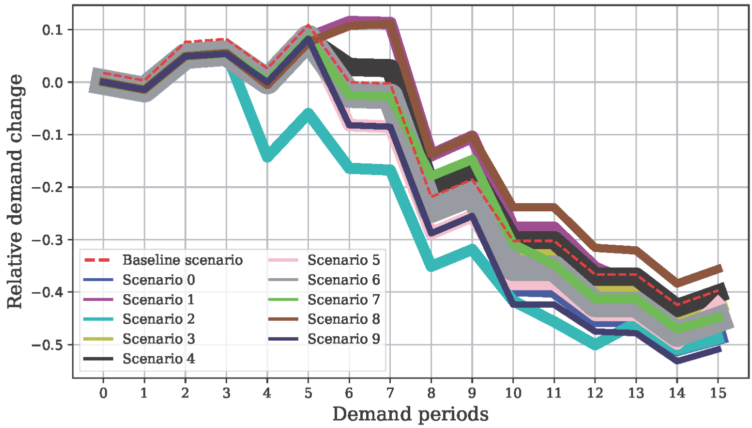


Figure 6-4: Different reference demand scenarios. The figure shows the periodic demand for $K = 10$ in 16 half-year demand periods. The line thickness indicates the probability weight p_ω of each scenario.

Since multiple individual products were considered, each curve displays the cumulated demand of all products in each period. The baseline scenario represents the demand forecast without any change drivers. Table 6-2 lists individual scenario probability weights and the cumulated demand volumes to provide some means of comparability. On a more detailed level, these generated scenarios provide us with precise information on the order size of each order in the specific scenario $\eta_{o,t,\omega}$, enabling the robust modelling approach.

Table 6-2: Scenario probabilities

Scenario (ω)	0	1	2	3	4	5	6	7	8	9
Probability weight (p_ω)	0.1266	0.0896	0.0789	0.1303	0.1314	0.09	0.1870	0.0642	0.0578	0.0437
Cumulated Demand	0.9097	0.9795	0.8439	0.9332	0.9574	0.9022	0.9226	0.9378	1	0.8833

6.1.3 Application of the Method to Identify Robust Decisions

The transformation process of the originally deterministic model to a stochastic optimisation model that identifies robust decisions must be examined through quantitative comparison. In this regard, the solution to identify robust decisions entails the costs incurred for integrated consideration of the demand scenarios by their respective probabilities (see Table 6-2).

To determine a baseline, first the most general means of comparison is performed by uniformly setting $\Phi^{(\cdot)}$ to be non-recourse for all demand periods and contrast the objective value with that of the deterministic model, where $\Phi^{(\cdot)}$ is generally recourse.

Considering the non-recourse nature of the decision variable $z_{l,t,\omega}$, the decision of which lines are active is made once for all scenarios, contrary to the deterministic model, where lines are deactivated in each scenario individually, as best fits. Cumulatively, the robust model shuts down lines over 52 periods exactly. In contrast, the deterministic model shuts down lines over 69.5 periods on average (25.2% increase), which is very similar to the 68 periods of the flexibility approach later in Section 6.1.5. This results in more than triple the underutilisation costs in the robust optimisation model as capacity then exceeds utilisation in the low-volume scenarios.

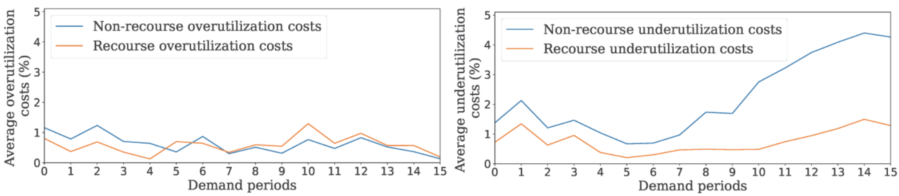
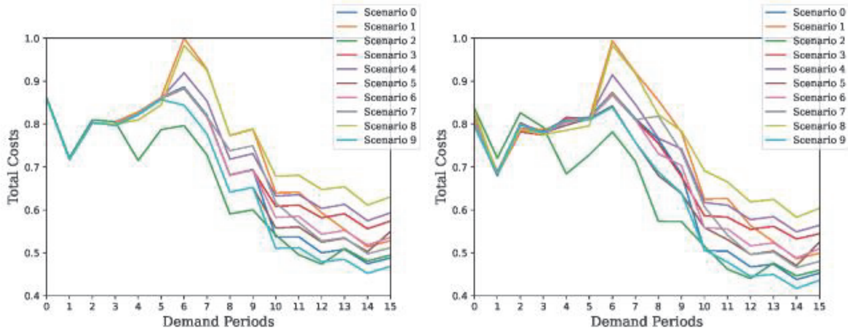


Figure 6-5: Periodical utilisation costs for the non-recourse and recourse decision of $z_{l,t,\omega}$

Figure 6-5 shows an increase in underutilisation costs for the robust optimisation model. A similar reverse effect for overutilisation costs in early periods, where demand is high, is observed. The relative cost increase when applying robust optimisation under these conditions amounts to 2.15% for 10 scenarios, which is considerable relative to potential savings due to the large-scale nature of this use case.



Periodic costs where $\Phi^{(\cdot)}$ is fully non-recourse   Periodic costs where $\Phi^{(\cdot)}$ is fully recourse

Figure 6-6: Periodic costs for ten scenarios

The costs of the robust and deterministic model are displayed on a periodical level in Figure 6-6 for each scenario. We observe an increased parallelism in the non-recourse graph, especially for periods 8 to 9. This directly relates to the fact that the non-recourse decision variables are decided upon once for all scenarios.

Subsequently, the analysis examines the impact of aversion on the performance of the robust model across various values of the risk-aversion parameter λ (see Table 6-3). For a fully conservative model ($\lambda = 1$), the overall costs experience a slight increase of 0.24%. To compare this with the alteration in demand consideration within the conservative robust optimisation model, a sum-product calculation is implemented for both $\lambda = 0$ and $\lambda = 1$, revealing a resulting reduction in demand of 0.08%. This shows that the slight decrease in the overall demand is offset by the increasing probability of high-demand scenarios, such as scenarios 1 and 8.

In this context, the analysis focuses on the model's performance in more exceptional situations, as λ is designed to address the impact of more severe demand changes. Regarding the current production capacities, the demand volume for the high-volume, low-probability scenario 8 is fictively increased by 10% to simulate overestimation. To facilitate a comparative assessment of outcomes in this scenario, the demand for the low-volume, low-probability scenario 2 is simultaneously decreased by 10%, representing underestimation.

The scenario probabilities for $\lambda = 0$ maintain the same. The increase in demand affects the objective value far more (+1.21%) than the decrease (-0.46%). When setting $\lambda = 1$, the divergence of the objective value impact is strongly decreased. The objective value change for the demand increase (+1.53%) outweighs the objective value change for the demand decrease (-0.89%) far less than for $\lambda = 0$. The described findings are summarised in Table 6-3.

Table 6-3: Impact of λ on the objective value for demand changes

Changed Scenario (ω)	Demand Change	$\lambda = 0$		$\lambda = 1$	
		Relative sumproduct of cumulated demand increase	Relative objective value increase	Relative sumproduct of cumulated demand increase	Relative objective value increase
baseline	baseline	baseline	baseline	-0.08%	+0.24%
8	+10%	+0.65%	+1.21%	+1,1%	+1.53%
2	-10%	-0.72%	-0.46%	-0.83%	-0.89%

The final section of the results analysis examines the impact of different recourse settings of decision variables on the overall cost of the GPN. The objective values for different recourse settings are listed in Table 6-4. Diverging from the original robust optimisation model, setting $z_{l,t,\omega}$ and consequently the line activity as a recourse variable results in an increase in the objective value, amounting to 1.1%. In the case of configuring release purchases $y_{o,l,\omega}^{line}$ and $y_{o,s,\omega}^{facility}$ as recourse decision variables, there is a noticeable reduction in average release costs. This, however, leads to an overall objective value increase of 2.02% compared to the model with fully recourse decisions. Similarly, by designating the decision variable for line upgrade purchases, $u_{l,t,\omega}^{receiving}$, as recourse, the model no longer prioritises upgrade investments in high-volume scenarios to ensure sufficient capacity on lines for all scenarios. This results in an objective value increase of 1.89% as compared to the model with fully recourse decisions.

Table 6-4: Result comparison for different recourse decisions

Recourse Indication for decision variables					Relative objective value increase
$e_{l,t,\omega}$	$u_{l,t,\omega}^{receiving}$	$y_{o,l,\omega}^{line}$	$y_{o,s,\omega}^{facility}$	$z_{l,t,\omega}$	
1	1	1	1	1	1
0	0	0	0	0	1.0215
0	0	0	0	1	1.011
0	0	1	1	0	1.0202
0	1	0	0	0	1.0189

Note that these recourse settings generally only serve to validate the impact of different settings. In reality, this setting does not optimise anything.

6.1.4 Industrial Application of the Methodology for Identifying Robust Decisions

The concrete settings of which variables are not recourse have to be derived from the company strategy and depend on the speed of implementation of decisions. E.g. for a test at Bosch, decisions on investments in new features and the activity of existing ones were considered non-recourse for three years in this early time period. Releases were considered to be recourse. A performed experiment shows that reducing the reaction time of the aforementioned three years by half to one and a half years led to expected savings of 0.01% for all scenarios but 0.32% for edge scenario 2 with low volume.

A further experiment compares how identified robust decisions perform against today's decisions from the deterministic model at the baseline scenario (see Figure 6-7). Therefore, the decisions of the first three years are predetermined, such that these investments must be made, and no others are possible within these time periods. Then, the model is applied deterministically 30 times on entirely new, randomly drawn scenarios from the Monte Carlo simulation, each by each. The result shows that the fixed decisions of the robust planning approach lead to expected relative objective decreases of 0.29% and outperform the baseline in 29 of 30 scenarios. Only for scenario 23 do the decisions based on the baseline perform better, because the indicated volumes are very close to the baseline scenario.

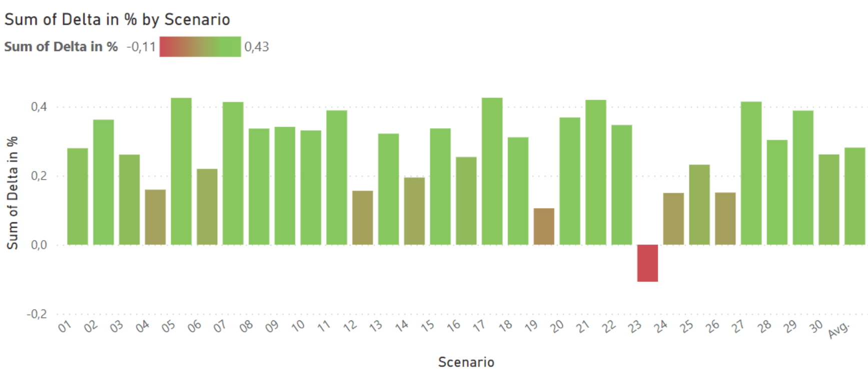


Figure 6-7: Relative cost savings by scenario for unforeseen scenarios for robust approach decisions against the decision from the baseline scenario

6.1.5 Evaluation of Flexibility Restriction without Forecasting

The effect of the flexibility constraints 33-40 of Section 4.1.5 regarding setting minimums for in- and outbound flexibility per site gets analysed for a specific volume scenario to test their effect for different settings. Costs are compared, focusing on inbound and outbound flexibility requirements, with a minimum requirement of 50% (high flexibility scenario) applied and no constraints on flexibility (baseline scenario). This means that in the tested case, each site has to be able to reallocate 50% of its overall site volumes to another site of the GPN, which is already capable of producing it, while transport is already planned through a warehouse because of being a flextype. On the other hand, in case of cancelled volumes, the site has to be able to source volumes amounting to the same volume (also 50% of the site's volume) as inbound flexibility.

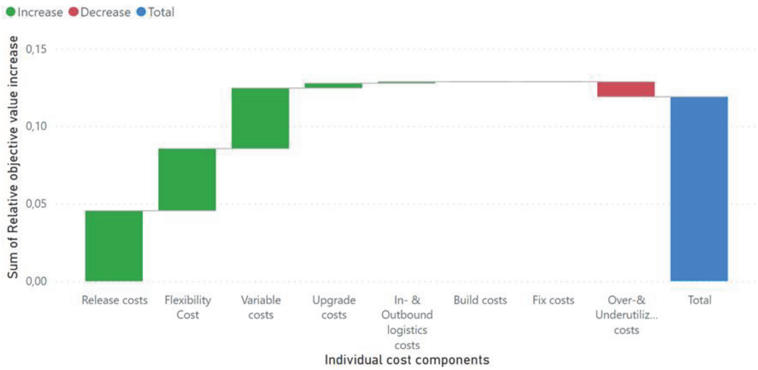


Figure 6-8: Relative change of the cost components by flexibility requirements

Figure 6-8 shows the effect of the mentioned flexibility requirements on different cost types. Overall costs increase by +11.90% compared to the baseline scenario. As the tool has to assure sufficient flexibility, it is forced to purchase more releases at several sites (+4.54%), make more product volumes producible on different lines by purchasing flextypes (+4.01%) and upgrading the remaining ones (+0.31%). Furthermore, the lines in the high-cost location are consistently used more intensively, as these lines are the most advanced in terms of existing features, thereby suffering higher variable costs (+3.9%), but at the same time decreasing overutilisation costs in low-cost sites (-0.97%).

The constraints on flexibility are leading to the desired outcome of incorporating more flexibility without the need to process additional demand scenarios. Thus, they offer a faster approach to improving the robustness of the GPN; however, they are not as accurate as applying the aforementioned method to identify robust decisions for given specific uncertainties.

6.2 Success Stories

The DSS within the GPN does not inherently yield any direct monetary benefits for the company. Its value becomes tangible through its application in the planning of GPN operations. After the exemplary complete application of the approach in Section 6.1, the following will show real-world applications of the approach to improve actual GPNs. To reduce the complexity while introducing such a DSS within GPNs, the approach was applied in each case for only one volume scenario, thus not considering robustness.

The collaborative effort undertaken has resulted in the exploration of various scenarios and strategies with the goal of improving productivity, adapting to changing external factors, and effectively managing internal changes, such as the introduction of new product variants within the GPN. Although specific quantification of the benefits derived from proactive decision-making cannot be disclosed completely, the following examples are presented to illustrate successful applications.

