EVALUATION AND SIMULATION METHODS FOR AMBIDEXTERITY ENGINEERING OF DIGITAL SUPPLY CHAIN SYSTEMS

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ABSTRACT

Global mergers and faster business cycles create weakly harmonized supply chain (SC) systems. Industry 4.0's smart digitalization opportunities significantly alter business model innovation rates. Consequently, the complexity of aligning value exploration and exploitation has increased, often missing the needed integration level. A holistic systems engineering (SE)-driven methodology for innovation, transformation, and optimizing smart SC systems is not available so far. Case studies at SAP SE's development organization for Industry 4.0 SCM solutions and three automotive companies explored objectives, obstacles, and methods for digital transformation. The results were synthesized into a holistic SC business model transformation and optimization methodology. Complementary to traditional SCM, the study proposes SE-driven meta-modelling to improve the performance, resilience, and synchronization of end-to-end supply chains. Moreover, holistic simulations and evaluation methods for the ambidexterity of SC business models have been developed, enhancing the effectiveness of value exploration and exploitation, and innovation productivity by holistically viewing emergence and convergence throughout SC capabilities' life cycles. Ambidexterity management and dynamic capabilities are addressed by SE methods like capability engineering and complex dynamic systems theory, integrated into a concise SE model.

KEY WORDS

systems engineering, supply chain engineering, ambidexterity engineering

JEL CODES

L21, M15, O32, O33

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1 INTRODUCTION

This follow-up study refers to a 2023 published systematic review of methods for activating SC business models' value potentials in the Industry 4.0 context using a systems engineering approach (Nuerk and Dařena, 2023). The previous and present study presents the result of the main author's PhD Dissertation in Systems Engineering and Informatics, submitted in July 2024 at Mendel University in Brno. The grounds for the need for a harmonized SE methodology are briefly stated in this introduction.

The complexity of SC business models is increasing due to industrial globalization, emerging ecosystems, and rising business dynamics (Davey et al., 2021; Dumitrescu et al., 2021). Weakly harmonized IT landscapes and fragmented alignment result in poor SC design, lack of integration, and unsynchronized supply chains (Childerhouse and Towill, 2011; Nuerk, 2019; Wu et al., 2006). Proper capability alignment with competitive strategies and SC integration drives performance in dynamic environments (Chen et al., 2018; Childerhouse and Towill, 2011; Liu et al., 2013; Nuerk, 2019; Shaw et al., 2005; Wang, 2011), though configuration depends on context (Godsell, 2008).

Investigating contingency relationships is needed for operationalising strategic fit, which can be implemented by a profile deviation approach (McLaren et al., 2011; Sabherwal and Chan, 2001). Many concepts exist for business-IT alignment, but integration into holistic engineering frameworks is lacking (Spósito et al., 2016). Integrating key constructs in an SE model for capability alignment in business model transformation will close this gap. Additionally, businesses must manage increasing environmental dynamics, higher demand variability, shorter product lifecycles, and ambitious sustainability goals (Hermann et al., 2016; Mo et al., 2023). Industry 4.0 enables processes like autonomous planning and manufacturing, sustaining performance in multi-tier supply chains (Zott and Amit, 2010).

Enterprises as complex dynamic systems reveal value opportunities through the emergence process and interactions of components (Levy, 2000; Rebovich, 2008). Thus, SC business models need continuous alignment to maintain operational excellence. In referring to the dynamic capability (DC) theory, evaluating fitness levels helps balance exploration and exploitation, relating to ambidexterity (Teece, 2018; Teece et al., 1997; O'Reilly and Tushman, 2008; Raisch et al., 2009). DC theory emphasizes the importance of exploring, assimilating, and exploiting knowledge for business performance (Liu et al., 2013; Arndt et al., 2018).

Absorptive capacity enables orchestrating and recombining capabilities to respond to business dynamics effectively (Brettel et al., 2011; Teece, 2007). Ideally, systematic findings on dynamic capabilities (DC), absorptive capacities, and ambidexterity can be modelled and adopted by systems engineering (SE) discipline capability engineering (Henshaw et al., 2011). To fully exploit the value potentials of the current economic paradigm change, concepts from business modelling, Industry 4.0, SCM, AI, and enterprise architecture need to be incorporated into an SE approach. A holistic view of enterprise systems and context enhances transparency, integrating functions and improving the understanding of the relationship between innovations and alignment processes (Brettel et al., 2011; Altman and Tushman, 2017).

Therefore, SE must integrate value-adding SC processes and balance innovation, transformation, and convergence. A SE-driven model with three main phases—(1) sensing and interacting, (2) SC design and transformation, and (3) SC planning and optimization—provides an integrated view of smart data-driven SC business models' emergence, convergence, and efficiency (Nuerk and Dařena, 2023). The methodological needs for innovating and maximizing digital SC systems' value potentials throughout these phases must be explored, focusing on objectives driven by digitalization.

Designing best practices and useful artefacts requires understanding interoperability drivers

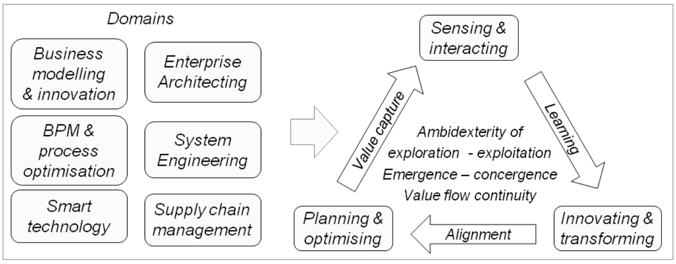


Fig. 1: The SE model phases and concepts' source domains (Nuerk and Dařena, 2023)

of smart processes, observed transformation obstacles, and promising approaches to overcome them. Systematic, qualitative research using case studies is needed to explore the requirements of target organizations and how smart SCM IT capabilities impact their deep structure (Silva and Hirschheim, 2007; van Donk and van der Vaart, 2005). Case studies help identify significant interoperability drivers for smart data-driven supply chains and methods useful for the SE model phases, balancing exploration and exploitation and leading to continuity in SC performance and resilience (Yin, 2018; Bryman and Bell, 2011).

2 RESEARCH OBJECTIVE

Businesses face declining visibility along their supply chains due to the rising distribution of value-added processes among more partners, coupled with increasing business volatility and uncertainties simultaneously. SC integration and interoperability significantly impact SC performance, agility, and resilience. This study explores the main requirements and methods for simulation and evaluation keeping SC business models in an ambidexterity state, ensuring continuous SC performance and resilience. The study aims to develop a holistic and concise SE methodology tested through case study research in the automotive industry. The research objective and question are:

RO: *Develop a SE-driven methodology for evaluating and simulating ambidexterity in digital SC business models to balance exploration and exploitation, ensuring continuous SC performance and resilience.*

RQ: *What core methods enable improving performance and resilience while balancing value exploration and convergence activities in SC business models?*

The explored SE methods should provide concise information for maintaining digital SC business models and their capabilities in a fit and ambidexterity state, addressing business dynamics. The findings aim to help SE systematically manage increasing dynamics in SC systems and environmental volatility, guiding organizations in ongoing innovation and value exploitation. The final model should offer methods for maintaining SC business models' efficiency and resilience, balancing exploration with exploitation activities. As SC systems often lack needed integration quality across domains and organizations, better-aligned and integrated SC innovations will significantly improve firms' performance relative to competitors (Chen et al., 2010; Rai et al., 2006).

This study drives SE towards becoming a key discipline for SC design, focusing on innovation, operational excellence, and resilience, aligning with the INCOSE Vision 2035 (Davey et al., 2021). A harmonized SE model, avoiding methodological redundancies, is seen as a driver for innovations and value exploitation in digital SC business models.

3 METHODOLOGY AND RESEARCH PROCESS

The study is grounded in a 2023 systematic literature review by Nuerk and Dařena, covering concepts from SE, business modelling, Industry 4.0, SCM, AI, and enterprise architecture methods. This review establishes the need for a harmonized SE-driven model with three main phases: (1) sensing and interacting, (2) SC design and transformation, and (3) SC planning and optimization (Nuerk and Dařena, 2023). The present study aims to enrich this SE model into a consistent methodology for systematically managing increasing SC dynamics and environmental volatility while fostering ongoing innovation and value exploitation. To detail these methodological requirements, qualitative research investigates target organizations and IT's strategic impact on their deep structure (Silva and Hirschheim, 2007).

According to Davey et al. (2021), SE needs a strong scientific base and shared formal ontologies across domains to adapt methods for maximizing application value (Wu et al., 2006). The field research explores the core methods of the SE model and develops reusable artefacts for evaluating SC business models' effectiveness. Additionally, the model must provide SE methods for assessing and balancing business model capabilities throughout their lifecycles. A multiple case study design was chosen for context-dependent generalization through replication (Yin, 2018). This approach ensures the development of a comprehensive SE methodology that addresses the increasing dynamics in SC systems and environmental volatility, enabling organizations to innovate continuously and exploit value effectively.

3.1 Case Study Research at SAP SE

To collect in-depth knowledge about the transformation and optimization of digital SC models, case study research was conducted at SAP SE's Headquarters in Walldorf, Germany. The selected business divisions at SAP SE are involved in various global digitalization initiatives, such as Catena-X for automotive, providing valuable insights into digitalization requirements and trends. The study explored core objectives, obstacles, and promising methods for industrial organizations using semi-structured interviews. These interviews were conducted with experts from SAP Business Units of Industry 4.0, Digital SC Innovations, Smart Manufacturing, and field services for Business Transformation and SC Planning and Optimization.

The research explored areas where traditional SC domain engineering is limited and how SE can holistically complement industrial digitalization. It also identified SC objectives and priorities that have evolved due to smart digitalization. Focused methods were identified to enable SE to quickly evaluate prevailing value enablers and the systematic processes of smart SC business operations. Extensive work sessions were conducted with nine participants (listed in Tab. 5 in the Annex). These sessions introduced the research topic, followed by semi-structured interviews, which were transcribed as shown in Fig. 2. Nine reports, each between 8,800 and 12,500 words, were created as the outcome of the case study and validated through workshops with participants. The case study transcripts were analyzed using QCAmap, following Mayring's (2014, 2023) qualitative content analysis method. Due to the explorative nature and complexity of the topic, inductive category formation was used to remain open to the concepts extracted from the reports. A summary of the category system, as the content analysis output, is highlighted in Fig. 3.