6.2.1 Decision on the Allocation of a New Product in an Existing GPN

The product group for the first case is the same as mentioned in Section 6.1.1. There are 1160 individual orders with about 200 variants, and its GPN comprises four production sites located in separate European and Asian countries. The four production sites accumulate a total of 15 existing production lines. The lines are at significantly different stages of expansion in terms of their capabilities and can, therefore, only produce specific variants. Moreover, operating costs, CTs, and capacities differ between the lines for specific product variants. Here, the focus is on two lines at two sites located in Europe, which were chosen to be upgraded by an investment in order to enable the production of a new product generation. While the investment at a lead site is irreversibly decided, the decision at a low-cost site is still under consideration. After the regular adjustments of the sales volumes, it became apparent that the volumes for this new product generation were decreased, such that a unique line upgrade would be enough to fulfil demand, which was not possible with the old sales volumes.

The outcomes of three distinct scenarios designed to optimise the production process for the new product generation with the new sales volumes are presented. In the baseline scenario, the original plan was kept such that the new generation production was initiated at the lead site, followed by an investment in an additional update at a low-cost site (scenario 1). Subsequently, a scenario where the entire production volume was concentrated at the lead site, utilising only one production line, was explored (scenario 2). An analysis of costs and flexibility was conducted to evaluate these strategies.

Surprisingly, the analysis indicated that despite the demand for the new generation not exceeding the capacity of one line, the cost savings by not investing in enabling an additional line at the low-cost site (scenario 1) are quite low in the end, while flexibility at the lead site is strongly reduced. This unexpected finding was attributed to the high cycle time of the new generation, leading to significant overall operational time savings at the high-cost lead site by exchanging the orders of the new product generation with higher cycle time with runner variants, which are much more effective at the high-cost sites. Therefore, the strategy constraint of producing a specific share of the overall order volume at the high-cost site was not violated. Consequently, scenario 3 was devised, involving the reallocation of the stations related to the production of the new generation from the introducing high-cost site to the low-cost site. The costs associated with reallocating the stations were factored into this scenario, and only one line was enabled for the new generation, akin to the second scenario.

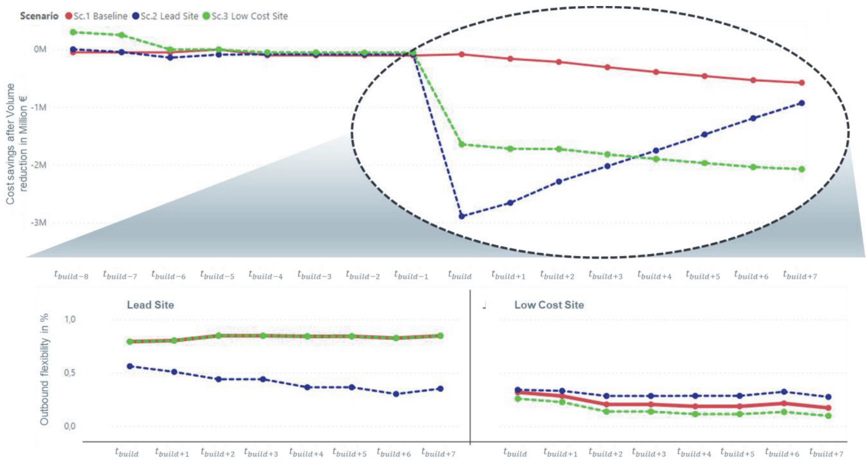


Figure 6-9: Comparison of costs and outbound flexibility for the different investment possibilities

In terms of costs, the reallocation in scenario 3 resulted in additional cost savings. Despite these savings, it is notable that the third scenario exhibited less flexibility compared to the second scenario at the low-cost site (see Figure 6-9). As this flexibility is too low for company standards, in a further step, it needs to be checked whether other volumes at the low-cost site can be used as flextypes in the future.

The controlling department rigorously examined these results in charge, and although there were minor differences in the recalculated savings, the overall conclusions remained consistent. The findings highlight the intricate balance between costs and flexibility in the context of the production strategies for the new generation.

6.2.2 Decision on Reallocation of a Production Line

Another use case involved optimising a further GPN and analysing critical decisions regarding the reallocation of a production line for the Asian market. This strategic move aims to capitalise on the advantages offered by regions with lower labour and operational costs, ultimately reducing the overall production expenses while producing locally for the customer and thereby reducing logistic costs.

Currently, the GPNs operate from two sites in Europe, one site in America and one site in China, and are suffering from decreasing volumes in the American market and increasing in the Asian market (see Figure 6-10). Investigations are to be done on whether the America line should be reallocated to an existing site or even to a further site in Asia. For this product, only six variants exist. Each production site currently only has one production line. There are only a few orders that are not transferrable, as there is one product variant that needs a particular station currently located at the lead plant in Europe.

Figure 6-10: World map showing the demand for different delivery countries by size

The decision-making process for the reallocation of the production line to a low-cost area is multifaceted. It requires a thorough analysis of the cost differentials, considering not only labour but also reallocation costs of machine resources, necessary costs by re-releasing existing customers from the current production site and logistic costs. By evaluating these elements, APVA supports the identification of regions where the production process can be executed with optimal efficiency and minimal expenditure.

Moreover, integrating the reallocated production line seamlessly into the existing network while optimising transportation and supply chain logistics is a pivotal aspect of this decision. Efficient coordination for the capacities at the leaving production sites during the reallocation, coupled with streamlined logistics, guarantees that the reallocation process results in higher cost savings.

The optimisation effort includes a supplier matching process based on current sourcing information to identify possible inbound logistic costs. One weakness is that new suppliers in Asia cannot be found for all parts. This led to an interesting finding by APVA, especially when changing the assumptions on the current Capital Cost rate (CC).

Scope:	Scenario 1 Outbound Low CC	Scenario 2 Outbound +Inbound Low CC	Scenario 3 Outbound +Inbound High CC
Reallocation of line to:	Asia	Asia	EU
Costs in Mio. [€]		Delta vs. Sc.1	Delta vs. Sc.2
Investment & Customer Releases	--	+0.7	-0.9
Manufacturing	--	+0.7	+2.0
Logistics	--	-4.3	-7.0
Total costs [€]	--	-3.0	-5.9

Insights		Volume switch EU LC -> EU HC based on inbound	Build up a new line in EU LC instead of Asia

CC = Capital Cost rate

Figure 6-11: Analysis of savings involves evaluating various logistical premises. The savings are derived from the examination of updated cost assumptions applied to existing allocation scenarios.

Figure 6-11 shows that the consideration of inbound logistic costs has a high impact on additional cost savings. In this case, APVA finds a solution where the high-cost (HC) site gets more volume from the low-cost (LC) site in Europe to save inbound logistic costs while suffering higher manufacturing costs. The reallocation of the production line to Asia still stands for Asian production volumes.

However, when the rates for capital costs are considered high, APVA recommends re-allocating production to the existing low-cost site in the EU. This recommendation is grounded in substantial savings for inbound logistics and investments. The advantage stems from the presence of an established supplier base at the low-cost EU site, coupled with the fact that during planning for certain pre-products, it could not be confirmed at that stage that they could be sourced in Asia. These savings outweigh the lower manufacturing costs in Asia.

6.3 Maturity Model for DSS as Digital Twins in GPN

After demonstrating the practical application of the approach, a maturity model is being developed aiming to offer a structured framework for assessing the evolution of process usage and automation within the context of DSS utilised as a digital twin for GPN based on Maatoug (A_ 2021), as the ones mentioned in Appendix H do not entirely fulfil the needs for this thesis. It will later serve as a basis for the evaluation of the overall implementation process.

The model encompasses two dimensions necessary for evaluating DSS in digital twins, as shown in Figure 6-12: the maturity levels of usage for the level of automation and the maturity levels of automation focusing on data interfaces. Each dimension is divided into distinct stages that represent the organisation's progress and sophistication in implementing regular usage and automation practices.

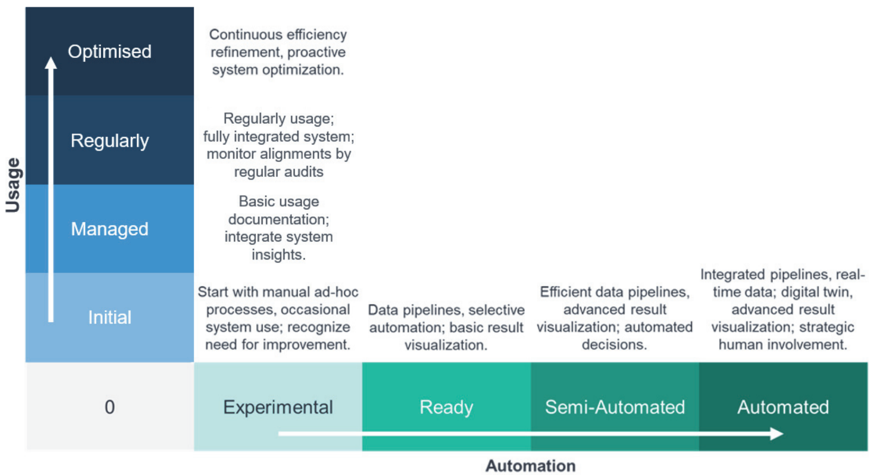


Figure 6-12: Two-axis maturity model for usage and automation based on Maatoug (A_ 2021)

6.3.1 Maturity Levels of Usage

Initial: In the Initial stage, organisations are at the outset of adopting the DSS throughout the process. Inserted data are ad hoc and lack consistency, relying on individual expertise. The DSS´s usage is sporadic, with a focus on recognising the need for process improvement.

Managed: Progressing to the Managed stage, organisations adopt a more structured approach to use the DSS efficiently. Fundamental processes are documented, and decision-making incorporates insights from the DSS more often. Key performance indicators (KPIs) success in the application of the DSS and regular reviews identify areas for improvement. This stage signifies a conscious effort to align processes with DSS´s capabilities.

Regularly: Advancing to the Regularly stage, the usage of the DSS becomes fundamental. High integration between the DSS and production processes leads to efficient decision-making. The commitment to the usage of the DSS is high, and decisions are regularly based on the DSS´s outcomes.

Optimised: The Optimised stage represents the highest level of usage for the DSS in production. Processes are continually refined for maximum efficiency and effectiveness, leveraging advanced analytics and machine learning. Data from the DSS is used proactively to anticipate production needs, identify trends, and optimise resource allocation. The DSS becomes indispensable for strategic decision-making, enhancing the organisation's adaptability and success in dynamic production environments. This stage reflects a mature and agile approach to production decision support through continuous improvement and innovation.

6.3.2 Maturity Levels of Automation

Experimental: In the initial stage, organisations rely on manual processes in their DSS for production, leading to potential inconsistencies and delays. Initial experiments explore the need for process automation and highlight the inefficiencies of manual methods, laying the groundwork for considering automation.

Ready: Progressing organisations introduce data pipelines and selective automation efforts within their DSS, establishing fundamental data pipelines to streamline data flow. Partial automation and basic automatic result visualisation enhance consistency, reliability, and transparency in decision-making, emphasising the significance of data pipelines and result visualisation.

Semi-Automated: Advancing to the Semi-Automated stage, data pipelines play a pivotal role in reducing manual efforts while automatic result visualisation becomes more sophisticated. Automation is incrementally integrated, significantly enhancing the efficiency, reliability, and transparency of production processes and highlighting the synergy between components.

Automated: In the final stage, fully integrated data pipelines enable comprehensive automation in the DSS for production. The DSS operates seamlessly, utilising real-time data for autonomous decision-making. The digital twin enhances capabilities for predictive analysis and optimisation, while automatic result visualisation provides intuitive insights. Human involvement focuses on continuous optimisation, emphasising the critical role of these components in achieving high-level automation performance and establishing a data-driven foundation for production.

6.3.3 Assessment of the Current Maturity Level

The assessment of the current maturity level of the DSS for production involves a structured and systematic approach that encompasses both usage and automation dimensions. The method is designed to provide a comprehensive understanding of the organisation's readiness and effectiveness in utilising the DSS for optimal decision-making and production processes. The following steps outline the assessment process:

Framework Development: A customised assessment framework needs to be developed, aligning with the organisation's specific production goals, industry standards, and objectives. The framework is designed to capture relevant factors within the usage and automation dimensions.

Data Collection: Comprehensive data is gathered through a combination of methods, including surveys, interviews, documentation analysis, and workshops. Key stakeholders from various levels of the organisation, including production managers, data analysts, technical experts, and decision-makers, are engaged in sharing their insights.

Scoring System: A scoring system is devised, assigning numerical values to different aspects within each dimension. The scoring is based on predefined criteria that reflect different maturity levels, ranging from poor to highly mature. This allows for a quantitative assessment of various elements.

Dimension Assessment:

- **Usage Dimension:** Each aspect within the usage dimension is evaluated based on the established criteria. The organisation's ability to document processes, engage stakeholders, align decision-making, foster collaboration, and incorporate feedback is scored.
- **Automation Dimension:** Like the usage dimension, each aspect of Automation is evaluated. The assessment includes measuring the impact of automation, adaptability to change, resource allocation, data accessibility, integration, result visualisation, and alignment with production goals.

Data Analysis: The collected data and scores are analysed to understand the organisation's strengths and weaknesses within each dimension.

Gap Identification: By comparing the obtained scores against predefined benchmarks, gaps in the organisation's maturity level become apparent. Areas that require improvement are pinpointed, helping to prioritise actions.

Actionable Recommendations: Based on the analysis, actionable recommendations are developed. These recommendations are tailored to address specific gaps and challenges identified during the assessment. They serve as a roadmap for improving both usage and automation aspects.

Implementation Strategy: An implementation strategy is formulated to guide the organisation in enhancing its DSS's maturity level. The strategy outlines the steps, timelines, responsible organisation, and resources required for successful execution.

Continuous Improvement: The assessment process doesn't end with recommendations; it's a continuous loop of improvement. The organisation monitors the implementation progress, adjusts strategies if necessary, and periodically reassesses the maturity level to track improvements.

6.3.4 Evaluation of the Maturity Level for Different GPN

After applying the methodologies to forecast representative demand scenarios and for identifying robust decisions in Section 6.1, a comparative analysis regarding the maturity levels of usage and automation at different GPNs at Robert Bosch GmbH, among others the already presented ones in Section 6.2, is performed (see Appendix I and Appendix J) and evaluated in Figure 6-13.

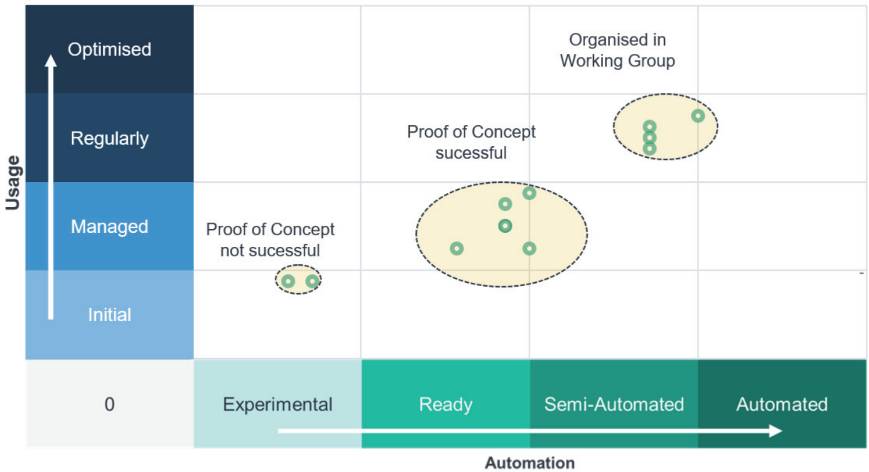


Figure 6-13: Maturity Level of usage and automation for twelve use cases where the APVA was applied

The maturity level of usage within the organisation for different GPNs hinges on official participation, with a dedicated workforce contributing to the overarching project. The four highlighted use cases at the top right of Figure 6-13 are members of the Working Group, showcasing organisational cohesion and heightened usage maturity. These GPNs play a pivotal role in processes related to collaboration, knowledge sharing, and stakeholder engagement. The cluster formed by these activities is characterised by consistently high levels of engagement, active participation, and effective communication among teams using the decision support system through the Working Group. The organisation excels in fostering a collaborative environment, ensuring that key stakeholders are actively engaged in implementing usage and contributing to the successful integration of the system within the planning process. While the result presentation is already automatic and in operative use by the end users, the automated input of data is also already accessible. Still, it can only be performed by data experts and not by the end users themselves.

Within the medium-degree cluster, use cases that have successfully applied a proof of concept are identified. If the stakeholders of these use cases decide to further engage in the application of APVA, user training, including skill development, adaptability to changing production scenarios, and alignment of decision-making processes with insights from the decision support system, begins. While these areas demonstrate a moderate degree of effectiveness, there is room for improvement.

Unfortunately, two use cases had to be discontinued due to an inadequate initial database, network complexity, and low estimated benefits within the fixed constraints of planning. In these areas, the organisation still faces challenges, such as high reliance on individual skills for data collection, affecting the alignment of processes.

The enhanced data collection method presented in Section 5.4.2 has elevated the maturity level of automation. Initially applied as a prototype in a specific use case, this method can be universally generalised and applied. Given the uniform storage of CTs and customer releases for other products in the Hadoop Cluster, the Python scripts and methodology have already been successfully practised for three other use cases (see top right of Figure 6-13). Consequently, if data quality is good enough, the automation of data acquisition becomes universally applicable, requiring only the modification of the database name in the SQL queries. The additional automation of data provides two primary advantages: a reduction in time and enhanced performance scalability. Managing extensive volumes of data from diverse sources, each with varied formats, is a complex undertaking. Automation significantly economises time in handling CTs within the data flow and diminishes human intervention, resulting in time savings, heightened data reliability, and reduced potential for human errors.

7 Conclusion and Research Perspectives

In conclusion, this thesis addresses critical research gaps in the field of Global Production Networks (GPNs). It contributes a valuable methodological framework to the existing literature that assesses the fulfilment of the objectives presented in Section 1.3, aligning with the initial motivation of this research. Table 7-1 evaluates this thesis using the criteria established in Section 3.2.

	Modeling of Flexibility in GPNs	Forecasting Representative Demand Scenarios	Identifying Robust Decisions within GPNs	Solution Approach	Integration within Planning Processses	Use Case	(Partially) Automated Data Input
Modeling production networks							
This thesis	●	●	●	Monte-Carlo Simulation, K-Means, PCA, MILP, Flexibility Constraints, SQL Server and Maturity Models, Digital Twins	◕	Automotive Supplier	◕

Table 7-1: Fulfillment of research requirements by the presented approach

By introducing a novel approach to incorporate and quantify outcomes within an industrial GPN using multiple demand scenarios, this research transcends the research gaps and answers the resulting research questions identified in Section 3.2 with the following key areas:

Flexibilities within the Network Model: This thesis significantly bridges the research gap by shedding light on the previously insufficient attention given to finding appropriate solutions that simultaneously consider both volume and product-mix flexibility in production systems. To incorporate volume and product-mix flexibility, sites possess outbound and inbound flexibility metrics. Outbound flexibility is defined by the production volume that is anticipated to be produced at the site under consideration but could also be produced at another site. Inbound flexibility is defined by the production volume that the site under consideration would be able to take over from another site. The constraints for flexibility are leading to the desired outcome of incorporating more volume and product-mix flexibility without the need to process additional demand scenarios. Thus, they offer a faster approach to improve the robustness of the GPN. However, they are not able to outperform the application of the method to identify robust decisions for given specific uncertainties.

Solution Robustness: The thesis tackles the research gap related to the difficulty in determining representative demand scenarios in stochastic models and the need for effective methods to condense information from multiple scenarios into fewer ones for robust, optimal decisions. The proposed methodology offers a promising avenue for enhancing results and optimal robustness for the entire planning horizon in the face of uncertainty. The empirical findings of this research demonstrate notable shifts in the cost structure, particularly in line utilisation and corresponding costs. Furthermore, it illuminates the impact of demand scenario estimations on robust decision-making, emphasising the vulnerability of robust decisions to overestimates rather than underestimates. From the results presented, it can be derived that edge scenarios benefit the most from shorter implementation cycles and that the approach leads to an overall improvement. At the same time, these decisions are still near optimal at a later point in time, leading to reliability and planning robustness. Lastly, the presented robust planning approach leads to more robustness in scenarios that were not used for optimisation itself, showing the information robustness of the approach. The implementation of the advanced approach regarding solution robustness still requires much expert knowledge and is not easily applicable for production planners without more profound knowledge in OR.

Implementation of Decision Support Systems in Production: Addressing the identified research gap, this thesis delves into practical steps, challenges, and best practices for successfully adopting and integrating DSS in GPNs. This encompasses considerations such as the design of the interface, user experiences, training of end users and data governance. The actual implementation at Bosch still lacks standardised processes with the DSS and thoroughly professional software with even higher useability. However, the usage of the tool and the commitment to further development already exist.

Data Integration: The thesis effectively navigates the challenge of integrating data from diverse sources within organisations to construct effective digital twins for GPNs. By emphasising the need for methodologies and strategies for data modelling, acquisition, and integration in GPN decision-making contexts, this thesis contributes to filling the identified research gap. The enhanced data collection method in the prototype case raised the maturity level of automation. The further automation of data acquisition for more GPN will provide advantages such as time reduction, enhanced performance scalability, and improved data reliability, reducing the potential for errors. As databases differ from company to company and even between different product GPNs, data pipelines still have to be adapted GPN-specifically and are time-consuming to establish. As the implementation of the data model is still prototypical for one use case, the integration of data from further GPNs into a Bosch-wide 'Data Market' remains a significant task which the company itself must take.

The maturity levels of usage and automation are contingent on official participation, with a cluster of first movers representing use cases within a Working Group, showcasing high organisational cohesion and usage maturity. These GPNs excel in collaboration, knowledge sharing, and stakeholder engagement, fostering a collaborative environment for effective DSS utilisation. In the medium degree cluster, use cases that successfully applied a proof of concept, supported by trained users from the high degree cluster, are identified. Further engagement involves user training, skill development, and aligning decision-making processes with insights from APVA. Unfortunately, two use cases had to be discontinued due to challenges like inadequate database support and network complexity, highlighting areas for improvement, particularly in data collection and decision-making alignment for the company, but for the tool itself, too. In the future, guidelines are needed on when the usage of the tool makes sense and under which circumstances the efforts are higher than the benefits. For example, small production networks or networks that only produce one product variant with a completely similar line configuration are not expected to benefit from the usage of APVA.

By integrating different parties in one tool, the tool enabled the company to first perform the product-mix-allocation process optimally, not only from a manufacturing point of view but also considering logistic costs order specifically. Apart from the economic advantages, on-site production is favoured due to these logistics costs and, thus, implicitly, the emission costs. The approach, therefore, not only improves the cost structure but also the sustainability aspects. The method can be extended to other GPNs and different types of scenarios. Overall, the method provides a valuable tool for decision-makers to plan and optimise GPNs under uncertain circumstances. The integration of production and logistics in the future might be further improved by considering the optimisation of the supplier base as well.

In the future, the method presented in this thesis holds the potential for extension and application to other GPNs. This would enable decision-makers to evaluate different scenarios, expanding the usefulness of the method beyond its current implementation in Bosch use cases. It can serve as a versatile tool for planning and optimising GPNs under uncertain circumstances, as well as for other companies.

Future research could explore innovative methodologies, such as implementing day-dreaming factories that optimise operations based on computational capacities (Nassehi et al. 2022). By analysing the points at which costs switch between different scenarios, we can gain a deeper understanding of bottlenecks within the GPN. This understanding will lead to solutions that broaden the range of possible options. For instance, if a scenario is disproportionately expensive when using the proposed framework, increasing the risk aversion factor may be considered. Suppose this adjustment does not yield improved results. In that case, it suggests that the tool's inputs are insufficient, and additional investments in stations or new production lines may be necessary to address these critical bottleneck scenarios.

This forward-thinking strategy aligns with the evolving landscape of computational capabilities and underscores the continuous commitment to addressing challenges in GPN optimisation.

Furthermore, the seamless integration of this DSS as a comprehensive digital twin of the GPN with other DTs and its subsequent integration into the company's business processes have the potential to enhance its capabilities significantly. This integration is pivotal in propelling the company towards complete digitalisation, unlocking a multitude of advanced functionalities and efficiencies within the overall operational framework.

8 Summary

Within this thesis, a need for a comprehensive strategy that introduces a decision support system (DSS) aimed at optimising global production networks (GPNs) and steering it towards the development of a digital twin (DT) designed for product allocation and robust line configuration is elaborated. The accelerated pace of product life cycles and heightened competition, e.g., in the automobile sector, necessitate cost-effective strategies. To address this, companies globally distribute production sites, creating challenges in aligning product allocation with long-term network planning decisions. Increasingly, model-based DSS are adopted to enhance planning reliability amid complexity.

The proposed model-based optimisation framework integrates a range of concepts, including Monte-Carlo Simulation, K-Means, PCA, MILP, flexibility constraints, SQL server, maturity models, digital twins, and assistance systems. At its core, this approach aims to empower employees, aiding them in navigating product mix allocation within GPN, thereby elevating the overall quality and robustness of the decision-making process.

To lay the groundwork for the proposed approach, the thesis delves into the fundamental principles of production planning within GPNs. This exploration encompasses diverse aspects such as GPN tasks, product allocation, operations research, environmental considerations, change drivers, uncertainty handling, scenario analysis, robust optimisation, assistant systems, and data management. A comprehensive review of existing literature in related areas exposes gaps in current approaches, thereby steering the formulation of research questions that guide the overarching thesis.

The subsequent sections of the thesis present the research on network configuration and solution robustness, offering a detailed exploration of a comprehensive decision support system framework for identifying robust decisions within GPN. This framework outlines the model design, parameters, variables, objective function, constraints, scenario forecasting, change driver identification, Monte Carlo simulation, and decision identification.

Transitioning further, the focus of the discussion shifts to the practical aspects of implementation and data integration. This section encompasses the real-world application of the proposed framework, detailing the establishment of a data pipeline, database identification, and the integration of automated data acquisition processes.

The outcomes of this comprehensive approach are thoroughly examined within the context of GPN. This evaluation encompasses critical aspects such as the validation of the quality of the representative demand scenarios, the application of robust decision-making, adherence to flexibility constraints, and an assessment of the maturity of implementation. Additionally, the section showcases successful operative applications that not only validate the quality of the research and model development but also provide tangible examples of the proposed approach in action. An integral component introduced is the maturity model, designed to serve as a validation tool for the various stages of implementation.

The presented approach successfully addresses the research requirements that emerged from both the motivation behind this thesis and the current state of research. Following an exploration of the benefits of this approach, additional possibilities for research emerge. These possibilities include applying the approach to more use cases.

Future research might aim to explore innovative methodologies for optimising factories based on computational capacities, employing a daydreaming approach. Analysing cost switching points between scenarios will deepen the understanding of GPN bottlenecks, leading to solutions that broaden the solution space. This strategy aligns with evolving computational capabilities, emphasising a continuous commitment to addressing GPN optimisation challenges. Additionally, integrating the DSS as a DT of the GPN with other DTs and incorporating it into the company's processes could enhance its potential, advancing toward a fully digitalised company with heightened capabilities.

Own Publications

Benfer, M.; Autenrieth, M.; Brützel, O.; Grützner, H.; Peukert, S. & Lanza, G. (2022), „Agile Erstellung von Materialflusssimulationen“, *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, 117(12), pp. 867–871, https://doi.org/10.1515/zwf-2022-1158.

Benfer, M.; Brützel, O.; Overbeck, L.; Peukert, S.; Nassehi, A. & Lanza, G. (2023), „Integrating Multiple Perspectives in Manufacturing Planning and Control: The Daydreaming Engine Approach“, *Procedia CIRP*, 120, pp. 177–182, https://doi.org/10.1016/j.procir.2023.08.032.

Bruetzel, O.; Voelkle, D.; Overbeck, L.; Stricker, N. & Lanza, G. (2022), „Automated Production Network Planning Under Uncertainty by Developing Representative Demand Scenarios“ in *Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems: Proceedings of the 8th Changeable, Agile, Reconfigurable and Virtual Production Conference (CARV2021),* Ed. Andersen et al., Springer, Cham, pp. 459–466.

Bruetzel, O.; Werz, P.; Overbeck, L.; May, M. C. & Lanza, G. (2023), „Development of a pull concept with a simulation model for the start-up phase of a fuel cell series production“. 20. ASIM Fachtagung Simulation in Produktion und Logistik 2023, p. 11, https://doi.org/10.22032/dbt.57892.

Brützel, O.; Di González Miele, R. I.; Overbeck, L. V.; May, M. C. & Lanza, G. , „Modeling of a Modular Discrete Event Simulation for Fuel Cell Assembly within a Factory Model“ in *FC³ Fuel Cell Conference. Chemnitz, 31.05./01.06.2022 (ursprünglicher Termin: 23./24.11.2021)*.

Brützel, O.; Küppers, F.; Overbeck, L.; Stricker, N.; Verhaelen, B. & Lanza, G. (2021), „Eine automatisierungsgerechte robuste Produktionsplanung“, *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, 116(1-2), pp. 44–48, https://doi.org/10.1515/zwf-2021-0009.