The categories formatted during the analysis were grouped into main categories for SC objectives and value enablers, and the SE model phases. Focus activities that enable orchestrating the SE model phases to balance SC performance, resilience, exploration, and exploitation were identified and emphasized in red ink Fig. 3. Based on the synthesized findings, methods were designed to evaluate the effectiveness of value signal sensing and value exploitation by business model components and SCM IT capabilities for driving useful conver-

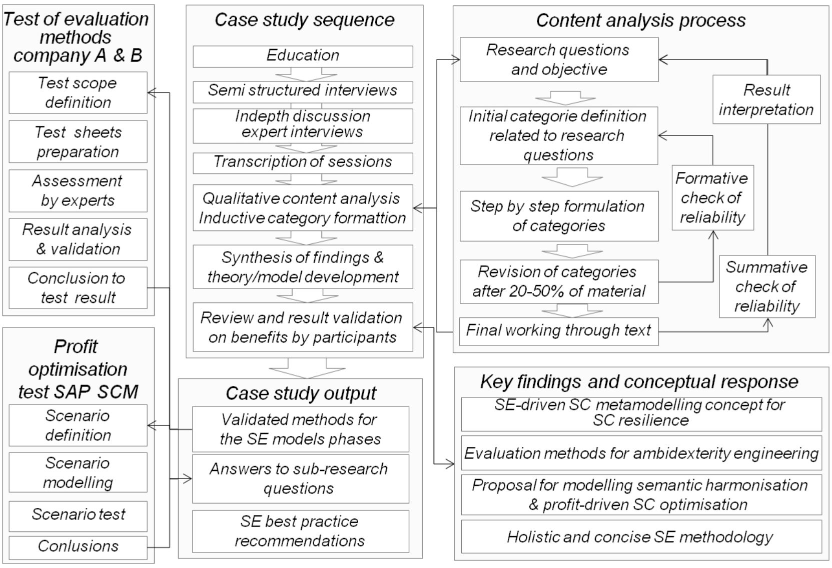


Fig. 2: The case study process including the content analysis due to Mayring (2014), the process for testing the evaluation methods using industry case and SCM scenario test (Nuerk, 2024)

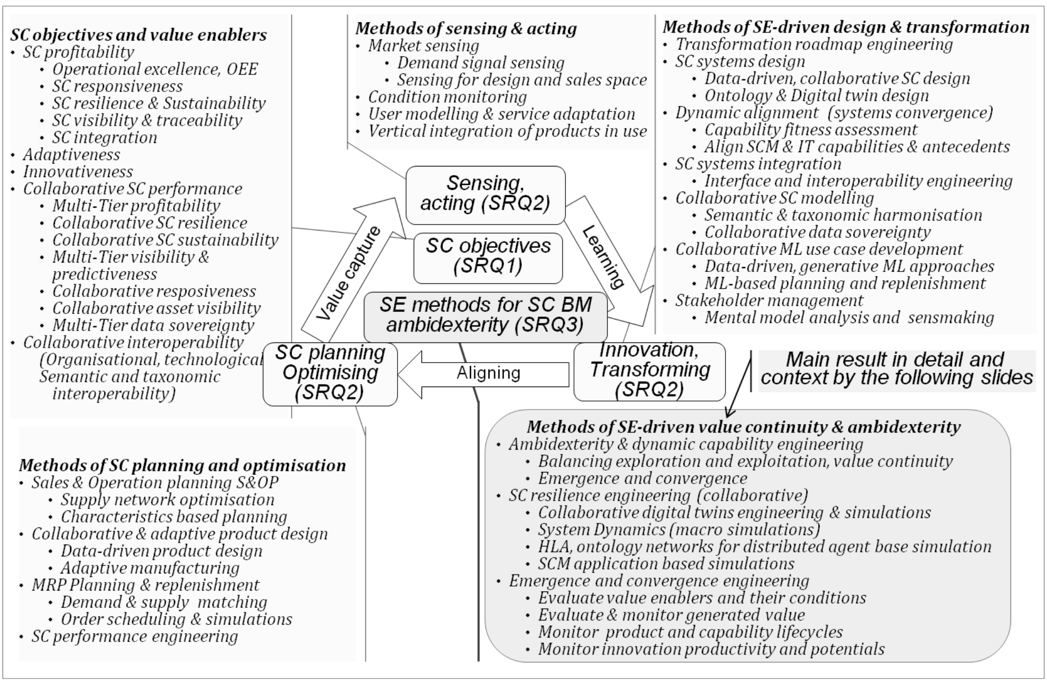


Fig. 3: Formatted SE methods for engineering SC business model ambidexterity (Nuerk, 2024)

gence processes. The case study was replicated at an innovative European make-to-order automotive supplier, an industrial manufacturer, an automotive systems supplier, and a European sports car maker, enriching the research with insights from industrial experts. The developed evaluation methods were tested at these companies. Contributions from the case study participants are indicated in the following sections as P_1 to P_9, according to Tab. 4 in the Annex.

3.2 Industrial Case Studies and Test of Evaluation Methods

As a core objective, the industrial case studies explored in-depth findings on current initiatives and implementation activities in Industry 4.0. Objectives, obstacles, and main efforts were examined and analyzed similarly to the SAP SE case studies. These findings were categorized and mapped to the SE model phases' activities. In addition, the two evaluation methods that have been tested are highlighted in the bottom left area of Fig. 2. The participants reviewed and validated the entire SE-driven methodology. Through this process, the study provides a robust framework for understanding and implementing SE-driven methodologies to enhance SC performance, resilience, and innovation in the context of Industry 4.0.

3.2.1 Test of SCM IT Capabilities' Fit Evaluation (Systems Convergence)

Evaluating companies' SCM IT capabilities has been identified as a significant component of the SE-driven model for achieving convergence in digital SC business models. Therefore, a systems theory-based approach, consistent with a configurational theory, was tested at sample Company B by participant P_9 and the author.

State-of-the-Art: According to contingency theory, aligning patterns between corporate strategic contexts and structural characteristics can lead to high business performance and prevent systemic misalignment (Oh and Pinsonneault, 2007). Strategic alignment is essential for formulating and implementing a strategy. Business value relies on resource-centred perspectives and contingency theory, which posits that aligning parameters of strategy, context, and structure leads to excellent performance. Makadok (2001) describes dynamic capabilities (DC) as potentials for innovative capacity, enabling organizations to transform by effectively reconfiguring capabilities to remain competitive (Makadok, 2001). Ambidexterity refers to balancing efforts to develop DC by exploring innovations and pre-creating enterprise capabilities such as artefacts and organizational knowledge against the exploitation efforts for rent creation (O'Reilly and Tushman, 2008). In this regard, the present measurement approach enables evaluating capabilities' levels concerning pre-developed artefacts, facilitating their fast and appropriate selection and utilization in various business situations. To fulfil fitness conditions, each high-order SCM IT capability must support SC objectives and align with the company's strategy, expressed as the desired future level of SC objectives. Fig. 4 illustrates how strategic business attributes determine the needed future capabilities, matched by current SC capabilities. The Euclidean distance between current and desired capabilities indicates the need for alignment activities. This systems approach is consistent with configurational theory, defining 'fit' as consistency across multiple design and context dimensions. The concepts combine holistic and detailed views of systems in their contexts.

Tab. 1 shows the detailed assessment filled out by Participant P_9, for evaluating SCM IT capabilities for Supply Network Planning and Factory Scheduling, which have a significant impact on SC objectives, rated on a five-point Likert scale. Fig. 5 presents the analysis of current and future levels for SNP and Factory planning IT capabilities, while Fig. 6 shows the fitness levels for SC objectives. The evaluation highlights strengths in (1) factory scheduling, optimizing plant schedules considering process technology constraints, and (2) multi-objective supply network plan optimization aligning with procurement and financials. The company's SCM simulations show fit for handling internal situations but lack early warnings of external adversities.

The misfit calculations in Fig. 7 and 8 highlight strengths in customer service, delivery reliability, and midterm Demand and Supply Network Planning. The company is highly profitable in internal processes but shows gaps in collaborative processes and lacks agile responsiveness to short-term changes. This aligns with SAP expert interviews, emphasizing the need for increased SC resilience from better collaboration and visibility. Fig. 7 shows high misfit levels, indicating a demand for improved SC synchronization. Fig. 8 highlights deficiencies in collaboration effectiveness and responsiveness,

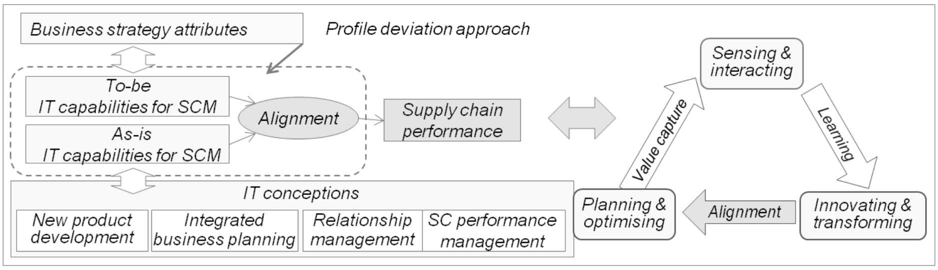


Fig. 4: Configurational theory-based capabilities fit evaluation (Nuerk, 2024; Sabherwal and Chan, 2001)

Tab. 1: Evaluation of SCM IT capabilities fitness by rating as-is and to-be levels

	SC capabilities	SC agility & responsiveness		SC profitability & OEE		SC resilience & sustainability		Collaboration effectiveness		Delivery reliability & predictability		Mean	Mean	Mistfil
		As-is	To-be	As-is	To-be	As-is	To-be	As-is	To-be	As-is	To-be	as-is	to-be	level
Supply Network planning	Demand signal management	3.00	5.00	4.00	4.00	3.00	4.00	4.00	5.00	5.00	5.00	4.54	4.60	2.45
	Multi-objective plan optimisation	4.00	4.00	5.00	5.00	4.00	5.00	4.00	5.00	5.00	5.00	4.40	4.80	1.41
	Plan optimisation based on profit	3.00	4.00	5.00	5.00	4.00	5.00	3.00	3.00	4.00	4.00	3.80	4.20	1.41
	Transportation optimisation	3.00	4.00	5.00	5.00	4.00	5.00	4.00	5.00	4.00	5.00	4.00	4.80	2.00
	Long-term capacity levelling	4.00	5.00	4.00	5.00	4.00	5.00	3.00	4.00	5.00	5.00	4.00	4.80	2.00
	S&OP alignment with procurement	5.00	5.00	4.00	4.00	3.00	4.00	4.00	5.00	4.00	4.00	4.00	4.40	1.41
	S&OP alignment with financials	4.00	4.00	3.00	3.00	3.00	3.00	3.00	4.00	4.00	4.00	3.40	3.60	1.00
	Strategic sourcing	3.00	4.00	4.00	4.00	4.00	5.00	3.00	4.00	4.00	4.00	3.60	4.20	1.73
Factory scheduling	Factory scheduling (Block planning)	4.00	5.00	4.00	4.00	3.00	3.00	3.00	4.00	5.00	5.00	3.80	4.20	1.41
	SC synchronisation (collaborative)	4.00	5.00	4.00	4.00	4.00	5.00	3.00	5.00	5.00	5.00	4.00	4.80	2.45
	SC end-to-end visibility in time	3.00	5.00	4.00	5.00	3.00	5.00	4.00	5.00	4.00	5.00	3.60	5.00	3.32
	Predictive Maintenance	4.00	5.00	3.00	4.00	3.00	4.00	3.00	4.00	4.00	5.00	3.40	4.40	2.24
	Modelling and simulations	4.00	5.00	4.00	5.00	4.00	5.00	4.00	5.00	3.00	3.00	3.80	4.60	2.00
	Means of fitness contribution	3.19	3.94	3.50	3.75	3.06	3.81	3.00	3.81	3.69	4.54			
	Misfit level	4.00		2.00		3.74		3.87		1.73				

Source: Nuerk (2024); Legend: 1 = no support for SC objectives; 2 = low support; 3 = medium support; 4 = high support; 5 = very high support.

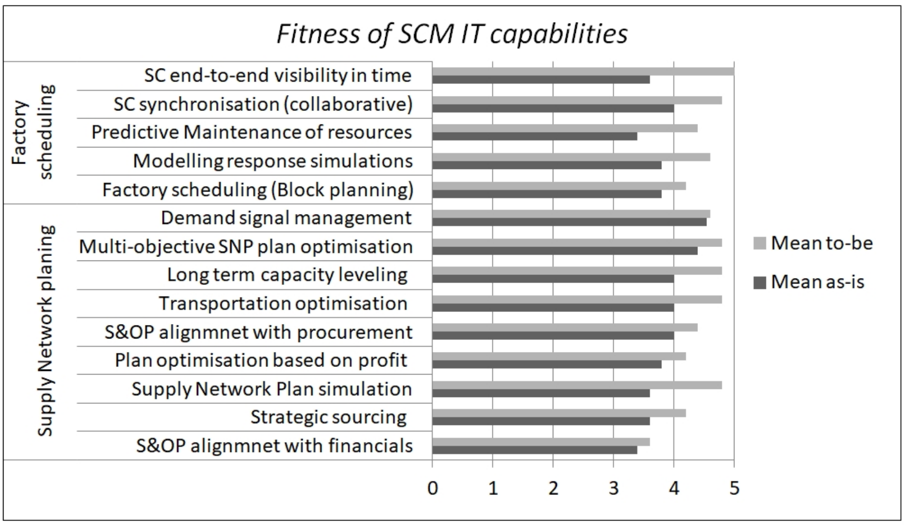


Fig. 5: Fitness levels of SCM IT capabilities (high levels are high support for SC objectives) (Nuerk, 2024)

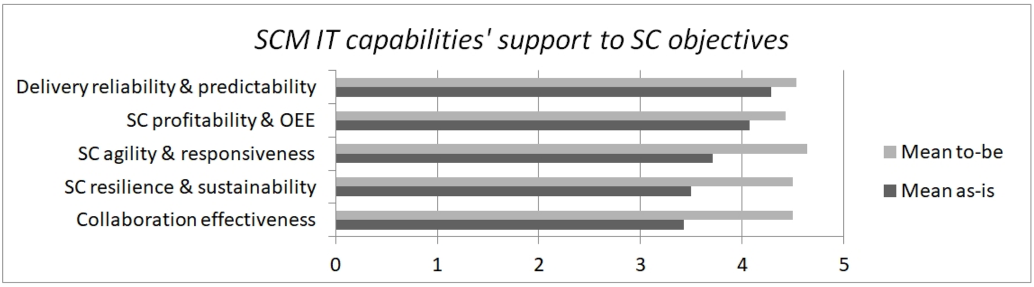


Fig. 6: SC capabilities' support to SC objectives (Nuerk, 2024)

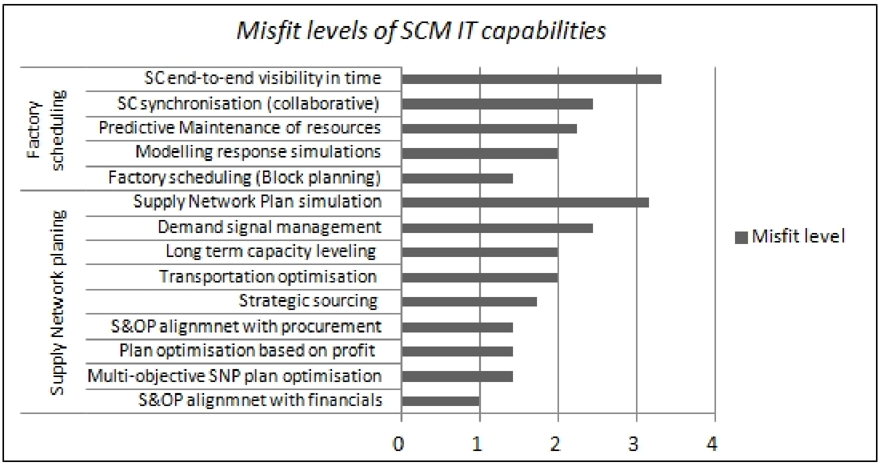


Fig. 7: Misfit levels of SCM IT capabilities (high levels indicate a high extent of misfits) (Nuerk, 2024)

affecting SC resilience and performance continuity.

Tab. 2 summarises the SCM IT capability fitness evaluation findings, demonstrating the method's ability to identify misfits concerning SC objectives. The result helps to define areas needing improvement for system and SC business model convergence, supporting value-oriented transformation and alignment roadmaps. The concept enables the evaluation of the various needed capability levels for changing business situations, contributing to dynamic capabilities development. Thus, the SCM IT capability fitness evaluation method is part of the SE-driven SC engineering and transformation model, leading to superior business performance by aligning as-is architecture with ideal fitness levels.

According to the test findings, the introduced capability fit evaluation answers the following

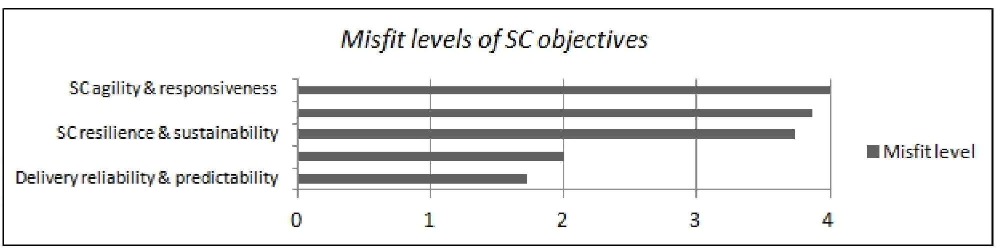


Fig. 8: SCM IT capabilities misfit impact on SC objectives (Nuerk, 2024)

Tab. 2: High priorities identified by the test analysis SCM IT capabilities fit

SCM IT Capability	As-is level	To-be level	Fit ratio	Comment	Related KPIs
SC end-to-end visibility in time	3.6	5.0	3.3	Higher transparency in the supply chain is needed to improve resilience by response in time.	SC responsiveness
Supply Network Plan simulation	3.6	4.8	3.2	Capabilities are needed that enable simulations of macro-level effects on the supply network.	Plan profitability
SC synchronization (collaborative)	4.0	4.8	2.5	Capabilities are needed to simulate better SC synchronization on the extended supply network.	Plan profitability, Collaboration effectiveness
Demand signal management	4.5	4.6	2.4	The company will exhaust real-time demand sensing to predict demand changes more reliably.	Forecast accuracy
Predictive Maintenance of resources	3.4	4.4	2.2	The need for more reliable simulation capabilities goes hand in hand with the reliability of resource maintenance prediction.	Plant utilization and OEE, Plant throughput in tonnes per day
Modelling response simulations	3.8	4.6	2.0	Better simulation modelling integrated from macro implications to real-time response is needed.	SC responsiveness, Profitability
Transportation optimization	4.0	4.8	2.0	The need for more reliable simulation capabilities goes hand in hand with the reliability of long-term capacity planning and transportation optimization.	Transportations adherence
Long-term capacity levelling	4.0	4.8	2.0		Resource & labour availability

questions necessary for developing a value-focused capability development and implementation roadmap:

1. What are the right levels of fit, needed for SCM IT capabilities?
2. What are the right levels of their antecedents?
3. What capability levels are needed for ideal contingencies in context?
4. What dynamics of capabilities are required?
5. What useful artefacts should be modelled as absorptive capacities?

3.2.2 Test of Evaluating Value Sensing and Exploitation (Systems Emergence)

Value sensing must detect signals with the potential for transformation into value propositions (VP) or business processes' benefits (exploitation).

Evaluating these value potentials and allocating them to business model components is crucial for innovation. These evaluations enhance understanding of organization-specific emergence processes and possible convergence deficiencies in exploiting expected value. A company's ability to use external knowledge relies on existing related knowledge, essential for identifying.

Tab. 3 shows the evaluation sheet with ratings of relationships between various sensing types as value signal sources impacting business model dimensions like value proposition, creation capabilities, and processes. This assessment, filled out with the participant, highlights how value-generating relationships between enablers and exploiting capacities vary over time. A pairwise Likert scale evaluation of current (as-is) and future (to-be) values expresses estimated potentials, supporting the development of dynamic capabilities. Participant P_7 consulted multiple business areas in Company A—marketing, sales, spare parts management, distribution partners, portfolio management, and product design—to sense value signals and proposition characteristics. Discussions with manufacturing, resource design, and process engineering provided insights into value drivers

Tab. 3: Sheet for evaluating the effectiveness of value sensing and exploitation

Value sources/sensing type	**Market & demand signal sensing**		**Environment & Operations sensing**		**Vertical Product data**		**Collaborative engineering**		**Expert knowledge**				
Business model dimension	**As-is**	**To-be**	**As-is**	**To-be**	**As-is**	**To-be**	**As-is**	**To-be**	**As-is**	**To-be**	**Mean as-is**	**Mean to-be**	**Potentials**
Value proposition													
Differentiation & customisation	5.00	5.00	1.00	1.00	1.00	5.00	4.00	5.00	5.00	5.00	3.20	4.20	4.12
Market relatedness, customer focus	5.00	5.00	1.00	1.00	2.00	5.00	4.00	5.00	5.00	5.00	3.40	4.20	3.16
Complementary products	4.00	4.00	1.00	1.00	2.00	5.00	4.00	4.00	3.00	5.00	2.80	3.80	3.61
Connected information flow	2.00	2.00	1.00	1.00	2.00	5.00	3.00	3.00	1.00	1.00	1.80	2.40	3.00
Value creation capabilities													
Short time-to-market	2.00	3.00	1.00	1.00	2.00	3.00	3.00	5.00	3.00	4.00	2.20	3.20	2.65
Enhancing product configuration	3.00	5.00	2.00	3.00	2.00	4.00	2.00	3.00	2.00	3.00	2.20	3.60	3.32
Reconfigurability, scalability	3.00	4.00	1.00	2.00	2.00	4.00	2.00	4.00	3.00	5.00	2.20	3.80	3.74
Synchronise product combinations	2.00	4.00			2.00	4.00	3.00	4.00	3.00	4.00	2.50	4.00	3.16
Faster adoption of opportunities	2.00	3.00	1.00	1.00	2.00	4.00	4.00	5.00	3.00	3.00	2.40	3.20	2.45
Value capture, processes													
Reduced R&D time	2.00	3.00	1.00	1.00	2.00	3.00	3.00	5.00	2.00	4.00	2.00	3.20	3.16
Enable data-driven design	3.00	5.00	1.00	1.00	2.00	4.00	3.00	4.00	3.00	3.00	2.40	3.40	3.00
Improve predictability	4.00	5.00	1.00	2.00	2.00	3.00	4.00	4.00	2.00	3.00	2.60	3.40	2.00
Improve synchronisation	2.00	3.00	3.00	5.00	2.00	5.00	3.00	5.00	3.00	4.00	2.60	4.40	4.36
Improve decision support	4.00	5.00	3.00	4.00	2.00	5.00	3.00	3.00	4.00	5.00	3.20	4.40	3.46
Increase flexibility, agility	3.00	3.00	4.00	4.00	3.00	4.00	4.00	5.00	5.00	5.00	3.80	4.20	1.41
Close experience gap	4.00	5.00	2.00	2.00	2.00	4.00	2.00	3.00	2.00	4.00	2.40	3.60	3.16
Improve resource availability	2.00	3.00	4.00	5.00	2.00	3.00	2.00	3.00	3.00	3.00	2.60	3.40	2.00
Enable preventive maintenance	2.00	2.00	5.00	5.00	3.00	4.00	2.00	3.00	2.00	3.00	2.80	3.40	1.73
Value contribution by sensing type (mean)	3.11	3.63	1.94	2.22	2.11	4.00	3.11	4.00	3.11	3.85			
Remaining value potentials		4.24		5.66		2.24		2.83		3.61			

Source: Nuerk (2024). Legend to model validation: 1 = does not contribute to value generation; 2 = contributes weakly to value generation; 3 = contributes to value generation; 4 = contributes strongly to value generation; 5 = contributes very strongly to value generation.

and relationships with external information and sensing.