Brützel, O.; Overbeck, L.; Nagel, M.; Stricker, N. & Lanza, G. (2020), „Generische Modellierung von halbautomatisierten Produktionssystemen für Ablaufsimulationen“, *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, 115(11), pp. 792–796, https://doi.org/10.3139/zwf-2020-1151112.

Brützel, O.; Thiery, D.; May, M. & Lanza, G. (2022), „Optimierung einer Materialflusssteuerung zur Energieeffizienzerhöhung in der Produktion“, *Zeitschrift für* *wirtschaftlichen Fabrikbetrieb*, 117(9), pp. 591–596, https://doi.org/10.1515/zwf-2022-1106.

Fries, C.; Hölscher, P.; Brützel, O.; Lanza, G. & Bauernhansl, T. (2023), „Approach for Evaluating Changeable Production Systems in a Battery Module Production Use Case“ in *Flexible Automation and Intelligent Manufacturing: The Human-Data-Technology Nexus,* Ed.K.-Y. Kim, L. Monplaisir & J. Rickli, Springer International Publishing, Cham, pp. 207–216.

Lanza, G.; Klenk, F.; Martin, M.; Brützel, O. & Hörsting, R. (2023), „Sonderforschungsbereich 1574: Kreislauffabrik für das ewige innovative Produkt“, *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, 118(12), pp. 820–825, https://doi.org/10.1515/zwf-2023-1164.

Overbeck, L.; Brunnenkant, F.; Brützel, O. & Lanza, G. (2023), „Simulation of a factory for the integrated manufacturing and remanufacturing of batteries“. 20. ASIM Fachtagung Simulation in Produktion und Logistik 2023, p. 71, https://doi.org/10.22032/dbt.57806.

Overbeck, L.; Brützel, O.; Stricker, N. & Lanza, G. (2020), „Digitaler Zwilling des Produktionssystems“, *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, 115(s1), pp. 62–65, https://doi.org/10.3139/104.112326.

Overbeck, L.; Brützel, O.; Teufel, M.; Stricker, N.; Kuhnle, A. & Lanza, G. (2021a), „Continuous adaption through real data analysis turn simulation models into digital twins“, *Procedia CIRP*, 104, pp. 98–103, https://doi.org/10.1016/j.procir.2021.11.017.

Overbeck, L.; Le Louarn, A.; Brützel, O.; Stricker, N. & Lanza, G. (2021b), „Continuous Validation and Updating for High Accuracy of Digital Twins of Production Systems“. *Simulation in Produktion und Logistik 2021, Erlangen, 15.-17.September 2021. Hrsg.: J. Franke,* Cuvillier Verlag, pp. 609–617. ISBN: 978-3-73697-479-1.

Overbeck, L.; Le Louarn, A.; Brützel, O.; Stricker, N. & Lanza, G. (2022), „Comprehensive Validation Metrics and Precise Updating of Digital Twins of Production Systems“, *SNE*, 32(3), pp. 135–142, https://doi.org/10.11128/sne.32.tn.10613.

References

References according to the scheme (A_Name Year) refer to student work that the author of the dissertation supervised.

A_Bouzidi 2022

Bouzidi, D.-E. (2022), *Produktionsnetzwerkoptimierung aus Fertigungs- und Logistiksicht*. Master Thesis, Karlsruher Institut für Technologie (KIT), Karlsruhe, wbk Institut für Produktionstechnik.

A_Delkof 2021

Delkof, N. (2021), *Allocation Optimization – Implementation of an Interface between an existing manufacturing optimization system and a tool for calculating logistics costs*. Master Thesis, Karlsruher Institut für Technologie (KIT), Karlsruhe, wbk Institut für Produktionstechnik.

A_Feldinger 2023

Feldinger, F. (2023), *Versionierung in einer Datenbank für das globale Produktionsmanagement*. Bachelor Thesis - Co-supervised together with Martin Benfer, Karlsruher Institut für Technologie (KIT), Karlsruhe, wbk Institut für Produktionstechnik.

A_Foran 2023

Foran, A. (2023), *Developing a Scenario Analysis Concept for Robust Decision Making in a Product Mix Allocation Application*. Master Thesis, Karlsruher Institut für Technologie (KIT), Karlsruhe, wbk Institut für Produktionstechnik.

A_Hartmann 2021

Hartmann, J. (2021), *Evaluation of methods to improve performance of an MIP for automated production planning in a ramping-up production network*. Master Thesis, Karlsruher Institut für Technologie (KIT), Karlsruhe, wbk Institut für Produktionstechnik.

A_Hemeury 2021

Hemeury, E. (2021), *Erhöhung der Flexibilität und Sensitivitätsanalyse eines Allokationsmodells auf Produktionsnetzwerkebene*. Master Thesis, Karlsruher Institut für Technologie (KIT), Karlsruhe, wbk Institut für Produktionstechnik.

A_Küppers 2020

Küppers, F. (2020), *Robuste Produktionsplanung in Netzwerken unter*

Berücksichtigung von Unsicherheit. Master Thesis, Karlsruher Institut für Technologie (KIT), Karlsruhe, wbk Institut für Produktionstechnik.

A_Maatoug 2021
Maatoug, M. G. (2021), *Database Maturity Model for the Automation of the Product-Mix-Allocation-Process*. Master Thesis, Karlsruher Institut für Technologie (KIT), Karlsruhe, wbk Institut für Produktionstechnik.

A_Orhan 2022
Orhan, M. C. (2022), *Development of an object-oriented base model for production network modelling*. Master Thesis - Co-supervised together with Martin Benfer, Karlsruher Institut für Technologie (KIT), Karlsruhe, wbk Institut für Produktionstechnik.

A_Rädler 2020
Rädler, C. (2020), *Gestaltung von Skalierungsstrategien für wandlungsfähige Montagesysteme globaler Produktionsnetzwerke bei unsicherer Zukunftsentwicklung*. Master Thesis, Karlsruher Institut für Technologie (KIT), Karlsruhe, wbk Institut für Produktionstechnik.

A_Sachsenweger 2022
Sachsenweger, D. (2022), *Wertstromübergreifende Auftragsallokation und Netzwerkkonfiguration*. Master Thesis, Karlsruher Institut für Technologie (KIT), Karlsruhe, wbk Institut für Produktionstechnik.

A_Schmidt 2023
Schmidt, K. L. (2023), *Development and Visualization of a Data Model for Analysis and Optimization of Product Allocations in a Global Production Network*. Master Thesis, Karlsruher Institut für Technologie (KIT), Karlsruhe, wbk Institut für Produktionstechnik.

A_Voelkle 2020
Voelkle, D. (2020), *Szenarioanalyse als Konzept zur Berücksichtigung von Unsicherheit in der Planung von globalen Produktionssystemen*. Master Thesis, Karlsruher Institut für Technologie (KIT), Karlsruhe, wbk Institut für Produktionstechnik.

Albach, H. (Ed.) (2002), *Wertschöpfungsmanagement als Kernkompetenz*. *Festschrift für Horst Wildemann [zum 60. Geburtstag],* Gabler, Wiesbaden. ISBN: 978-3-409-11927-6.

Alden, J. M.; Costy, T. & Inman, R. R. (2002), „Product-to-plant allocation assessment in the automotive industry“, *Journal of Manufacturing Systems*, 21(1), pp. 1–13, https://doi.org/10.1016/S0278-6125(02)90008-7.

Apt, W.; Bovenschulte, M.; Priesack, K.; Weiss, C. & Hartmann, E. (2018), *Einsatz von digitalen Assistenzsystemen im Betrieb,* Bundesministerium für Arbeit und Soziales, [Berlin].

ISO 23247

ISO 23247 (2021), *Automation systems and integration—digital twin framework for manufacturing—Part 1: overview and general principles.*International Organization of Standardization.

Azaron, A.; Venkatadri, U. & Farhang Doost, A. (2021), „Designing profitable and responsive supply chains under uncertainty“, *International Journal of Production Research*, 59(1), pp. 213–225, https://doi.org/10.1080/00207543.2020.1785036.

Bachlaus, M.; Pandey, M. K.; Mahajan, C.; Shankar, R. & Tiwari, M. K. (2008), „Designing an integrated multi-echelon agile supply chain network: a hybrid taguchi-particle swarm optimization approach“, *Journal of Intelligent Manufacturing*, 19(6), pp. 747–761, https://doi.org/10.1007/s10845-008-0125-1.

Backhaus, K.; Erichson, B.; Plinke, W. & Weiber, R. (2018), *Multivariate Analysemethoden,* Springer Berlin Heidelberg, Berlin, Heidelberg. ISBN: 978-3-662-56654-1.

Bamberg, G.; Coenenberg, A. G. & Krapp, M. (2019), *Betriebswirtschaftliche Entscheidungslehre,* Verlag Franz Vahlen, München. ISBN: 978-3-800-65885-5.

Barck, R. (2018), „Supply Chain Network Design. Ein intelligentes Netzwerk aufbauen“, *IT&Production*(12/2018), pp. 82–84.

Baringo, L. & Conejo, A. J. (2013), „Risk-Constrained Multi-Stage Wind Power Investment“, *IEEE Transactions on Power Systems*, 28(1), pp. 401–411, https://doi.org/10.1109/TPWRS.2012.2205411.

Becker, A.; Stolletz, R. & Stäblein, T. (2017), „Strategic ramp-up planning in automotive production networks“, *International Journal of Production Research*, 55(1), pp. 59–78, https://doi.org/10.1080/00207543.2016.1193252.

Becker, L. T. & Gould, E. M. (2019), „Microsoft Power BI: Extending Excel to Manipulate, Analyze, and Visualize Diverse Data“, *Serials Review*, 45(3), pp. 184–188, https://doi.org/10.1080/00987913.2019.1644891.

Benfer, M.; Brützel, O.; Overbeck, L.; Peukert, S.; Nassehi, A. & Lanza, G. (2023), „Integrating Multiple Perspectives in Manufacturing Planning and Control: The Daydreaming Engine Approach“, *Procedia CIRP*, 120, pp. 177–182, https://doi.org/10.1016/j.procir.2023.08.032.

Bergmann, S.; Straßburger, S. & Schulze, T. (2013), *Automatische Generierung adaptiver Modelle zur Simulation von Produktionssystemen,* Univ.-Verl. Ilmenau; Univ.-Bibliothek, Ilmenau. ISBN: 978-3-863-60084-6.

Bertsimas, D. & Sim, M. (2003), „Robust discrete optimization and network flows“, *Mathematical Programming*, 98(1-3), pp. 49–71, https://doi.org/10.1007/s10107-003-0396-4.

Bihlmaier, R.; Koberstein, A. & Obst, R. (2009), „Modeling and optimizing of strategic and tactical production planning in the automotive industry under uncertainty“, *OR Spectrum*, 31(2), pp. 311–336, https://doi.org/10.1007/s00291-008-0147-2.

Blutner, D.; Cramer, S.; Krause, S.; Mönks, T.; Nagel, L.; Reinholz, A. & Witthaut, M. (2007), „Ergebnisbericht der Arbeitsgruppe 5 “Assistenzsysteme für die Entscheidungsunterstützung”“, *Univ. Dortmund, Lehrstuhl für Förder- und Lagerwesen, https://doi.org/*10.17877/DE290R-8115.

Briskorn, D. (2020), *Operations Research*. *Eine (möglichst) natürlichsprachige und detaillierte Einführung in Modelle und Verfahren,* Springer Gabler, Berlin. ISBN: 9783662607831.

Bruetzel, O.; Voelkle, D.; Overbeck, L.; Stricker, N. & Lanza, G. (2022), „Automated Production Network Planning Under Uncertainty by Developing Representative Demand Scenarios“ in *Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems: Proceedings of the 8th Changeable, Agile, Reconfigurable and Virtual Production Conference (CARV2021),* Ed. Andersen et al., Springer, Cham, pp. 459–466.

Brützel, O.; Küppers, F.; Overbeck, L.; Stricker, N.; Verhaelen, B. & Lanza, G. (2021), „Eine automatisierungsgerechte robuste Produktionsplanung“, *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, 116(1-2), pp. 44–48, https://doi.org/10.1515/zwf-2021-0009.

Buergin, J.; Blaettchen, P.; Kronenbitter, J.; Molzahn, K.; Schweizer, Y.; Strunz, C.; Almagro, M.; Bitte, F.; Ruehr, S.; Urgo, M. & Lanza, G. (2019), „Robust assignment of customer orders with uncertain configurations in a production network for aircraft manufacturing“, *International Journal of Production Research*, 57(3), pp. 749–763, https://doi.org/10.1080/00207543.2018.1482018.

Buergin, J.; Helming, S.; Andreas, J.; Blaettchen, P.; Schweizer, Y.; Bitte, F.; Haefner, B. & Lanza, G. (2018), „Local order scheduling for mixed-model assembly lines in the aircraft manufacturing industry“, *Production Engineering,* pp. 759–767, https://doi.org/10.5445/IR/1000129757.

Bundschuh, M. (2008), *Modellgestützte strategische Planung von Produktionssystemen in der Automobilindustrie*. *Ein flexibler Planungsansatz für die Fahrzeughauptmodule Motor, Fahrwerk und Antriebsstrang*. Diss., Universität Augsburg. ISBN: 978-3-830-03794-1.

Cisek, R.; Habicht, C. & Neise, P. (2002), „Gestaltung wandlungsfähiger Produktionssysteme“, *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, 97(9), pp. 441–445, https://doi.org/10.3139/104.100566.

Cleveland, G.; Schroeder, R. G. & Anderson, J. C. (1989), „A Theory of Production Competence“, *Decision Sciences*, 20(4), pp. 655–668, https://doi.org/10.1111/j.1540-5915.1989.tb01410.x.

CMMI (2002), „CMMISM for Systems Engineering, Software Engineering, Integrated Product and Process Development, and Supplier Sourcing (CMMI-SE/SW/IPPD/SS, V1.1) Staged Representation; CMU/SEI-2002-TR-012; ESC-TR-2002-012“.

Coe, N. M.; Dicken, P. & Hess, M. (2008), „Global production networks: realizing the potential“, *Journal of Economic Geography*, 8(3), pp. 271–295, https://doi.org/10.1093/jeg/lbn002.

Date, C. J.; Lorentzos, N. A. & Darwen, H. (2014), *Time and relational theory*. *Temporal databases in the relational model and SQL,* Morgan Kaufmann, Waltham. ISBN: 978-0-128-00631-3.

Domschke, W.; Drexl, A.; Klein, R. & Scholl, A. (2015), *Einführung in Operations Research,* Springer Gabler, Berlin, Heidelberg. ISBN: 978-3-662-48215-5.

ElMaraghy, H.; Schuh, G.; ElMaraghy, W.; Piller, F.; Schönsleben, P.; Tseng, M. & Bernard, A. (2013), „Product variety management“, *CIRP Annals*, 62(2), pp. 629–652, https://doi.org/10.1016/j.cirp.2013.05.007.

ElMaraghy, W.; ElMaraghy, H.; Tomiyama, T. & Monostori, L. (2012), „Complexity in engineering design and manufacturing“, *CIRP Annals*, 61(2), pp. 793–814, https://doi.org/10.1016/j.cirp.2012.05.001.

Fattahi, M. (2020), „A data-driven approach for supply chain network design under uncertainty with consideration of social concerns“, *Annals of Operations Research*, 288(1), pp. 265–284, https://doi.org/10.1007/s10479-020-03532-9.

Ferdows, K. (1997), „MADE IN THE WORLD: THE GLOBAL SPREAD OF PRODUCTION“, *Production and Operations Management*, 6(2), pp. 102–109, https://doi.org/10.1111/j.1937-5956.1997.tb00418.x.

Few, S. (2009), *Now you see it*. *Simple visualization techniques for quantitative analysis,* Analytics Press, Oakland, CA. ISBN: 978-0-970-60198-8.

Fink, A.; Schlake, O. & Siebe, A. (2001), *Erfolg durch Szenario-Management*. *Prinzip und Werkzeuge der strategischen Vorausschau,* Campus-Verl., Frankfurt/Main. ISBN: 978-3-593-36714-9.

Fleischmann, B. & Meyr, H. (2003), „Planning Hierarchy, Modeling and Advanced Planning Systems“, *Handbooks in Operations Research and Management Science*, 11, pp. 455–523, https://doi.org/10.1016/S0927-0507(03)11009-2.

Fleischmann, B.; Meyr, H. & Wagner, M. (2015), „Advanced Planning“ in *Supply chain management and advanced planning. Concepts, models, software, and case studies,* Ed.H. Stadtler, C. Kilger & H. Meyr, Springer, Berlin, Heidelberg, New York, Dordrecht, London, pp. 71–95.

Friese, M. (2008), *Planung von Flexibilitäts- und Kapazitätsstrategien für Produktionsnetzwerke der Automobilindustrie*. Diss., Leibniz Universität Hannover, PZH Produktionstechn. Zentrum. ISBN: 978-3-939026-83-9.

Gausemeier, J.; Dumitrescu, R.; Echterfeld, J.; Pfänder, T.; Steffen, D. & Thielemann, F. (2019), *Innovationen für die Märkte von morgen*. *Strategische Planung von Produkten, Dienstleistungen und Geschäftsmodellen,* Carl Hanser Verlag GmbH & Co. KG, München [u.a.]. ISBN: 978-3-446-42972-7.

Gausemeier, J.; Fink, A. & Schlake, O. (1996), *Szenario-Management*. *Planen und Führen mit Szenarien,* Hanser, München. ISBN: 978-3-446-18721-9.

Gausemeier, J. & Plass, C. (2014), *Zukunftsorientierte Unternehmensgestaltung*. *Strategien, Geschäftsprozesse und IT-Systeme für die Produktion von morgen,* Hanser, München. http://www.hanser-elibrary.com/isbn/978-3-446-43631-2. ISBN: 978-3-446-43842-2.

Gentsch, P. (2018), *Künstliche Intelligenz Für Sales, Marketing und Service - Mit AI und Bots Zu Einem Algorithmic Business - Konzepte, Technologien und Best Practices,* Palgrave Macmillan US, Cham. ISBN: 978-3-319-89957-2.

Gölzer, P.; Simon, L.; Cato, P. & Amberg, M. (2015), „Designing Global Manufacturing Networks Using Big Data“, *Procedia CIRP*, 33, pp. 191–196, https://doi.org/10.1016/j.procir.2015.06.035.

Götze, U. (1991), *Szenario-Technik in der strategischen Unternehmensplanung,* Deutscher Universitätsverlag, Wiesbaden. ISBN: 978-3-8244-0078-2.

Govindan, K. & Fattahi, M. (2017), „Investigating risk and robustness measures for supply chain network design under demand uncertainty: A case study of glass supply chain “, *International Journal of Production Economics*, 183, pp. 680–699, DOI: 10.1016/j.ijpe.2015.09.033.

Grangel-González, I.; Rickart, M.; Rudolph, O. & Shah, F. (2023), „LIS: A Knowledge Graph-Based Line Information System“ in *The Semantic Web,* Ed.C. Pesquita, E. Jimenez-Ruiz, J. McCusker, D. Faria, M. Dragoni, A. Dimou, R. Troncy & S. Hertling, Springer Nature Switzerland, Cham, pp. 591–608.

Hambach, J. & Albrecht, F. (2014), „Methoden der Szenariotechnik in der Fabrikplanung“, *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, 109(3), pp. 117–120, https://doi.org/10.3139/104.111103.

Han, J.; Pei, J. & Kamber, M. (2012), *Data mining*. *Concepts and techniques,* Morgan Kaufmann; Elsevier, Amsterdam, Boston, Heidelberg, Amsterdam, Boston, Heidelberg. ISBN: 978-0-12-381479-1.

Handl, A. (2010), *Multivariate Analysemethoden,* Springer Berlin Heidelberg, Berlin, Heidelberg. ISBN: 978-3-642-14986-3.

Harjunkoski, I.; Maravelias, C. T.; Bongers, P.; Castro, P. M.; Engell, S.; Grossmann, I. E.; Hooker, J.; Méndez, C.; Sand, G. & Wassick, J. (2014), „Scope for industrial applications of production scheduling models and solution methods", *Computers & Chemical Engineering*, 62, pp. 161–193, https://doi.org/10.1016/j.compchemeng.2013.12.001.

Heinz, M. P. (2006), *Network Master Planning for a global manufacturing company*. Ph.D. Thesis, Cranfield University, Cranfield. http://hdl.handle.net/1826/1105 [29.02.2024].

Hochdörffer, J. (2018), *Integrierte Produktallokationsstrategie und Konfigurationssequenz in globalen Produktionsnetzwerken*. Diss., Karlsruher Institut für Technologie (KIT), Karlsruhe, wbk Institut für Produktionstechnik. ISBN: 978-3-844-05845-1.

Hochdörffer, J.; Buergin, J.; Vlachou, E.; Zogopoulos, V.; Lanza, G. & Mourtzis, D. (2018), „Holistic approach for integrating customers in the design, planning, and control of global production networks", *CIRP Journal of Manufacturing Science and Technology*, 23, pp. 98–107, https://doi.org/10.1016/j.cirpj.2018.07.004.

Hochdörffer, J.; Klenk, F.; Fusen, T.; Häfner, B. & Lanza, G. (2022), „Approach for integrated product variant allocation and configuration adaption of global production networks featuring post-optimality analysis", *International Journal of Production Research*, 60(7), pp. 2168–2192, https://doi.org/10.1080/00207543.2021.1884765.

Hoffer, J. A.; Scott, M. B. & Topi, H. (2009), *Modern database management,* Pearson/Prentice Hall, Upper Saddle River, NJ. ISBN: 978-0-137-13048-1.

IBM Institute for Business Value and IBM Strategy and Change (2007), „The IBM Data Governance Council Maturity Model : Building a roadmap for effective data governance", *Gov. An Int. J. Policy Adm.,* pp. 1–16.

Ivanov, D. & Dolgui, A. (2021), „A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0“, *Production Planning & Control*, 32(9), pp. 775–788, https://doi.org/10.1080/09537287.2020.1768450.

Jones, D.; Snider, C.; Nassehi, A.; Yon, J. & Hicks, B. (2020), „Characterising the Digital Twin: A systematic literature review“, *CIRP Journal of Manufacturing Science and Technology*, 29, pp. 36–52, https://doi.org/10.1016/j.cirpj.2020.02.002.

Kauder, S. & Meyr, H. (2009), „Strategic network planning for an international automotive manufacturer“, *OR Spectrum*, 31(3), pp. 507–532, https://doi.org/10.1007/s00291-009-0171-x.

Kessler, W. (2006), *Multivariate Datenanalyse,* Wiley. ISBN: 978-3-527-31262-7.

Khatami, M.; Mahootchi, M. & Farahani, R. Z. (2015), „Benders' decomposition for concurrent redesign of forward and closed-loop supply chain network with demand and return uncertainties“, *Transportation Research Part E: Logistics and Transportation Review*, 79, pp. 1–21, https://doi.org/10.1016/j.tre.2015.03.003.

Kilger, C. & Wetterauer, U. (2015), „The Selection Process“ in *Supply chain management and advanced planning. Concepts, models, software, and case studies,* Ed.H. Stadtler, C. Kilger & H. Meyr, Springer, Berlin, Heidelberg, New York, Dordrecht, London, pp. 301–316.

Klein, R. (2012), *Planung und Entscheidung*. *Konzepte, Modelle und Methoden einer modernen betriebswirtschaftlichen Entscheidungsanalyse,* Franz Vahlen, München. ISBN: 9783800638857.

Knight, D.; Knight, B.; Pearson, M. & Quintana, M. (2018), *Microsoft Power BI quick start guide*. *Build dashboards and visualizations to make your data come to life,* Packt Publishing, Birmingham, UK. ISBN: 978-1789138221.

Kritzinger, W.; Karner, M.; Traar, G.; Henjes, J. & Sihn, W. (2018), „Digital Twin in manufacturing: A categorical literature review and classification“, *IFAC-PapersOnLine*, 51(11), pp. 1016–1022, https://doi.org/10.1016/j.ifacol.2018.08.474.

Lanza, G.; Ferdows, K.; Kara, S.; Mourtzis, D.; Schuh, G.; Váncza, J.; Wang, L. & Wiendahl, H.-P. (2019), „Global production networks: Design and operation“, *CIRP Annals*, 68(2), pp. 823–841, https://doi.org/10.1016/j.cirp.2019.05.008.

Lanza, G.; Moser, E.; Stoll, J. & Haefner, B. (2015), „Learning Factory on Global Production“, *Procedia CIRP*, 32, pp. 120–125, https://doi.org/10.1016/j.procir.2015.02.081.

Lanza, G. & Moser, R. (2014), „Multi-objective optimization of global manufacturing networks taking into account multi-dimensional uncertainty“, *CIRP Annals*, 63(1), pp. 397–400, https://doi.org/10.1016/j.cirp.2014.03.116.

Liebler, K.; Beissert, U.; Motta, M. & Wagenitz, A. (2013), „Introduction OTD-NET and LAS: Order-to-delivery network simulation and decision support systems in complex production and logistics networks“. *2013 Winter Simulations Conference (WSC),* IEEE, pp. 439–451. ISBN: 978-1-4799-3950-3.

Link, M. & Hamann, K. (2019), „Einsatz digitaler Assistenzsysteme in der Produktion“, *ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb*, 114(10), pp. 683–687, https://doi.org/10.3139/104.112161.

Litt, G.; Jackson, D.; Millis, T. & Quaye, J. (2020), „End-user software customization by direct manipulation of tabular data“. *Proceedings of the 2020 ACM SIGPLAN International Symposium on New Ideas, New Paradigms, and Reflections on Programming and Software,* Ed.S. Kell & D. Verna, ACM, New York, NY, USA, pp. 18–33. ISBN: 978-1-450-38178-9.

Lotfi, R.; Sheikhi, Z.; Amra, M.; AliBakhshi, M. & Weber, G.-W. (2021), „Robust optimization of risk-aware, resilient and sustainable closed-loop supply chain network design with Lagrange relaxation and fix-and-optimize“, *International Journal of Logistics Research and Applications,* pp. 1–41, https://doi.org/10.1080/13675567.2021.2017418.

Lotze, H. (2018), *Automated Optimization in Production Planning*. Masterarbeit, RWTH Aachen, Lehrstuhl für Softwaremodellierung und Verifikation. https://gereon-kremer.de/static/thesis_2018_lotze.pdf [28.02.2024].

MacKay, D. J. C. (2003), *Information theory, inference, and learning algorithms,* Cambridge University Press, Cambridge. ISBN: 978-0-521-64298-9.

Matthews, R.; Rutherford, B. N.; Edmondson, D. & Matthews, L. (2022), „Uncertainty in industrial markets: The COVID-19 pandemic“, *Industrial Marketing Management*, 102, pp. 364–376, https://doi.org/10.1016/j.indmarman.2022.02.006.

Meier, A. & Kaufmann, M. (2016), *SQL- & NoSQL-Datenbanken,* Springer Berlin Heidelberg, Berlin, Heidelberg. http://nbn-resolving.org/urn:nbn:de:bsz:31-epflicht-1494660. ISBN: 978-3-662-47664-2.

Mersmann, T.; Goßmann, D. & Klemke, T. (2013), „Grundlagen der Wandlungsfähigkeit“ in *Wandlungsfähige Produktion : heute für morgen gestalten ; WaProTek - Wandlungsförderliche Prozessarchitekturen ; … im Rahmenkonzept “Forschung für die Produktion von morgen” ; … im Rahmen des Ideenwettbewerbs “Standortsicherung durch Wandlungfähige Produktionssysteme” das Verbundprojekt “Wandlungsförderliche Prozessarchitekturen” (WaProTek),* Ed. P. Nyhuis, PZH-Verl., Garbsen, pp. 18–22.

Mietzner, D. (2009), *Strategische Vorausschau und Szenarioanalysen,* Gabler, Wiesbaden. ISBN: 978-3-8349-1687-7.

Milde, M. & Reinhart, G. (2022), „Automated Model Development for the Simulation of Global Production Networks“ in *Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems: Proceedings of the 8th Changeable, Agile, Reconfigurable and Virtual Production Conference (CARV2021),* Ed. Andersen et al., Springer, Cham, pp. 467–474.

Mir, S. A. & Quadri, S. M. K. (2009), „Decision Support Systems: Concepts, Progress and Issues – A Review“ in *Climate Change, Intercropping, Pest Control and Beneficial Microorganisms,* Ed. E. Lichtfouse, Springer Netherlands, Dordrecht, pp. 373–399.

Moser, R. , *Strategische Planung globaler Produktionsnetzwerke*. *Bestimmung von Wandlungsbedarf und Wandlungszeitpunkt mittels multikriterieller Optimierung*. Diss., Shaker, Karlsruher Institut für Technologie (KIT), Karlsruhe, wbk Institut für Produktionstechnik. ISBN: 978-3-844-02823-2.

Mourtzis, D. (2016), „Challenges and future perspectives for the life cycle of manufacturing networks in the mass customisation era“, *Logistics Research*, 9(1), https://doi.org/10.1007/s12159-015-0129-0.

Mourtzis, D.; Doukas, M. & Psarommatis, F. (2015), „A toolbox for the design, planning and operation of manufacturing networks in a mass customisation environment“, *Journal of Manufacturing Systems*, 36, pp. 274–286, https://doi.org/10.1016/j.jmsy.2014.06.004.