The broad information scope and central impact of many parties on the effectiveness of emergence and convergence highlight the need for a central SE role to maximize value contributions from investments in value signals. Fig. 10 presents the evaluated current (as-is) and expected future (to-be) value potentials by sensing types for a business division, using means calculation. Fig. 9 highlights the current value exploitation and expected potentials by business model components.

The Euclidean distance measures the gap between current (as-is) and projected (to-be) value potentials. Fig. 11 and 12 show the effectiveness between value exploitation and the remaining potential for BM dimensions and sensing types. The test findings highlight where value is sensed, and exploited, and where further sensing or alignment is needed. They also show where value expectations were not met or exceeded. Participants of the industrial case studies and SAP SE affirmed this method as a high-priority, continuous lessons-learned activity in innovation and transformation management (P_1, P_3, and P_7). Such evaluations enhance transparency on innovation potentials and knowledge, delivering insights into value-enabling sensing patterns. Assessing sensed signals and exploited business value as a ratio of innovation capacities to potentials significantly benefits product and capability innovation. Collecting value signals in a repository and regularly learning from these opportunities can enhance pre-knowledge and drive value-generating business model dimensions. Fig. 11 and 12 present evaluated unfulfilled value

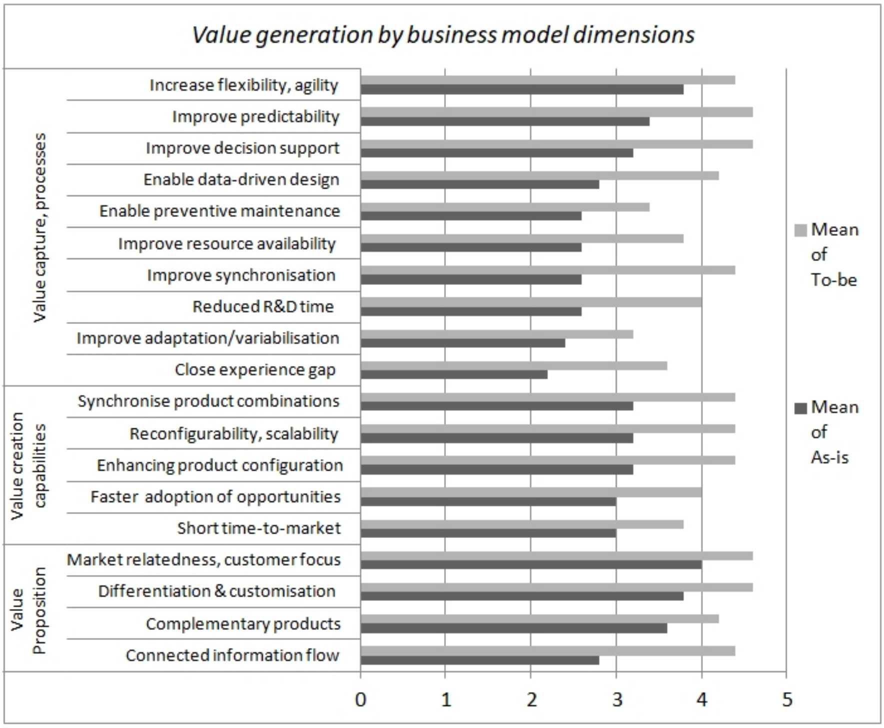


Fig. 9: Effectiveness of value exploitation (high levels show high effectiveness (Nuerk, 2024)

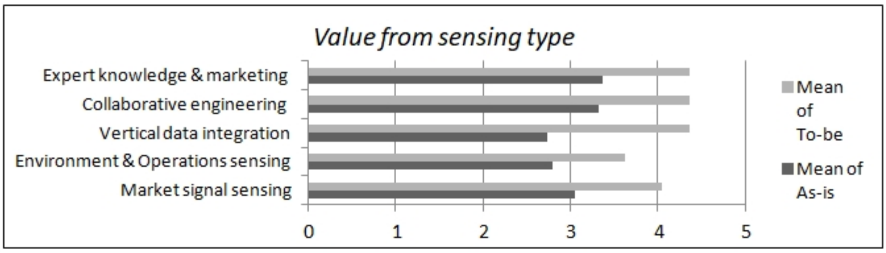


Fig. 10: Effectiveness of value sensing by sensing type (Nuerk, 2024)

expectations by BM dimensions and sensing types, respectively (Nuerk, 2024).

Repetitive evaluations over time build knowledge about innovation emergence and monitor value, providing insights into the organization- and context-specific value processes and their promoter conditions. Evaluating the relationships between innovation potentials and capacities offers valuable information for balancing exploration and exploitation efforts, significantly contributing to SC business model ambidexterity engineering. The tested method for evaluating value sensing and exploitation effectiveness provides insights in:

1. Which sensing sources contribute to different levels of value?
2. Which BM components release value?
3. Which conditions promote the emergence of value enablers?

The findings on simulation methods and the tested evaluation methods are discussed in the context of SC business model ambidexterity in Chapter 4.

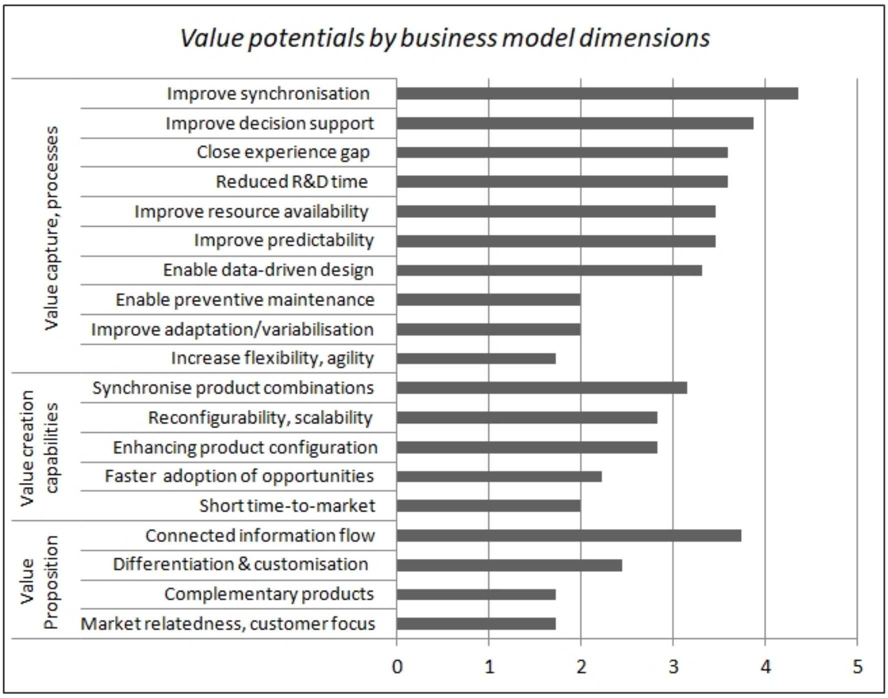


Fig. 11: Unfulfilled value expectations by BM dimension (Nuerk, 2024)

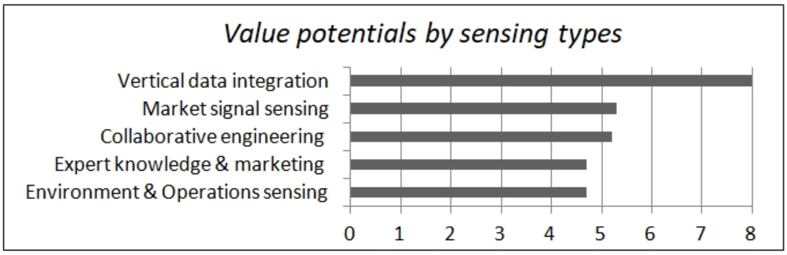


Fig. 12: Unfulfilled value expectations by sensing types (Nuerk, 2024)

4 RESULT AND DISCUSSION

The results presented in this chapter focus on SE-driven meta-modelling (4.1) to enable collaborative SC resilience and support ambidexterity of SC business models (4.2) through macro and micro simulations (4.3) and evaluations of performance and emergence and convergence (4.4). Section 4.5 summarises the findings in the context of the SE methodology and highlights their benefits for mastering various ambidexterity challenges.

4.1 Meta-Modelling for Resilience Along the Extended Supply Chain

Nearly all case study participants note that SC visibility decreases steadily due to increased process separation by more business partners. Rising environmental uncertainties and business dynamics lead to greater adversities, with roots and effects spread across SC domains. Therefore, improving SC resilience (SCR) and SC agility are top priorities in many man-

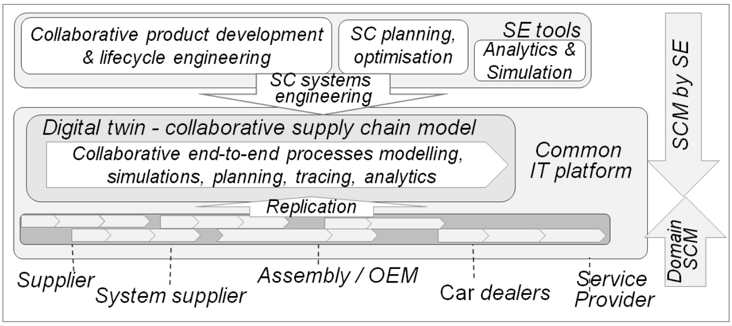


Fig. 13: Meta-modelling resilient SC networks—an end-to-end process perspective (Nuerk, 2024)

ufacturing sectors. The literature recognizes SCR as crucial for handling volatile, uncertain, complex, and ambiguous (VUCA) business situations, focusing on adaptiveness, responsiveness to disruptions, SC risk management, and performance management. However, all participants and industry initiatives, such as Catena-X for automotive, believe current SCR challenges must be addressed collaboratively and holistically across ecosystems, where approaches are currently lacking. SCR is significantly influenced by macroeconomic factors, often impacting locations different from the roots.