Mulvey, J. M.; Vanderbei, R. J. & Zenios, S. A. (1995), „Robust Optimization of Large-Scale Systems“, *Operations Research*, 43(2), pp. 264–281, https://doi.org/10.1287/opre.43.2.264.

Nassehi, A.; Colledani, M.; Kádár, B. & Lutters, E. (2022), „Daydreaming factories“, *CIRP Annals*, 71(2), pp. 671–692, https://doi.org/10.1016/j.cirp.2022.05.002.

Neuner, C. (2009), *Konfiguration internationaler Produktionsnetzwerke unter Berücksichtigung von Unsicherheit,* Gabler, Wiesbaden. ISBN: 978-3-8349-1912-0.

Newman, D. & Logan, D. (2008), „Gartner Introduces the EIM Maturity Model“, *Gart. Res. ID Number G00160425,* pp. 1–8.

Nyhuis, P. (Ed.) (2008), *Wandlungsfähige Produktionssysteme*. *Heute die Industrie von morgen gestalten,* PZH Produktionstechnisches Zentrum, Garbsen. https://e-docs.tib.eu/files/e01fb10/633626406.pdf. ISBN: 9783939026969.

Nyhuis, P.; Heins, M.; Pachow-Frauenhofer, J.; Reinhart, G.; v. Bredow, M.; Krebs, P.; Abele, E. & Wörn, A. (2008), „Wandlungsfähige Produktionssysteme – Fit sein für die Produktion von morgen“, *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, 103(5), pp. 333–337, https://doi.org/10.3139/104.101285.

O’Hara, J. & Fleger, S. (2020), *Human-System Interface Design Review Guidelines,* Brookhaven National Lab. (BNL), Upton, NY (United States) and US Nuclear Regulatory Commission (NRC), Rockville, MD (United States).

Overbeck, L.; Brützel, O.; Teufel, M.; Stricker, N.; Kuhnle, A. & Lanza, G. (2021), „Continuous adaption through real data analysis turn simulation models into digital twins“, *Procedia CIRP*, 104, pp. 98–103, https://doi.org/10.1016/j.procir.2021.11.017.

Park, K. T.; Son, Y. H. & Noh, S. D. (2021), „The architectural framework of a cyber physical logistics system for digital-twin-based supply chain control“, *International Journal of Production Research*, 59(19), pp. 5721–5742, https://doi.org/10.1080/00207543.2020.1788738.

Power, D. J. (2002), *Decision support systems*. *Concepts and resources for managers,* Quorum Books, Westport, Conn. ISBN: 978-1-567-20497-1.

Power, D. J. & Sharda, R. (2007), „Model-driven decision support systems: Concepts and research directions“, *Decision Support Systems*, 43(3), pp. 1044–1061, https://doi.org/10.1016/j.dss.2005.05.030.

Prestifilippo, G. (2020), „IT für die digitale Transformation“ in *Logistik – die unterschätzte Zukunftsindustrie,* Ed. P. H. Voß, Springer Fachmedien Wiesbaden, Wiesbaden, pp. 57–69.

Reibnitz, U. von (1992), *Szenario-Technik,* Gabler Verlag, Wiesbaden. ISBN: 978-3-409-23431-3.

Rohde, J.; Meyr, H. & Wagner, M. (2000), „Die supply chain planning matrix“, *PPS Management 5(1),* pp. 10–15.

Romeike, F. & Hager, P. (2020), *Erfolgsfaktor Risiko-Management 4.0,* Springer Fachmedien Wiesbaden, Wiesbaden. ISBN: 978-3-658-29445-8.

Rudberg, M. & Olhager, J. (2003), „Manufacturing networks and supply chains: an operations strategy perspective“, *Omega*, 31(1), pp. 29–39, https://doi.org/10.1016/S0305-0483(02)00063-4.

Salam, A. F. & Stevens, J. R. (2006), *Semantic web technologies and e-business*. *Toward the integrated virtual organization and business process automation,* Idea; Eurospan [distributor], Hershey, Pa., London. ISBN: 978-1-599-04192-6.

Santoso, T.; Ahmed, S.; Goetschalckx, M. & Shapiro, A. (2005), „A stochastic programming approach for supply chain network design under uncertainty“, *European Journal of Operational Research*, 167(1), pp. 96–115, https://doi.org/10.1016/j.ejor.2004.01.046.

Scholl, A. (2001), *Robuste Planung und Optimierung*. *Grundlagen - Konzepte und Methoden - experimentelle Untersuchungen*. Zugl.: Darmstadt, Techn. Univ., Habil.-Schr, Physica-Verl., Heidelberg. ISBN: 978-3-790-81408-8.

Schuh, G.; Potente, T.; Kupke, D.; Varandani, R. & Hausberg, C. (2012), „An Evolutionary Approach for Global Production Network Optimisation“, *Procedia CIRP*, 3, pp. 382–387, https://doi.org/10.1016/j.procir.2012.07.066.

Schuh, G.; Potente, T.; Varandani, R. & Schmitz, T. (2014), „Global Footprint Design based on genetic algorithms – An “Industry 4.0” perspective“, *CIRP Annals*, 63(1), pp. 433–436, https://doi.org/10.1016/j.cirp.2014.03.121.

Schuh, G.; Prote, J.-P. & Dany, S. (2017), „Internet of Production“ in *Engineering Valley - Internet of Production auf dem RWTH Aachen Campus : Festschrift für Univ.-Prof. em. Dr.-Ing. Dipl.-Wirt. Ing. Dr. h. c. mult. Walter Eversheim / Schuh, Günther; Brecher, Christian; Klocke, Fritz; Schmitt, Robert (Hrsg.),* Apprimus Verlag, Aachen, pp. 1–10. https://publications.rwth-aachen.de/record/710980.

Schuh, G.; Prote, J.-P.; Gützlaff, A. & Rodemann, N. (2019), „Gestaltung von Produktionsnetzwerken“, *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, 114(1-2), pp. 7–10, https://doi.org/10.3139/104.112038.

Schuh, G. & Stich, V. (2012), *Produktionsplanung und -steuerung 1*. *Grundlagen der PPS,* Springer Vieweg, Wiesbaden. ISBN: 978-3-642-25422-2.

Sethi, A. & Sethi, S. (1990), „Flexibility in manufacturing: A survey“, *International Journal of Flexible Manufacturing Systems*, 2(4), pp. 289–328, https://doi.org/10.1007/BF00186471.

Shi, Y. & Gregory, M. (1998), „International manufacturing networks-to develop global competitive capabilities“, *Journal of Operations Management*, 16(2-3), pp. 195–214, https://doi.org/10.1016/S0272-6963(97)00038-7.

Siepmann, D. & Graef, N. (2016), „Industrie 4.0 – Grundlagen und Gesamtzusammenhang“ in *Einführung und Umsetzung von Industrie 4.0,* Ed. A. Roth, Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 17–82.

Stadtler, H.; Kilger, C. & Meyr, H. (Ed.) (2015), *Supply Chain Management and Advanced Planning*. *Concepts, Models, Software, and Case Studies,* Springer Berlin Heidelberg, Berlin, Heidelberg. ISBN: 978-3-642-55309-7.

Stähr, T.; Englisch, L. & Lanza, G. (2018), „Creation of configurations for an assembly system with a scalable level of automation“, *Procedia CIRP*, 76, pp. 7–12, https://doi.org/10.1016/j.procir.2018.01.024.

Stähr, T. J. (2020), *Methodik zur Planung und Konfigurationsauswahl skalierbarer Montagesysteme - Ein Beitrag zur skalierbaren Automatisierung*. Diss., Karlsruhe, Karlsruher Institut für Technologie (KIT), Karlsruhe, wbk Institut für Produktionstechnik. https://doi.org/10.5445/IR/1000117748.

Stark, R.; Kind, S. & Neumeyer, S. (2017), „Innovations in digital modelling for next generation manufacturing system design“, *CIRP Annals*, 66(1), pp. 169–172, https://doi.org/10.1016/j.cirp.2017.04.045.

Steven, M. (1994), *Hierarchische Produktionsplanung,* Physica-Verlag HD, Heidelberg, s.l. ISBN: 978-3-642-57987-5.

Stricker, N. (2016), *Robustheit verketteter Produktionssysteme*. *Robustheitsevaluation und Selektion des Kennzahlensystems der Robustheit,* Shaker Verlag, Aachen. ISBN: 9783844048018.

Stricker, N. & Lanza, G. (2014), „The Concept of Robustness in Production Systems and its Correlation to Disturbances“, *Procedia CIRP*, 19, pp. 87–92, https://doi.org/10.1016/j.procir.2014.04.078.

Teich, E.; Brodhun, C. & Claus, T. (2021), „Einsatz der Szenariotechnik in der Produktionsplanung“ in *Produktionsplanung und -steuerung,* Ed.T. Claus, F. Herrmann & M. Manitz, Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 79–109.

Thomas, S.; Scherrer-Rathje, M.; Fischl, M. & Friedli, T. (2015), „Linking network targets and site capabilities“, *International Journal of Operations & Production Management*, 35(12), pp. 1710–1734, https://doi.org/10.1108/IJOPM-10-2014-0464.

Turban, E. (2015), *Business intelligence and analytics*. *Systems for decision support,* Pearson, Boston. ISBN: 978-0-13-305090-5.

van Steenbergen, M.; Bos, R.; Brinkkemper, S.; van de Weerd, I. & Bekkers, W. (2010), „The Design of Focus Area Maturity Models“ in *Global Perspectives on Design Science Research,* Ed.D. Hutchison, T. Kanade, J. Kittler, J. M. Kleinberg, F. Mattern, J. C. Mitchell, M. Naor, O. Nierstrasz, C. Pandu Rangan, B. Steffen, M. Sudan, D. Terzopoulos, D. Tygar, M. Y. Vardi, G. Weikum, R. Winter, J. L. Zhao & S. Aier, Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 317–332.

Váncza, J.; Monostori, L.; Lutters, D.; Kumara, S. R.; Tseng, M.; Valckenaers, P. & van Brussel, H. (2011), „Cooperative and responsive manufacturing enterprises“, *CIRP Annals*, 60(2), pp. 797–820, https://doi.org/10.1016/j.cirp.2011.05.009.

Vereecke, A. & van Dierdonck, R. (2002), „The strategic role of the plant: testing Ferdows’s model“, *International Journal of Operations & Production Management*, 22(5), pp. 492–514, https://doi.org/10.1108/01443570210425147.

Volling, T. (2009), *Auftragsbezogene Planung bei variantenreicher Serienproduktion*. *Eine Untersuchung mit Fallstudien aus der Automobilindustrie,* Gabler Verlag / GWV Fachverlage GmbH Wiesbaden, Wiesbaden. ISBN: 9783834980717.

Westkämper, E. & Löffler, C. (2016), *Strategien der Produktion*. *Technologien, Konzepte und Wege in die Praxis,* Springer Vieweg, Berlin, Heidelberg. ISBN: 978-3-662-48913-0.

Wiendahl, H.-P. (2014), *Handbuch Fabrikplanung*. *Konzept, Gestaltung und Umsetzung wandlungsfähiger Produktionsstätten,* Hanser; Ciando, München, Wien, München. ISBN: 978-3-446-43702-9.

Wiendahl, H.-P.; ElMaraghy, H. A.; Nyhuis, P.; Zäh, M. F.; Wiendahl, H.-H.; Duffie, N. & Brieke, M. (2007), „Changeable Manufacturing - Classification, Design and Operation", *CIRP Annals*, 56(2), pp. 783–809, https://doi.org/10.1016/j.cirp.2007.10.003.

Wiendahl, H.-P.; Hernández, R. & Grienitz, V. (2002), „Planung wandlungsfähiger Fabriken", *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, 97(1-2), pp. 12–17, https://doi.org/10.3139/104.100499.

Wiendahl, H.-P. & Lutz, S. (2002), „Production in Networks", *CIRP Annals*, 51(2), pp. 573–586, https://doi.org/10.1016/S0007-8506(07)61701-6.

Wiendahl, H.-P.; Reichardt, J. & Nyhuis, P. (2015), *Handbook Factory Planning and Design,* Springer Berlin Heidelberg, Berlin, Heidelberg. ISBN: 978-3-662-46390-1.

Williams, H. P. (2013), *Model building in mathematical programming,* J. Wiley & Sons, Chichester, U.K. ISBN: 978-1-118-50617-2.

Wittek, K. (2013), *Standortübergreifende Programmplanung in flexiblen Produktionsnetzwerken der Automobilindustrie*. Zugl.: Braunschweig, Techn. Univ., Diss., 2012, Springer Gabler, Wiesbaden. ISBN: 978-3-658-01837-5.

Zhang, Q.; Vonderembse, M. A. & Lim, J.-S. (2003), „Manufacturing flexibility: defining and analyzing relationships among competence, capability, and customer satisfaction", *Journal of Operations Management*, 21(2), pp. 173–191, https://doi.org/10.1016/S0272-6963(02)00067-0.

Zhou, B.; Zheng, Z.; Zhou, D.; Cheng, G.; Jiménez-Ruiz, E.; Tran, T.-K.; Stepanova, D.; Gad-Elrab, M. H.; Nikolov, N.; Soylu, A. & Kharlamov, E. (2022), „The Data Value Quest: A Holistic Semantic Approach at Bosch" in *The Semantic Web: ESWC 2022 Satellite Events,* Ed.P. Groth, A. Rula, J. Schneider, I. Tiddi, E. Simperl, P. Alexopoulos, R. Hoekstra, M. Alam, A. Dimou & M. Tamper, Springer International Publishing, Cham, pp. 287–290.

Zimmermann, H.-J. (2008), *Operations Research*. *Methoden und Modelle ; für Wirtschaftsingenieure, Betriebswirte, Informatiker,* Vieweg, Wiesbaden. ISBN: 978-3-8348-0455-6.

Zwick, W. R. & Velicer, W. F. (1986), „Comparison of five rules for determining the number of components to retain", *Psychological Bulletin*, 99(3), pp. 432–442, https://doi.org/10.1037/0033-2909.99.3.432.

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Appendix

The appendix contains the larger tables, lists, etc. resulting from the work. The appendix is excluded from the normal numbering.