Traditionally, SC experts specialize in business functions like procurement, production, and sales. A holistic, cross-domain view of the multiple-tier supply chain is needed to sustain SCR. Cross-SC-domain knowledge is crucial for dealing with unforeseen vulnerabilities. To achieve overall SC visibility and identify local implications, the study recommends a bottom-up approach for domain-driven SCM by lines of business and a SE-driven top-down, cross-domain approach for modelling meta-structures along the supply chain, as highlighted in Fig. 13. This meta-systems perspective allows SE to identify vulnerabilities and latent structures using complexity engineering, simulation, and evaluation methods, safeguarding the resilience of the entire supply chain.

A systemic view of material and value flow across the supply chain, capacities, and bottlenecks among SC members requires new types of interoperability implemented in industries not yet. High visibility across the end-to-end supply chain enables informed decisions based on timely insights into operational flows between SC partners and deviations from plans, impacting delivery accuracy and SC agility, which presents vital variables of SC resilience. SE can significantly contribute to SC design and evaluation methods for controlling SC systems given SC integration's high variability, complexity, dynamics, and context-dependency. SE can provide SCR and performance continuity with a view of the entire end-to-end processes, keeping the supply chain stable and under control. A digital twin (DTW) can serve as a technical basis, enabling collaborative SC modelling connected to various partners' SCM systems, acting as a single source of truth. A DTW can also act as a common process platform, optimizing SC performance, energy consumption, and CO_2 emissions, synchronizing supply networks, and controlling resource sharing.

4.2 Ambidexterity Engineering of SC Business Models

Performance continuity and resilience in dynamic SC ecosystems depend on the right innovations, system convergence, and balanced ambidexterity between exploration and exploitation, strengthened by SE methods such as complexity engineering. Complexity, as a phenomenon of emergence, presents both an engineering challenge and a value source. Organizations must manage innovation streams and value-generating operations in a balanced way, integrating external knowledge and designing socio-technical systems considering:

1. *Sequential Ambidexterity:* Exploiting technological innovations while coordinating transition architectures to balance business and environmental changes.
2. *Structural Ambidexterity:* Simultaneously exploring and exploiting innovations, and aligning corporate units, assets, and culture.
3. *Contextual Ambidexterity:* Designing and transforming processes to fit both exploratory and exploiting activities within the context.

Studies on ambidexterity emphasize cultural and structural characteristics. The current study highlights the importance of cross-organizational ambidexterity among supply network partners. Mastering ambidexterity requires SE to interact holistically across all SC business model lifecycle phases, integrating analytics and simulations of product lifecycles, SC optimization, and innovation processes. This supports planning reliability and precise product lifecycle management, which in turn provides valuable data for innovation management. In SC business models, ambidexterity refers to exploitation (enhancing existing capabilities) and exploration (developing new capabilities). Continuous evaluations of value exploration and exploitation effectiveness, as well as capability fitness, are core methods for safeguarding value continuity in digital SC models. Current SCM systems cannot consistently evaluate market adversities across the supply chain.

Ambidexterity engineering between innovation exploration and exploitation must be supported by simulations ideally integrating product development, lifecycle management, SC optimization, and macro-environmental implications. A digital twin can provide a platform for designing integrated processes and data models for simulations using real-time data from sensing, SC operations, and environmental conditions. Evaluating SC business model inputs, outputs, and object dependencies can be modelled using System Dynamics (SD). However, SD lacks granularity, so sub-models are needed to detect faults in detail. Combining two perspectives—a macro-level view from SD and a micro-level view using detailed sub-models—provides a feasible approach.

4.3 Modeling Simulations for SC Business Model Ambidexterity

Increasing complexity and business dynamics necessitate simulations in SC systems to enhance planning reliability and resilience. Simulations analyze SC systems' behaviour in complex conditions, supporting SC planning decisions and safeguarding investment projects. Simulation systems support:

1. Increasing distributed manufacturing networks.
2. Increased need for SC resilience by design and pre-emptive simulations.
3. Rising product complexity and variety.
4. Increased flexibility and customization.
5. Shortening product and service lifespan.
6. Growing quality requirements and cost factors.

These needs lead to shorter development and planning cycles, requiring intelligent strategies for complex technical systems in global companies. Analyzing complex dependencies between linking modules, production facilities, and supply systems is limited to mathematical-analytical methods. Simulation is a recognized method for analyzing and improving value-adding processes in production and supply chains. Case study participants see SE as essential for enabling closed monitoring of overall supply chains. SE requires a mindset across business domains to drive SC performance and resilience by design. SE must model analytics capabilities at the meta-level, providing early warnings of events affecting the supply chain across domains.

SCM application providers must offer modelling capabilities for creating meta-process structures for analytics and alerting. Evaluations of SC business model inputs, outputs, and dependencies can be modelled using SD, and are suitable for analysing economic macro effects and latent SC structures. However, SD lacks detail, so sub-models must be developed

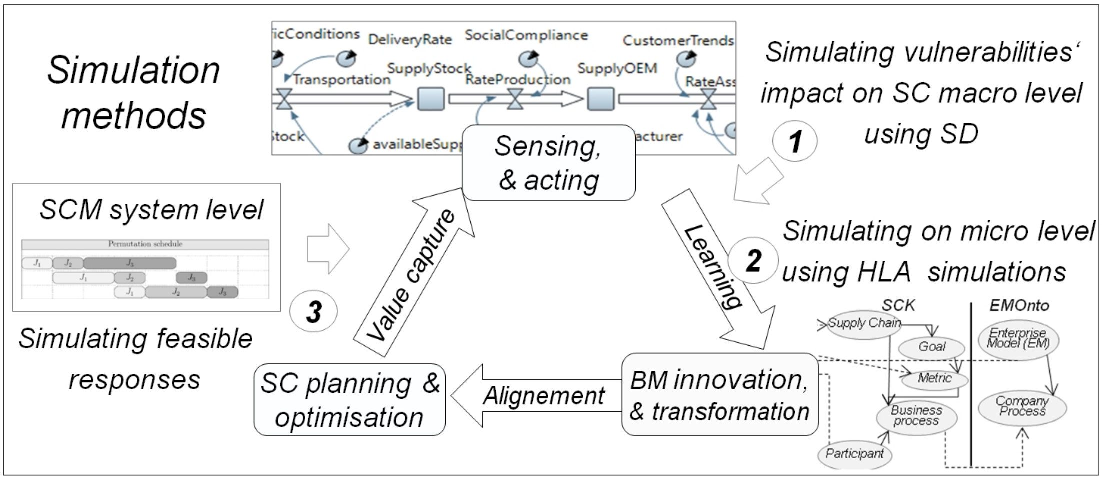


Fig. 14: Simulating local causes of macro effects and discrete responses (Nuerk, 2024)

to identify problems quickly. A combined simulation approach is needed, where the study proposes three levels for simulating supply networks and manufacturing plants:

1. *Macro Simulations* using SD.
2. *Micro Simulations* using agent-based high-level architecture (HLA) federations.
3. *SCM Application-Based Simulations* for detailed engineering change implications on SC planning.

Microscopic SC operations behaviour can be modelled using agent-based methods like HLA Federations. A top-down approach models supply networks based on SC strategies, addressing resilience to macroscopic effects (e.g., SD simulations) and microscopic responses to adverse events (e.g., HLA Federates). A bottom-up approach using agent-based modelling enables the evaluation of operational performance and resilience of critical locations along the supply network. A hierarchical network of agent-based SC operations entities allows simulation-based analysis to identify effective supply network designs to mitigate risks. A hybrid model using agent-based models like networked HLA Federates, which receive macro implications from SD for further simulations, is proposed. Distributed agent-based simulations can be structured using ontology networks like SCOR notation and HLAs are suitable for modelling and simulating complex scenarios across heterogeneous SCM systems.

A federation describes the overall simulation process, with participating systems (federates) linked via HLA middleware by a runtime infrastructure (RTI). HLA supports interoperability, reusability, extensibility, and refinement of existing models, enabling time-critical couplings and message exchanges across agent-based simulation infrastructure. This approach is useful for complex engineering-to-order projects and simulating circular economy use cases, where products can be traced and reused. Evaluating SC business model inputs, outputs, object dependencies, and environmental adversities can be modelled and simulated using SD combined with HLA federates for identifying local implications along the supply chain as shown in Fig. 14.

4.3.1 System Dynamics (SD) and Agent-Based Supply Network Simulations

SD fits for analyzing economic macro effects and latent SC structures but is not granular enough to detect detailed faults. Therefore, agent-based simulations modelled using ontology networks and High-Level Architecture (HLA) Federations are recommended by the SAP case study participants (P_1). Such simulations help understand emergent order in complex SC systems and search for the best local design for performance, resilience and effectiveness on a local micro-level of the supply chain.

HLA Federates ontologies, linked with SCM SCOR ontology, enable modelling of local system effects, considering crossover effects through HLA runtime infrastructures (RTI). Hence, it can be stated that HLA Federates ontologies linked with SCM SCOR ontology enable the modelling of agent-based simulations about local systems effects considering systems' crossover effects enabled by HLA runtime infrastructures.

Finally, discrete SCM application-based simulations enable detailed analysis of phasing in new products, engineering change management, and phasing out products, providing early insights to safeguard resilience and performance continuity. Discrete, SCM application-based simulations enable detailed implications analysis of phasing-in of new products, engineering change management, and phasing-out products onto the overall SC planning, which provides early insights on necessary activities to safeguard resilience and performance continuity.

Fig. 14 highlights an integrated simulation use case, where expected environmental macro adversities are simulated on their impact on the supply chain using systems dynamics (SD) (no. 1 in Fig. 14) and further simulated using HLA modelling for evaluating their local effect on SC locations (no. 2). Based on these findings, SCM simulation capabilities can be used for exploring workarounds as response alternatives to adversities (no. 3). These can be alternative suppliers, sub-contracting manufacturers, alternative transportation routes, etc. Implementing an SD simulation concept involves:

1. Defining simulation objectives for SC efficiency and resilience.
2. Identifying key variables and relationships influencing the supply network.
3. Developing a conceptual model using SD techniques.
4. Translating the conceptual model into simulation software.
5. Modelling key SC processes and policies.
6. Calibrating and validating the simulation model.
7. Designing scenarios and executing simulations to explore different strategies and assess resilience.

4.3.2 Design, Implement, and Integrate an HLA Simulation Landscape

Designing and implementing a High-Level Architecture (HLA) landscape involves creating a distributed simulation environment that allows collaboration among multiple simulation components. Designing an HLA simulation landscape involves:

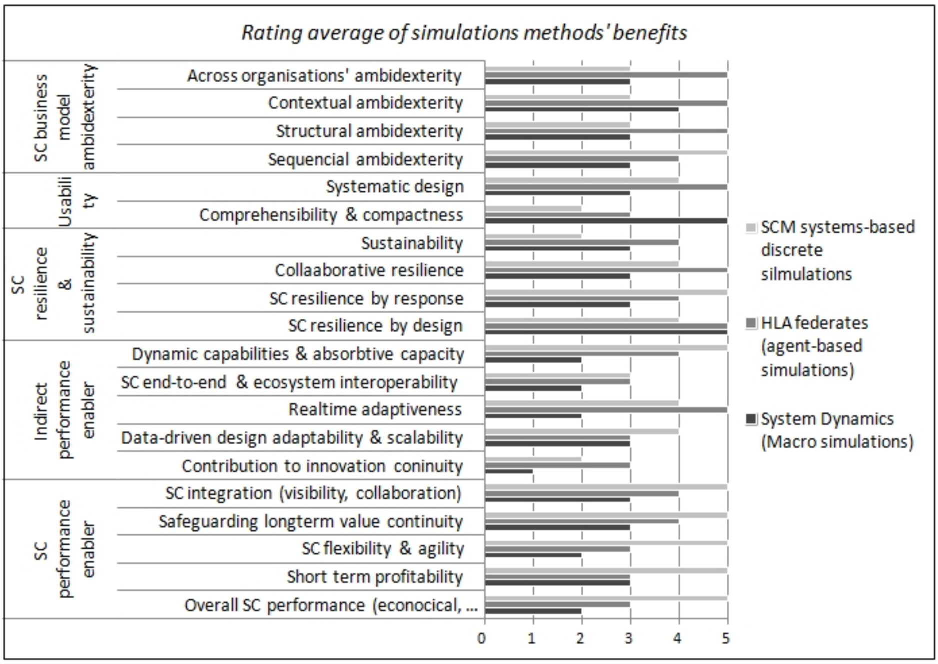
1. Defining simulation objectives and requirements.
2. Selecting an HLA-compliant simulation framework.
3. Defining simulation federates and their interactions.
4. Developing federated implementations.
5. Integrating federates with RTI.
6. Modelling simulation scenarios.
7. Configuring and deploying the simulation federation.
8. Executing and monitoring simulations.
9. Refining and optimizing simulations based on results.

Integrating SD simulation outputs into HLA simulations involves:

1. Defining data exchange requirements.
2. Exporting relevant SD simulation outputs.
3. Designing data interoperability mechanisms.
4. Transforming and integrating data into the HLA simulation.
5. Incorporating data into HLA simulation logic.
6. Validating integration and ensuring data consistency.

4.3.3 Supply Chain Simulations Using Digital Twins and SCM Applications

Business dynamics can be simulated to assess direct impacts on the supply network using SCM application simulation features. Multi-objective optimization and simulations provide insights into worst-case scenarios and help prioritise high-profit orders. Digital twins offer value through visualization, analysis, optimization, and simulations based on real-time data. SE activities for designing resilient supply



Legend to Model Validation: 1 = does not contribute to SC objective; 2 = contributes weakly to SC objective; 3 = contributes to SC objective; 4 = contributes strongly to SC objective; 5 = contributes very strongly to SC objective.

Fig. 15: Validation ratings of the benefits through the explored simulation methods (Nuerk, 2024)

chains include reviewing SC process design, balancing redundancies and economic performance, evaluating risks, and developing ML use cases (P_1, P_2).

4.3.4 Validation of the Explored Simulation Methods

The validation results of simulation methods (Fig. 15) highlight the benefits of SCM application-based simulations for identifying workarounds and optimising manufacturing schedules. However, HLA federates and SD simulations provide greater insights into SC business model ambidexterity. Combining these methods offers long-term effectiveness, agility, and responsiveness to business changes.

4.4 Evaluating the Emergence and Convergence of SC Business Models

Supply chain performance by operational SC processes is measured by key performance indicators (KPIs), with the SCOR standard providing useful hierarchical references. State-of-the-art SC metrics include KPIs for costs, delivery reliability, fulfilment rates, inventory levels, and more. Companies select KPIs based on specific needs, setting timeframes and thresholds to receive alerts for significant deviations. The study shows that performance evaluations using KPIs, value exploration and exploitation effectiveness (emergence), and capability fit (convergence) give a holistic business overview. This approach provides detailed insights into current performance, value exploitation, and capability fitness and enables informed predictions of future performance and value developments.

According to dynamic capability theory, continuous capability alignment is essential, and complex adaptive systems theory suggests that innovation potentials emerge with the creation of new order. Therefore, continuously evaluating value exploration, exploitation effectiveness, and capability fitness are core methods for value continuity. Case studies using sample companies showed that these methods offered rich insights and qualitative findings, particu-

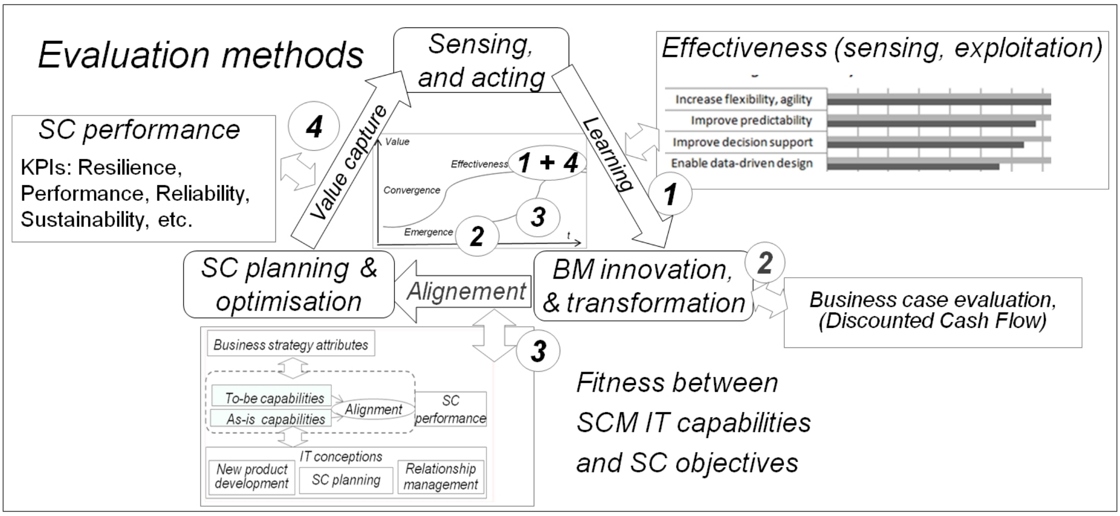


Fig. 16: Monitoring SC performance and evaluating value exploration and exploitation simultaneously to sustain profitability continuity (Nuerk, 2024)

larly in assessing the relationships between SC objectives and SCM IT capabilities and the effectiveness of value sensing and exploitation. To safeguard digital SC models' value continuity, the study proposes ongoing activities: evaluating the effectiveness between value enabler sensing and exploitation (Fig. 16, no. 2), evaluating capabilities' fitness levels (no. 3), and SC performance measurements using KPIs (no. 1). Assessing SCM IT capabilities supports enterprise convergence by providing alignment information. A systems approach, consistent with configurational theory, evaluates fitness levels, considering SC objectives and SCM IT capabilities, enabling a holistic system view. Misfit levels are calculated using the Euclidean distance. Such evaluations help in developing useful artefacts to prepare for economic change.

Investments in artefacts need economic proof, like the Discounted Cash Flow (DCF) method, to ensure monetary effectiveness. This approach also assesses the effectiveness of value sensing and exploitation by business model components, improving innovation productivity. It helps SE understand innovation processes during capability and product lifecycles and offers insight into value-enabling promoters and conditions.

4.4.1 Evaluating the Effectiveness of Value Sensing and Exploitation (Emergence)

A company's ability to use external knowledge for future innovations depends on existing related knowledge. Hence, a strong connection between innovation strategy, knowledge management, and market-sensing capabilities boosts innovativeness and market responsiveness. Collecting value signals and regular lessons learned contribute to the required pre-knowledge. Fig. 17 shows the relationship between value sourcing types and business model components where value opportunities can be adopted. Pairwise evaluations using a Likert scale can express estimated potentials for focused actions. Repetitive evaluations contribute to understanding innovation emergence and monitoring value during lifecycles. These evaluations provide insights into innovation potentials and value-enabling sensing patterns. Observing these patterns offers insights into organization-specific value processes and their conditions.

The case study participants concluded that value sensing improves awareness of signals' value from transforming into value propositions or business process benefits. Evaluating sensed value potentials and prioritizing BM components is crucial for innovation and ambidex-

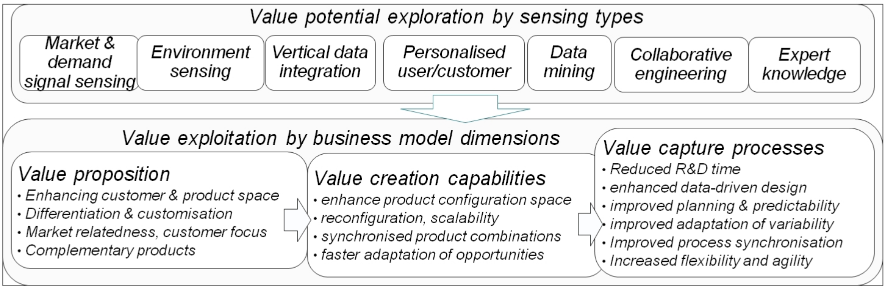
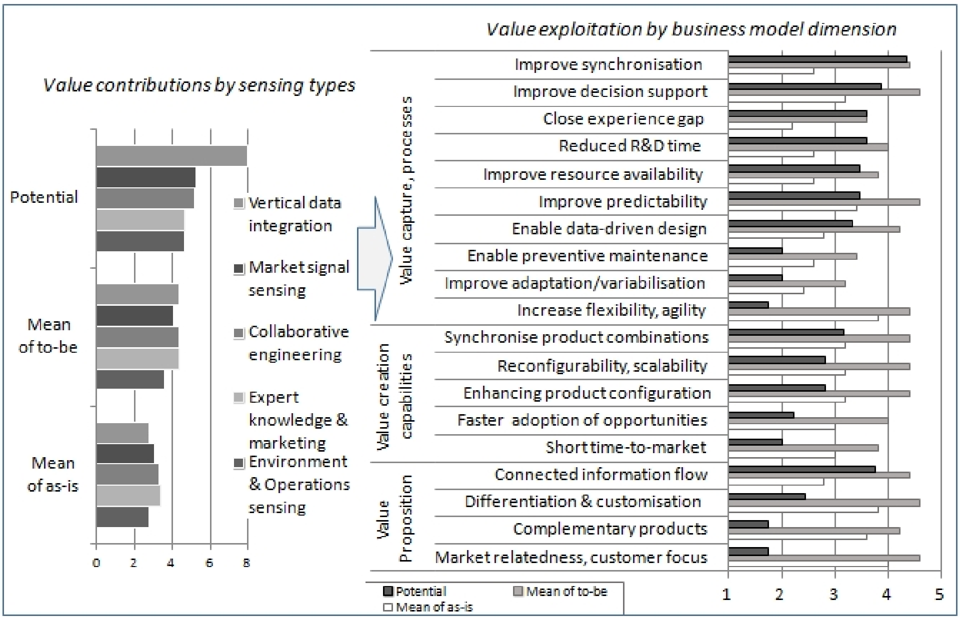


Fig. 17: Relationships of sensed value enablers and value contributors (Nuerk, 2024)



Legend: 1 = does not contribute to value generation; 2 = contributes weakly to value generation; 3 = contributes to value generation; 4 = contributes strongly to value generation; 5 = contributes very strongly to value generation.