Appendix A: Supply Chain Planning Matrix Approach

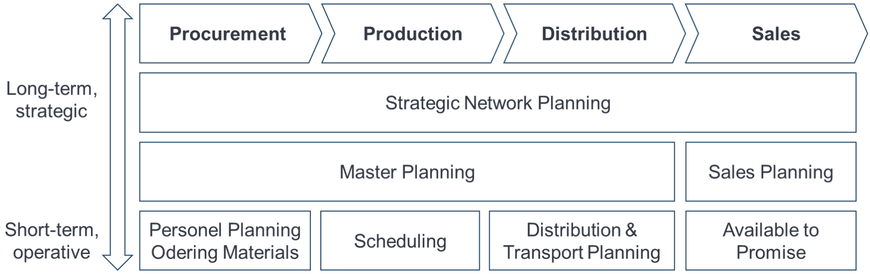

Figure A-1: Supply Chain Planning Matrix is based on (Rohde, Meyr & Wagner 2000)

Starting from the perspective of the entire value chain, the planning matrix may also consider just the internal section of the respective value chain (Fleischmann, Meyr & Wagner 2015, p. 76). The overall planning problem is divided into two dimensions. Regarding the planning horizon, a distinction is made between a long-term, medium-term, and short-term level. In the value creation process, a horizontal division is made into procurement, production, distribution and sales (Fleischmann, Meyr & Wagner 2015, p. 77).

In literature, the subdivision by planning horizon is regularly combined with the subdivision by planning scope (Kiener et al. 2018, p. 25; Scholl 2001, pp. 14–15). Regarding the definition of adequate time horizons of different planning levels, substantial differences can be observed in the literature (Wittek 2013, p. 61). For instance, regarding specific company sub-areas, longer-term operational planning may be conceivable, whereas, in others, this would not be sufficient to derive effective control details (Klein & Scholl 2012, p. 19).

According to the value creation process, procurement includes all activities providing the resources necessary for production in the subdivision. In production, these resources are then transformed into outputs (products). The products created reach their customers through distribution. The preceding processes are triggered by sales (Fleischmann, Meyr & Wagner 2015, p. 77). This may occur reactively by sales to be fulfilled or anticipatively based on market forecasts and sales planning (Fleischmann & Meyr 2003, p. 462). Whereas the matrix displays the main flow of information in its horizontal axis, it should well be noted that the flow of information has its source in the sales process, its role being the interface to the customer. So, the information flow begins in marketing and sales planning, intended to forecast future sales volumes (Rohde, Meyr & Wagner 2000, p. 10).

At the top, long-term level of the supply chain planning matrix, strategic network planning involves an overarching consideration of decisions regarding sites, suppliers, customers, and distribution centres. The decisions made here determine the basis for further medium- and short-term planning activities (Rohde, Meyr & Wagner 2000, p. 10). As described in the example of the overall company planning process, it takes vertical information flows between the levels of planning to transfer the restrictions from the higher to the lower levels. An information flow in the opposite vertical direction also takes place. Information regarding actual key figures of running processes is transmitted through it. This information can be used to anticipate the effects of decisions on subordinate levels at the upper planning levels (Fleischmann, Meyr & Wagner 2015, p. 82).

Master Planning covers the whole internal program planning, along with production, procurement, and distribution plans across all sites. Frequently, information at this level is aggregated to a relatively high degree (Volling 2009, pp. 59–60). Production program planning focuses on cost-efficient utilisation of the capacities available at the various sites (Fleischmann, Meyr & Wagner 2015, p. 82).

The planning outcomes of the production program planning determine planning at the lowest and most detailed level. At this short-term level, detailed material requirements, production sequences and machine allocation plans are determined. In distribution and transport planning, decisions are made regarding the physical transport of produced goods. These should reach the customer as agreed (Volling 2009, p. 61).

Appendix B: Forms and Approaches of Scenario Analysis

This section explains the different forms of scenario analysis and their differences. It also shows the difference between the two primary methodologies of scenario analysis and examines their suitability for GPN planning.

Scenario analysis can be differentiated according to various criteria. Fink, Schlake & Siebe (2001) describe the four different characteristics: Starting Point, Direction, Targetedness and Complexity (Fink, Schlake & Siebe 2001, pp. 61–63).

Scenarios can be developed starting from the present. This is called an exploratory approach. Here, several development possibilities are presented, starting from an analysis-based current state. Anticipatory scenarios start from a fixed future state, and the backwards-looking development paths represent possibilities for reaching this state. In terms of direction, scenarios can be developed inductively, deductively, or incrementally. In inductive scenario analysis, scenarios are created by systematically linking developments of individual factors. In the deductive approach, a framework is defined for each scenario at the beginning of the process. In the incremental approach, different variants are designed based on the most probable future. A distinction is made between descriptive and prescriptive scenarios. In the first case, the scenarios are developed independently of the user's goals, and there is a cause-effect relationship. If, on the other hand, the goals flow directly into the scenarios, there is a so-called means-goal relationship, and prescriptive scenarios are developed. (Fink, Schlake & Siebe 2001, pp. 61–62; Mietzner 2009, pp. 111–113)

The term scenario analysis summarises various approaches. However, a fundamental distinction can be made between the two methodological approaches. Their distinction is made by Fink, Schlake & Siebe (2001) under the characteristic of complexity. The model-based approach uses unique mathematical models to manage complex future situations. The intuitive approach dispenses with this and builds the scenarios on the evaluation basis of individual persons or groups. In Europe, the systematic model-based approaches, which take cause-effect relationships into account and create scenarios by linking factors, have become the most popular. In the Anglo-American world, on the other hand, intuitive approaches are more widespread (Fink, Schlake & Siebe 2001, pp. 62–63; Mietzner 2009, p. 113).

In the field of factory and production system planning, scenario management by Gausemeier, Fink & Schlake (1996) is often used as a representative of model-based approaches (Hambach & Albrecht 2014, p. 117). However, it was initially developed for strategic corporate management and is also used in product planning, mainly in a strategic context. Wiendahl, Hernández & Grienitz (2002) cite factory strategy planning, factory concept planning and factory analysis as examples of the main fields of application (Wiendahl, Hernández & Grienitz 2002, pp. 15–16). The use of model-based approaches can be justified by the many different change drivers to which a production system is exposed, as well as their uncertainty. Due to the possibility of causal mapping and systematic analysis of conceivable developments of the individual influencing factors, these methods are considered suitable for developing sustainable solutions in the production context (Wiendahl, Hernández & Grienitz 2002, p. 15).

Intuitive approaches that emerged in the context of scenario development at Royal Dutch Shell can be summarised under the term "scenario planning". Here, a narrowing down to specific topics takes place in advance, resulting in a deductive development process that simplifies the picture of the future and accelerates the development. This makes these approaches well-suited for evaluating existing strategies and for use in strategic management processes. However, a central problem of these approaches is their limited comprehensibility and their limited suitability for representing complex situations. This limits their applicability in planning, especially in production planning. (Fink, Schlake & Siebe 2001, p. 22; Teich, Brodhun & Claus 2021, p. 63)

Appendix C: Scenario Management Approach

The following describes the concept of scenario management initially developed by Gausemeier, Fink & Schlake (1996), representing a structured way to perform scenario analysis. The methodology of scenario management is divided into five phases. These are listed in Figure A-2, together with a summary of the tasks and the result of each stage.

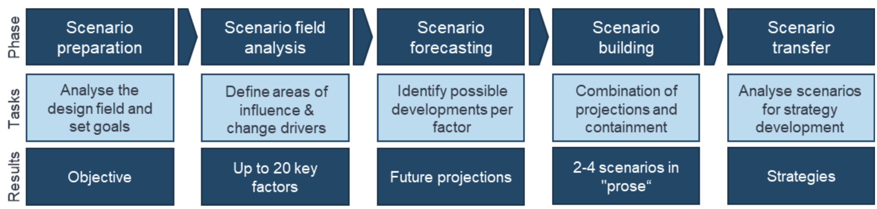

Figure A-2: Phase model of scenario management. Own representation based on Gausemeier, Fink & Schlake (1996, p. 101) and Gausemeier & Plass (2014, p. 48).

The first phase is scenario preparation. Here, the goals are set, and the project, as well as the design field, are defined. The design field refers to the area to which the findings from the scenarios are to be applied. (Gausemeier, Fink & Schlake 1996, p. 125; pp. 163-164)

The actual process of scenario development begins with the scenario field analysis. In this phase, areas that influence the design field are first formed, and a list of possible influencing factors is drawn up. Then, based on influence and relevance analyses, up to 20 so-called key factors are identified. (Gausemeier, Fink & Schlake 1996, p. 167; p.212; pp. 217-219)

Scenario forecasting represents a "look into the future." In this phase, possible development paths within the period under consideration are developed and justified for each key factor. These are called future projections. Each development is described qualitatively and must be specified in a way that can be easily understood later. These projections represent possible building blocks for scenarios. (Gausemeier, Fink & Schlake 1996, p. 221; pp. 248-250)

In scenario building, meaningful scenarios are formed from the projections via projection bundles and raw scenarios. First, bundles are created by combining the projections and checking for consistency and plausibility. The relevant and consistent bundles are summarised in a projection bundle catalogue. (Gausemeier, Fink & Schlake 1996, pp. 251–252; p. 270)

From this catalogue, either a few bundles can be taken out on the basis of suitable criteria and directly interpreted as scenarios, or the relevant bundles can be summarised on the basis of their similarity. Gausemeier, Fink & Schlake (1996) use hierarchical cluster analysis methods for this purpose. They calculate the similarity of two projection bundles by comparing the projections contained in the bundles. (Gausemeier, Fink & Schlake 1996, p. 251; pp. 272-279)

Subsequently, the relevant bundles are combined into two to four clusters, so-called raw scenarios. The scenario creation is completed with the scenario visualisation and qualitative scenario description. (Gausemeier, Fink & Schlake 1996, pp. 317–318)

The scenario transfer no longer belongs to the actual scenario development but describes the transfer of the scenarios to decision-making processes for the development of strategies. Here, the scenarios are applied to the design field to identify opportunities and risks. (Gausemeier, Fink & Schlake 1996, p. 321)

Overall, this approach is characterised by a strongly systematic procedure and uses various comparatively elaborate methods. Thus, it requires a high level of methodological competence and finally delivers a limited number of formulated scenarios. Other model-based approaches usually follow a similar procedure, although the phases and methods differ. For example, the approach of (Reibnitz 1992, pp. 30–70), which contains eight phases. The result here is limited to two scenarios at different ends of the scenario funnel (Reibnitz 1992, p. 30).

Appendix D: Classification of Scenario Analysis

Scenario analysis is one way of taking uncertainty into account. In contrast to forecasts, which aim to predict a potential future by extrapolating the past, scenario analysis looks at different images of the future. In addition, forecasts usually assume that essential framework conditions will not change, whereas this requirement does not exist for scenarios. (Reibnitz 1992, pp. 15–16)

Scenario analysis differs from sensitivity analysis in that several input parameters are changed simultaneously. This means that it is not possible to conclude the influence or potential of individual parameters but that the future is depicted more realistically. Sensitivity analysis is, therefore, particularly suitable for evaluating alternatives and identifying potential and particularly risky factors. Scenarios, on the other hand, show possible representations of the future and thus enable robust planning. (Klein 2012, pp. 338–339; Reibnitz 1992, p. 29)

Based on these two comparisons, the unique nature of scenario analysis in taking uncertainty into account becomes clear since, unlike most other methods, the so-called ceteris paribus condition is abandoned, and changes in the framework conditions are included (Mietzner 2009, p. 120).

Overall, according to Fink, Schlake & Siebe (2001), the use of scenarios is beneficial when the industry is exposed to significant changes and accelerated environmental developments. Furthermore, scenarios are well suited when it is difficult to predict customer needs in advance. This is especially the case when the planning horizon increases. Therefore, Fink, Schlake & Siebe (2001) separately emphasise that scenarios cannot be used as a short-term rescue measure in emergencies. From this, it can again be deduced that scenarios should be used, particularly for companies in turbulent and uncertain markets. (Fink, Schlake & Siebe 2001, pp. 59–61)

In planning, the origin of the application of scenario analysis lies in the strategic context. Nevertheless, quantitative approaches may also be suitable for the creation of scenarios in the medium and short-term planning horizon. (Scholl 2001, p. 214; Teich, Brodhun & Claus 2021, p. 65).

Especially in robust planning, scenarios and their quality are of decisive importance, as they are used to decide on the robustness of a plan. Scholl (2001) justifies the use of scenario-based modelling to represent uncertainty in robust planning with the excellent suitability of discrete scenarios to include the entire spectrum of developments. In addition, he cites as an advantage the more straightforward depiction of correlations between the various influencing factors compared to the use of individual random variables (Scholl 2001, pp. 206–207)

In addition to the use of scenario analysis in strategic corporate planning, Teich, Brodhun & Claus (2021), for example, also see a high benefit in the consideration of scenarios for production planning. This is due to the already described high level of uncertainty caused by today's turbulent environment, mainly due to volatile demand and a high number of variants. (Teich, Brodhun & Claus 2021, p. 85)

In summary, the advantage of scenario analysis lies in its consideration of uncertainty and drivers of change as well as the resulting conceivable developments. The high time expenditure and the dependence on subjective assessments speak against the use of scenario analysis in comparison to the use of forecasts. (Mietzner 2009, pp. 160–161)

In the context of this thesis, the advantages, especially in relation to the volatile and uncertain environment of a GPN, are considered to outweigh the disadvantages, which is why scenario analysis is used in this thesis.

Appendix E: Context for Assistant Systems

In the field of research on digitalisation and Industry 4.0, a profound transformation is reshaping the landscape of work. This transformation is not solely characterised by the potential replacement of humans by technical systems but also by the opportunity for a closer collaboration between humans and machines. The goal is to combine humans' exceptional abilities with the unique characteristics of machines, fostering optimal synergy (Apt et al. 2018, p. 20). In this collaboration, technical systems provide tailored support to humans, adapted to their specific abilities, needs, and the demands of their work environment.

This trend has led to the increasing implementation of digital assistance systems in operational practices (Apt et al. 2018, p. 106). Digital assistance systems, as defined by Link & Hamann (2019, p. 684), are computer-based tools designed to aid humans in information gathering, decision-making, and task execution. To categorise and describe these systems systematically, Apt et al. (2018, p. 19) have developed a classification scheme, as depicted in Figure A-3Figure A-, outlining various types of digital assistance systems.