Fig. 18: Evaluation result of value contribution by sensing types (exploration) and value exploitation by business model dimensions (a business division of sample company A) (Nuerk, 2024)

terity engineering. The approach requires the consultation of a broad variance of involved stakeholders for qualitative Likert scale assessments, supplemented by quantitative metrics. This holistic evaluation approach offers a comprehensive view of value sensing, exploitation, and innovation productivity benefiting SE and stakeholder collaboration. Findings improve understanding of emergence processes and convergence deficiencies in exploiting expected value, informing the development of artefacts and transformation roadmaps. Case study participants affirmed the value enabler evaluation as a high-priority, continuous lessons-learned activity in innovation management (P_1–P_7).

Hence, evaluating sensed signals and related exploited business value, as a ratio between innovation capacities and potentials, significantly benefits product and capability innovation (P_3, P_7–P_9). Fig. 18 summarises value potentials by sensing type, as evaluated with company A (P_7). Means calculation expresses as-is and to-be value potentials, while the Euclidean distance expresses the gap as remaining value potentials. This provides a holistic view of where value is sensed, and exhausted, and where further activities can target remaining potentials. It also reveals where expectations were not met or exceeded. Iterative evaluation localizes value drivers and maps them to value propositions (VP), enriching capability matrices in lines of business (LoB) domains. The method gives an overview of the sensed value and exhausted value in the business model, identifying remaining value potentials for a focused roadmap of further activities. It also improves transparency on unmet or exceeded value expectations. This evaluation method is affirmed by industrial case study participants and SAP SE as a high-priority, continuous lessons-learned activity in innovation and transformation management (P_1, P_3, P_7). Such evaluations enhance the transparency of innovation potentials and awareness, providing insights into value-enabling sensing patterns.

Additionally, collecting value signals in a repository and learning from adopting these opportunities to value-generating business model dimensions can lead to pre-knowledge. Repetitive evaluations contribute to understanding innovation emergence and monitoring value, providing insights into organizational- and context-specific value emergence processes and promoter conditions. Evaluating relationships between innovation potentials and capacities helps balance exploration and exploitation efforts, crucial for SC business model ambidexterity engineering. The tested method reveals which sensing sources contribute to value levels, how BM components release value, and which conditions promote value enablers.

4.4.2 Quantitative Metrics and Linking with Qualitative Assessment

Innovation performance is evaluated using quantitative and qualitative measures to capture the effectiveness of innovation efforts. Common methods and metrics are detailed in Tab. 5 in the Annex. These assessments consider the impact of innovation on financial outcomes, market competitiveness, customer satisfaction, operational efficiency, and strategic alignment. Metrics for such evaluations are provided in Tab. 6. Linking KPI performance evaluations with Likert scale evaluations integrates quantitative metrics with qualitative assessments, offering a comprehensive view. Tab. 8 outlines activities for effectively linking these systems, combining quantitative measures with qualitative insights. This comprehensive approach allows organizations to demonstrate their ability to create value, drive growth, and achieve strategic objectives through innovation.

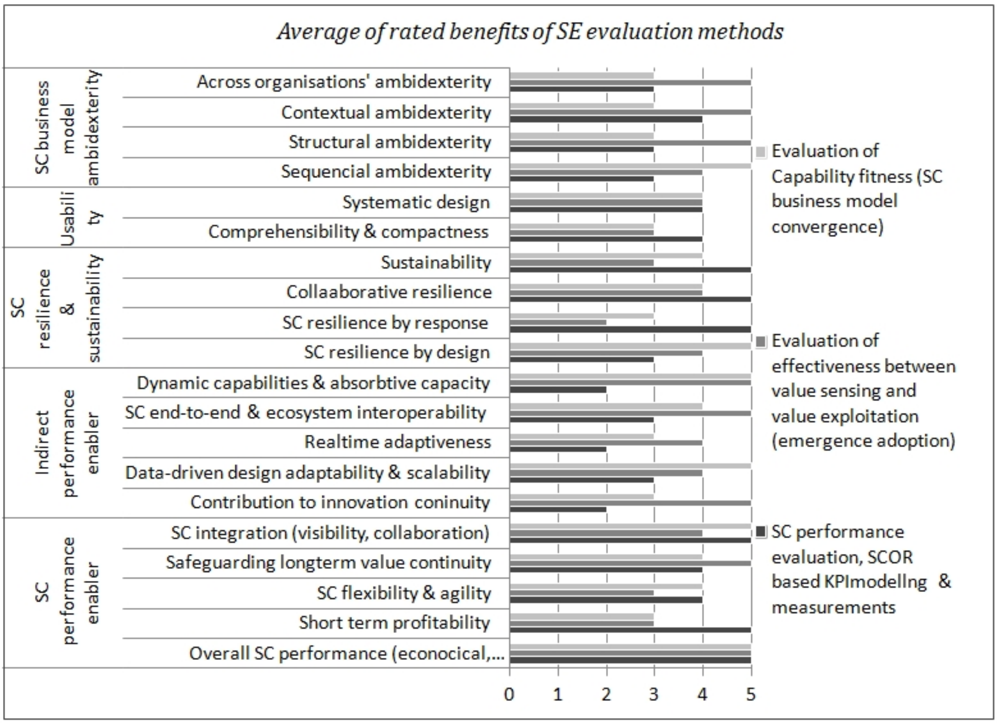
4.4.3 Capability Fit Evaluation for SC Business Model Convergence

Fit is defined as consistency across corporate design and context dimensions. A 2019 study developed a model to measure the fitness of SCM IT capabilities to the prevailing business model strategy, adapted to Industry 4.0 and SC objectives, and applied in sample company B. The model evaluates the as-is levels of SCM IT capabilities supporting SC objectives and the ideal to-be levels, identifying misfit levels and necessary alignment measures. The results align with SAP expert findings on SC collaboration gaps affecting agility and resilience. This evaluation confirms gaps in SC visibility as a root cause of limited resilience. The approach combines a holistic and detailed system view in context to evaluate needed capability levels for changing business situations and the development of dynamic capabilities using artefacts. This evaluation approach is suggested for assessing capability levels to support SC objectives, forming part of the SE-driven SC engineering and transformation model for strategic alignment and convergence.

4.4.4 Validation of Explored Evaluation Methods

Integrated evaluations of SC performance, the effectiveness of innovation adaptation, and capability fitness are the main components of analyzing the business model's ambidexterity.

Fig. 19 shows that participants rated ongoing KPI-based assessments to manage short-term SC performance and profitability as high. However, long-term performance requires business model ambidexterity and SC visibility for agility and responsiveness to unforeseen events. The case study research indicated that the evaluation approaches identify necessary SCM IT capabilities and their levels for ideal SC performance. These methods also enable the development of dynamic capabilities, fostering



Legend: 1 = no contribution; 2 = weak contribution; 3 = contributes; 4 = strong contribution; 5 = very strong contribution.

Fig. 19: Validation rating of the explored SE evaluation methods' benefits (Nuerk, 2024)

value emergence from innovations and convergence by implementing appropriate SCM IT capabilities. Ongoing evaluations and simulations create qualitative knowledge for responding to macro and micro implications.

4.5 The Study Contribution to Ambidextrous SC Business Models

According to dynamic capability theory, capability alignment must be continuous. Complex adaptive systems theory suggests that enterprise innovation potentials emerge with the creation of new order. Therefore, continuously evaluating value exploration, exploitation effectiveness, and capability fitness is crucial for value continuity. To safeguard digital SC models' value continuity, the study proposes the following ongoing activities:

1. Evaluation of Effectiveness between Value Enabler Sensing and Value Exploitation (Fig. 20, no. 2)
2. Evaluation of Capabilities' Fit Levels (Fig. 20, no. 5)
3. SC Performance Measurements Using KPIs (Fig. 20, no. 7)

Evaluating SCM IT capabilities' fitness levels supports enterprise convergence by providing information for value-focused alignment activities. This systems approach is consistent with configurational theory and has been implemented using a profile deviation approach. 'Fit' is defined as consistency across multiple corporate design and context dimensions and evaluated by a holistic and detailed system view. This approach was used to measure the fit of a highly innovative sample company's SCM IT capabilities to its business strategy. Fit and misfit are measured using Likert scales and calculated by Euclidean distance. These

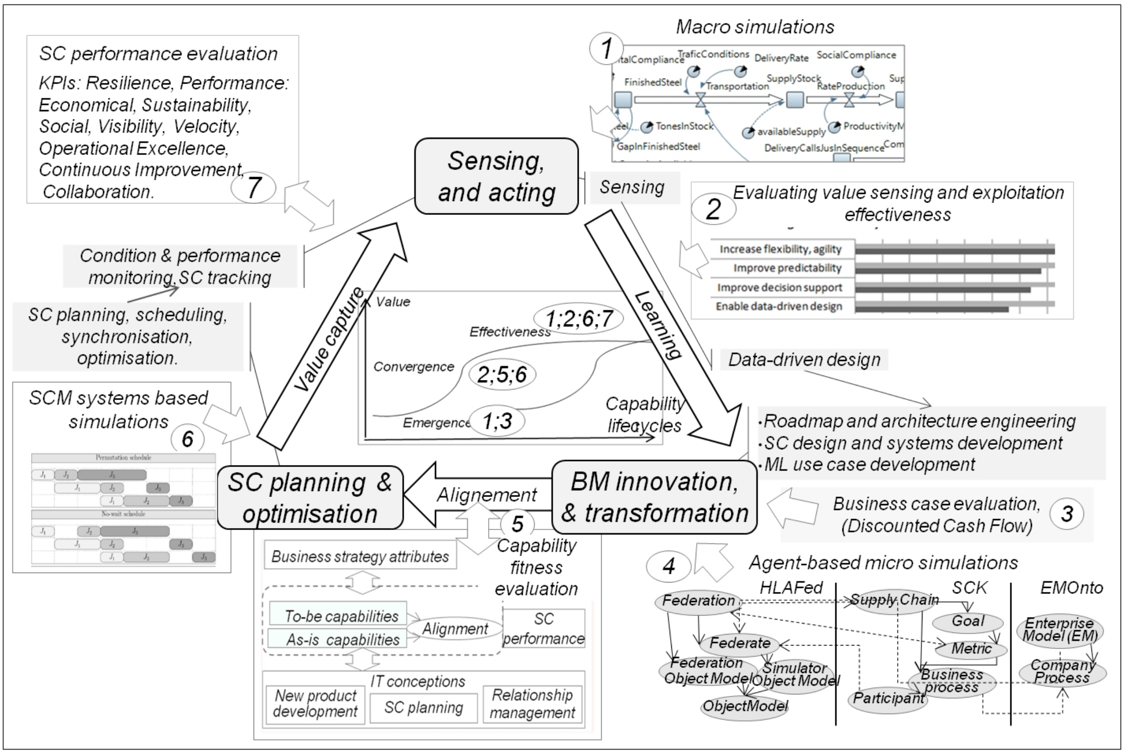


Fig. 20: Simulation and evaluation methods for ambidexterity of SC business models (Nuerk, 2024)

evaluations can develop artefacts for economic change preparation.