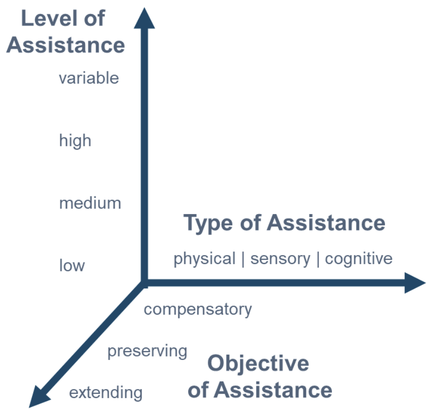

Figure A-3: Characterisation of digital assistance systems (own representation cf. Apt et al. (2018, p. 19))

The categorisation of assistance systems delineates three fundamental approaches. Firstly, physical assistance systems are engineered to aid in physically demanding tasks, compensating for limited physical capabilities. These systems vary from essential mechanical power support to adaptive robotic systems tailored for intricate production processes, primarily focusing on bolstering the musculoskeletal system. Sensory assistance systems, on the other hand, target support for sensory organs such as hearing or vision. For instance, augmented reality glasses offer combined cognitive-sensory support, enhancing users' perception of their environment. Cognitive support systems, often referred to as decision support systems within this context, provide information crucial for decision-making processes. These systems focus on reducing reaction times, cognitive processing, memory, and reasoning abilities, frequently utilising interactive visualisation tools. (Apt et al. 2018, p. 21)

Furthermore, the level of assistance is categorised from low to high and variable. Figure A-4 illustrates the relationship between different task types and the complexity of digital assistance systems required to support them (Apt et al. 2018, p. 23). Systems with low complexity can aid in simple movements or exertion of high forces. They provide basic instructions or assist in physical movements, supporting muscles, tendons, or sensory organs. Medium-level assistance systems can support rule-based decisions, swiftly communicating recommended actions, thereby enhancing information processing and reducing reaction time in corresponding tasks. High-level assistance systems excel at handling rule-based decisions of substantial complexity or even expertise-based decisions. As data and information volumes grow, these systems prove indispensable in analysing and optimising intricate processes. Finally, Apt et al. (2018, p. 25) describe variable applicable assistance systems equipped with modular structures capable of addressing diverse support tasks.

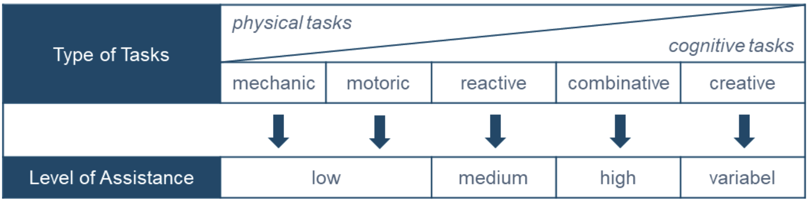

Figure A-4: Mapping between type of tasks and complexity of assistance (own representation cf. Apt et al. (2018, p. 23)

In the classification scheme's third dimension, digital assistance systems are categorised based on their intended purpose of support. Assistance falls into three types: compensatory assistance, designed to level handicaps and crucial for inclusivity, especially for individuals with limited abilities; ability-preserving assistance, emphasising the promotion of healthy working conditions; and ability-extending assistance, tailored for enhancing overall performance. (Apt et al. 2018, p. 29)

Appendix F: PowerBI

PowerBI, a prominent business intelligence tool developed by Microsoft, serves as a sophisticated platform for transforming raw data into comprehensible visuals and interactive dashboards. This analytical process involves a systematic flow of data, advanced data preparation techniques, custom calculations, and intricate visualisation methodologies (see Figure A-5). (Knight et al. 2018, p. 7)

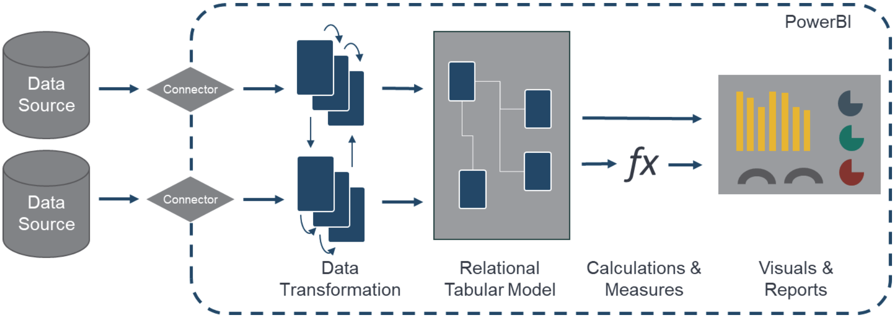

Figure A-5: Graphic representation of data flow in PowerBI based on (A_Schmidt 2023, p. 21)

PowerBI accommodates an extensive range of data sources, encompassing traditional databases such as SQL Server, Oracle, and MySQL, along with cloud-based platforms like Azure SQL Database and flat file formats including Excel and CSV. The initial step involves meticulous selection and integration of pertinent data sources. (Knight et al. 2018, pp. 10–18)

Upon data source selection, PowerBI employs two primary methods: direct querying and data importing. The Power Query Editor, underpinned by the M language, facilitates data cleansing and transformation tasks. Ranging from fundamental operations like column renaming and row filtering to intricate tasks like table pivoting and dataset merging, these transformations are essential for refining the dataset. Data integrity and relevance are ensured through these preparatory steps. (Knight et al. 2018, pp. 22–24)

Post-cleansing, the data undergoes structuring into a relational tabular model. Relationships between tables are established based on shared fields, defining 'one-to-many,' 'one-to-one,' or 'many-to-many' associations. These relationships form the foundation of a semantic model, facilitating comprehensive data analysis and multidimensional exploration. (Knight et al. 2018, pp. 49–62)

The Data Analysis Expressions (DAX) language empowers users to create custom calculations, referred to as measures. These measures are contextually adaptive, dynamically adjusting their values based on applied filters, ensuring flexibility and precision in analytical scenarios. The advantage lies in their responsiveness to varying contexts, enabling intricate data analysis and nuanced insights. (Knight et al. 2018, pp. 79–97)

PowerBI provides a diverse array of visual elements, from charts to graphs, enabling users to represent data and measures graphically. These visuals are meticulously crafted and integrated into reports and dashboards. Furthermore, PowerBI enhances interactivity through features like slicers, filters, and drill-through capabilities. These interactive components empower users to explore the data landscape comprehensively, fostering an in-depth understanding of the dataset. (Knight et al. 2018, pp. 98–133)

In summary, PowerBI stands as an analytical framework that meticulously processes, refines, and visualises complex datasets. By seamlessly integrating diverse data sources, employing advanced transformation techniques, enabling contextual adaptability through DAX measures, and offering interactive visualisations, PowerBI facilitates profound data analysis. Its contribution to informed decision-making within organisational contexts is invaluable, making it a quintessential tool in the realm of business intelligence. (Becker & Gould 2019)

Appendix G: Project Team

Project Lead: The Project Lead is responsible for project coordination, planning, and execution. Responsible for aligning the project with business goals, the Project Lead interfaces with various teams, stakeholders, and senior management to ensure smooth progress and successful outcomes.

Development Lead: The Development Lead oversees the technical aspects of DSS implementation. This role involves coordinating the work of different development teams, ensuring compliance with architectural standards, and making critical technical decisions to maintain system integrity.

- **Development Team - Optimisation Software:** This team is entrusted with developing the core optimisation algorithms and software modules that power the DSS. Expertise in mathematical modelling, algorithm design, and optimisation techniques is essential for crafting efficient solutions.
- **Development Team - Webtool:** The Webtool Development Team focuses on creating the user interface and frontend components of the DSS. They ensure an intuitive and user-friendly experience for end-users interacting with the system.
- **Development Team - Database:** The Database Development Team handles the architecture and management of the data repository that supports the DSS. Their role includes designing efficient database structures, ensuring data integrity, and optimising data retrieval processes.

Process Owner: The Process Owner possesses deep domain knowledge and oversees the alignment of the DSS with existing organisational processes. They bridge the gap between technical implementation and real-world application, ensuring that the system integrates seamlessly into the operational workflow.

Product Owner: The Product Owner acts as the voice of the customer, defining and prioritising requirements for the DSS based on user needs and business objectives. They collaborate closely with development teams to guide feature development and iteration.

Working Group of Collaborating End-Users: The input and insights from end-users who will be directly interacting with the DSS are invaluable. A working group comprising digitally motivated end-users provides real-world context, identifies pain points, and offers suggestions for user-centred improvements.

Reviews - Stakeholder Involvement: Engaging stakeholders from Controlling, Network Planning, and Logistics teams and, most important, the end users ensures that the DSS caters to their specific needs. This involvement facilitates alignment with business requirements and validates the system's effectiveness from the user perspective.

Steering Committee - High Management Involvement: The presence of high-level management in the steering committee provides oversight, strategic direction, and resource allocation for the project. Their involvement ensures that the project aligns with organisational goals and garners necessary support.

Appendix H: Approaches of Maturity Models

Structured frameworks, such as the Capability Maturity Model (CMM), Capability Maturity Model Integration (CMMI), and others, play a crucial role in assessing and improving various aspects of the introduction of organisational processes and capabilities. Whether it is in the domains of data governance, AI, algorithm usage, risk management, or data management, these models provide a roadmap for organisations to enhance their practices and align them with strategic objectives.

The Capability Maturity Model (CMM) is a structured framework that assesses and improves an organisation's processes. It has five maturity levels: Initial (chaotic), Managed (primary control), Defined (documented processes), Quantitatively Managed (measured processes), and Optimising (continuous improvement). Initially designed for software, it is now well-established in industries. The CMM helps organisations enhance their processes and capabilities over time.

The Capability Maturity Model Integration (CMMI) is a framework that helps organisations improve their processes and performance in areas like software development, project management, and engineering. It defines maturity levels (from Initial to Optimising) and capability levels (from Incomplete to Optimised) to guide process enhancement and efficiency. CMMI aids organisations in assessing, benchmarking, and enhancing their process maturity and effectiveness. (CMMI 2002)

The IBM Data Governance Maturity Model, established in 2007, assesses progress within 11 data governance domains. It categorises maturity into levels, from Initial to Optimising. Each level corresponds to characteristics such as awareness, process automation, and enterprise-wide adoption. The model is flexible, allowing organisations to focus on specific domains. Most organisations begin at Level 2 (Managed), with higher levels more common in particular data domains than across the enterprise. (IBM Institute for Business Value and IBM Strategy and Change 2007)

The Gartner Data Governance Maturity Model, established in 2008 and updated in 2016, assesses enterprise information management (EIM) across six phases of maturity. It focuses on EIM's broader goals and characteristics for each stage. From being unaware of data governance to achieving effectiveness, the model emphasises the gradual evolution of EIM and its importance in creating value and efficiencies. (Newman & Logan 2008)

The Algorithmic Maturity Model is a framework that assesses an organisation's proficiency in using algorithms. It spans stages from Exploration (initial understanding) to Transformation (deep integration). The model helps organisations improve their algorithmic skills, apply algorithms effectively, and align them with business goals. (Gentsch 2018)

Appendix I: Assessment Questions

Assessment Question	Poor	Partially	Moderately	Well	Highly
Maturity Levels of Usage					
How effectively are processes documented and standardised within your decision support system for production?					
To what extent does the reliance on individual expertise for data collection affect the alignment of the decision-making process? *Higher number signifies lower reliance.*					
How actively are key stakeholders engaged in the process of implementation, ensuring the successful integration of the decision support system with your production processes?					
To what degree does your organisation prioritise the development of skills to innovate within usage of the decision support system?					
How aligned are decision-making processes with insights from the decision support system across different stages of the decision process?					
How well does your organisation foster collaboration and knowledge sharing between teams involved in the usage of the decision support system?					
How proactive is your organisation in adapting to changing production scenarios and optimising resource allocation through the use of data-driven insights by the application of the decision support system?					
How effectively does your organisation gather feedback from users and stakeholders and use it to improve the processes within the decision support system iteratively?					
Maturity Levels of Automation					
What level of measurement and evaluation is in place to assess the impact of automation on production efficiency, quality, and decision-making?					
How adaptable and scalable are the automated processes to meet evolving production demands and challenges?					
How well does your organisation support the implementation and advancement of automation with the necessary resources and expertise?					
How well is data necessary for decision support system's automation processes accessible?					
How well data pipelines are established and integrated within your decision support system's automation processes?					
How well do automatic result visualisation tools provide actionable insights into your automated processes for stakeholders?					
How well does your organisation's automation strategy align with the goals and long-term vision of the decision support system?					

Appendix J: Assessment Evaluation

	Use Case 1	Use Case 2	Use Case 3	Use Case 4	Use Case 5	Use Case 6	Use Case 7	Use Case 8	Use Case 9	Use Case 10	Use Case 11	Use Case 12
How effectively are processes documented and standardised within your decision support system for production?	1	1	1	1	1	1	1	1	1	1	1	1
To what extent does the reliance on individual expertise for data collection affect the alignment of the decision-making process? *Higher number signifies lower reliance.*	1	0	3	2	2	3	0	1	2	1	2	1
How actively are key stakeholders engaged in the process of implementation, ensuring the successful integration of the decision support system with your production processes?	1	1	2	2	2	3	1	2	3	2	3	1
To what degree does your organisation prioritise the development of skills to innovate within usage of the decision support system?	1	1	3	2	2	3	1	2	3	2	3	1
How aligned are decision-making processes with insights from the decision support system across different stages of the decision process?	1	0	3	1	1	3	0	1	3	1	2	1
How well does your organisation foster collaboration and knowledge sharing between teams involved in the usage of the decision support system?	2	2	3	2	2	3	2	2	3	2	3	1
How proactive is your organisation in adapting to changing production scenarios and optimising resource allocation through the use of data-driven insights by the application of the decision support system?	1	0	3	2	2	2	0	1	2	1	2	3
How effectively does your organisation gather feedback from users and stakeholders and use it to improve the processes within the decision support system iteratively?	2	2	3	2	3	3	2	2	3	2	3	1
Maturity Levels of Usage average	1.3	0.9	2.6	1.8	1.9	2.6	0.9	1.5	2.5	1.5	2.4	1.3
Maturity Levels of Automation												
What level of measurement and evaluation is in place to assess the impact of automation on production efficiency, quality, and decision-making?	2	2	2	2	2	2	2	2	2	2	2	2
How adaptable and scalable are the automated processes to meet evolving production demands and challenges?	3	0	3	3	3	3	0	3	3	3	3	3
How well does your organisation support the implementation and advancement of automation with the necessary resources and expertise?	0	0	3	0	0	3	0	0	3	0	3	2
How well is data necessary for decision support system's automation processes accessible?	2	0	3	2	2	2	1	2	2	2	2	2
How well data pipelines are established and integrated within your decision support system's automation processes?	1	0	3	1	1	1	0	1	1	1	1	1
How well do automatic result visualisation tools provide actionable insights into your automated processes for stakeholders?	3	0	3	3	3	3	0	3	3	3	3	3
How well does your organisation's automation strategy align with the goals and long-term vision of the decision support system?	3	0	4	3	3	4	0	3	4	3	4	3
Maturity Levels of Automation average	2.00	0.29	3.00	2.00	2.00	2.57	0.43	2.00	2.57	2.00	2.57	2.29

Figure A-6 Evaluation of maturity

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