Continuous evaluation of value sensing sources' effectiveness and the exploited value by business model components provides insights into emergence drivers for value possibilities and transformation methods. For ambidexterity, investments in artefacts need economic proof, using methods like the Discounted Cash Flow (DCF) to demonstrate monetary effectiveness over time. Pairwise assessment of sensing and exploitation value by business model components allows a detailed evaluation of how value opportunities are identified and adopted into business value.

Value-generating relationships between sensing types and exploiting capacities have been assessed for effectiveness, providing transparency between value sources and actual exploitation capabilities. This evaluation improves innovation productivity and creates knowledge on innovation emergence and convergence during capability and product lifecycles. It also offers insights into value-enabling promoters and conditions, affirmed by participants as a high-priority, continuous lessons-learned activity. Ambidextrous objectives in SC business models focus on balancing exploration and exploitation within the supply chain, enhancing agility, resilience, and innovation while optimizing operational efficiency. Tab. 7 in the Annex outlines key ambidexterity dimensions, main challenges, and how this study proposes to address them.

5 CONCLUSION

Based on multiple case studies, this research identified key methods for reaching ambidexterity in supply chain business models, identifying vulnerabilities from increasing business dynamics and environmental uncertainties. The study proposes SE-driven metamodelling for resilience engineering in end-to-end supply chains and develops a simulation and evaluation methodology for SC business models.

Using common platforms like digital twins holistically enhances the monitoring and control of SC processes, complementing traditional SCM with a top-down SE approach for improving resilience across multi-tier supply chains. Collaborative meta-modelling across ecosystems using digital twins enables the development of cycle-business models, improves transparency of multi-tier supply chains, and enables holistic evaluation of performance and capability fitness and the effectiveness between value exploration and exploitation. Moreover, it supports modelling simulations of macro-environmental events for identifying appropriate responses to micro-level adversities and the most profitable plans that can be synchronized among SC members. Combining System Dynamics, HLA Federates and SCM application-based simulation methods drives the designing of innovative, resilient, and effective SC systems by exploring SC ecosystem contexts and the effects of macro conditions on micro levels.

SE is vital for maximizing the value of digital SC business models and ensuring resilience. Agent-based simulations help understand complex SC systems, improve transparency, and create profitable plans across SC members. The evaluation methods help to identify enablers of emergence and performance and their promoters and preventers. The methods improve collaborative resilience, align capabilities to market needs, and optimize processes through holistic evaluation. The study's methods enable organizations to better exploit supply chain value potentials by:

1. *Improving collaborative end-to-end process resilience* through increased visibility and agility enabled by metamodelling.
2. *Driving cycle business development* by metamodelling multi-tier supply chains driving collaborative product development, life cycle management, engineering change management, SC planning and optimization, and reuse.
3. *Enabling agile capability alignment* responsive to market demands and contextual needs.
4. *SC business model ambidexterity:* Optimising the emergence and convergence processes through holistic simulation and evaluation methods.

The SE methodology delivered by the research is validated to be compact, comprehensive, scalable, and adaptable. The qualitative evaluation methods for SC business model ambidexterity were underpinned by various quantitative metrics as provided in the appendix. Further research on detailed findings and patterns between qualitative and quantitative metrics from long-term studies is recommended. Such findings can enrich the SE framework leading to AI-based analytics use cases for ambidexterity engineering of SC business models.

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7 ANNEX

Tab. 4: The case study participants and their area of contribution

Partic.	Qualification	Roles of the participants	Area of contribution	Company
P1	Dr.-Ing.	Chef developer & development team lead of SAP Industry 4.0 Application	Semi-structured interviews and expert interviews. Review of the model and research theory; ML use cases for SCM. Industry 4.0 developments, and initiatives; Evaluation and validation of the overall model.	SAP SE; SAP Deutschland AG
P2	Diplom-Informatiker	Member of Industry 4.0 product development team		
P3	Dr.-Ing.	Business Enterprise Transformation Principal and Project Manager	Semi-structured interviews and expert interviews. SCM AI and ML capabilities and use cases. Industry 4.0 initiatives. Evaluation and validation of the overall model and validation of approaches.	
P4	Diplom-Informatiker	Chef developer and department manager of SAP SCM APO		
P5	Dr. rer. pol.	SCM Chief Expert Consultant for S&OP, IBP Optimization and Manufacturing Scheduling and optimization	Scheduling and Optimization and solution approaches for manufacturing and process industry. Opportunities from digitalization capabilities. Model evaluation on planning and optimization	
P6	Diplom-Wirt.–ingenieur	Chef Product Manager for SAP SCM APO, IBP; and Solution Architect	Focus group discussions about maturity levels of SCM domains and strategies and related KPIs	
P7	B.A. Business Administration & Betriebswirt (VWA)	SCM Expert for Automotive, OEM, automotive whole sales and automotive supplier; former SCM expert at an automotive supplier, and an automotive wholesaler	Value opportunities along the supply chain and across automotive ecosystems and transformation obstacles. ML use case in SC planning and replenishment. Evaluation of the overall model regarding SCM digitalization and innovation.	Company A
P8	Diplom-Wirtschafts-informatiker	IT Project Manager and SW Development Expert at Siemens AG, Area: Application Systems for R&D, PLM, & Manufacturing	The benefit of SE and effectiveness in innovation, transformation and reusability in big organizations. Requirements engineering and MBSE as an enabler of a common view	Company C
P9	Professor of Engineering Science	Chief IT Strategist; SCM process expert at a high-end product steel producer	Value contribution of digitalization capabilities to SC processes. Contributions of SE in industrial digitalization, Evaluation of capability alignment.	Company B
P10	PhD in computer science	Senior Director Product Management -Predictive ML; and Senior Director, Analytics and ML	SAP S/4HANA Predictive Machine Learning. Python API and ML library for S/4HANA; Possibilities and capabilities.	SAP SE
P11	Diplom-Ingenieur	Director of SAP Digital Supply Chain (Presentation and discussion)	Machine Learning and Automation in SAP IBP, capabilities, and use cases.	
P12	Dr.-Ing. IT	Technical Evangelist, Microsoft Germany, and SAP	Deep Learning on Azure. Capabilities of Azure and how to use and embed.	Microsoft; SAP SE
P13	Informatiker; PhD in Mathematics	CTO of IBM Global Technology Services (retired) and SAP (Presentation and discussion)	Transforming the IT service lifecycle with AI technology. A data-driven and knowledge-base approach to IT optimization.	IBM; SAP SE
P14	PhD in Informatics	Head of Competence KMI Institute Leipzig & SAP	Rapid and automated Supply and Demand matching. Semantically matching demand with supply.	KMI InfA; SAP SE
P15	PhD in Informatics	Lead Development Architect and expert for ontological alignment	Ontology alignment, semantic matching of demand and supply, and automated schema-matching	SAP SE; Signavio

Source: Nuerk (2024)

Tab. 5: Methods and metrics for expressing innovation performance

Method/metric	**Description**
R&D investment	Measure the investment in research and development activities. Including personnel, equipment, facilities, and external collaborations. Express R&D investment as a percentage of revenue or as absolute monetary value.
Patents & intellectual property assets	Count the number of patents granted to the organization of IP assets developed, including patents, trademarks, copyrights, and trade secrets. Evaluate the quality and significance of patents based on factors such as citation counts, patent family size, and licensing revenue.
New product development	Track the number of new products introduced to the market over a specific period. Assess the success of new product launches based on factors such as market share, sales growth, customer satisfaction, and profitability.
Time-to-market	Measure the time taken to develop and launch new products or innovations from concept. Express time-to-market as the average development cycle time or the percentage of projects meeting target launch dates.
Market share and penetration	Monitor changes in market share and penetration resulting from innovative products, technologies, or business models. Compare market share metrics before and after the introduction of innovations to assess their impact.
Customer adoption & satisfaction	Survey customers to assess their awareness, adoption, usage, and satisfaction with innovative products or services. Metrics are Net Promoter Score (NPS), customer retention rates, lifetime value, sentiment, and loyalty.
Revenue from New Products	Track the revenue generated from sales of new products or innovations as a percentage of total revenue. Assess the contribution of new products to overall revenue growth and profitability.
Employee engagement and creativity	Measure employee engagement in innovation activities through surveys, feedback mechanisms, and participation rates in innovation programs. Recognize and reward employees for their contributions to innovation, creativity, and problem-solving.
Partnerships & collaborations	The number of strategic partnerships, alliances, and collaborations established to drive innovation. Evaluating the impact of partnerships on access to new markets, technologies, resources, and knowledge.
Innovation Culture and Climate	Assess the organizational culture and climate for innovation through employee surveys, leadership assessments, and cultural audits. Measure factors such as risk tolerance, openness to new ideas, tolerance for failure, and support for experimentation.
Social and environmental impact	Evaluate the social and environmental impact of innovations using metrics such as carbon footprint reduction, resource efficiency, social equity, and community engagement. Express impact metrics in terms of sustainability goals, and social responsibility initiatives.
Innovation awards and recognition	Participate in industry awards programs and competitions to gain recognition for innovative products, technologies, or initiatives. Showcase awards and accolades received for innovation performance as external validation of organizational achievements.

Source: Nuerk (2024)

Tab. 6: Value contribution evaluation approaches and metrics

Approach	**KPIs for the evaluation approach**
Financial metrics	(1) Revenue Growth: Measure the increase in revenue attributed to innovative products, services, or business models. (2) Profitability: Assess the impact of innovations on profitability through metrics such as gross margin, operating margin, and net income. (3) Calculate the return on investment from innovation projects by comparing the financial benefits (e.g., revenue, cost savings) with the investment costs (e.g. R&D expenses, capital expenditures). (4) Cost Reduction: Evaluate the cost savings or efficiency gains achieved through innovations in processes, technologies, or resource utilization.
Market metrics	(1) Market Share: Monitor changes in market share resulting from successful innovations that capture new customers or displace competitors. (2) Customer Acquisition and Retention: Assess the ability of innovations to attract new customers, increase customer loyalty, and reduce customer churn rates. (3) Brand Equity: Measure the impact of innovations on brand perception, brand awareness, and brand loyalty among target customers.
Customer metrics	(1) Customer Satisfaction: Evaluate customer satisfaction levels with innovative products, services, or experiences using surveys, feedback mechanisms, and customer ratings. (2) Customer Lifetime Value. (3) Customer Loyalty: Assess the loyalty of customers who engage with offerings through metrics such as Net Promoter Score and repeat purchase rates.
Operational metrics	(1) Process Efficiency: Measure improvements in operational efficiency, productivity, and cycle times resulting from innovations in processes, workflows, or automation. (2) Resource Utilization: Evaluate the optimal use of resources, including human capital, equipment, and materials, achieved through innovative practices or technologies. (3) Quality and Reliability: Assess the impact of innovations on product quality, reliability, defect rates, and customer satisfaction with product performance.
Strategic metrics	(1) Alignment with Strategic Objectives: Evaluate the extent to which innovations align with organizational goals, priorities, and strategic initiatives. (2) Competitive Advantage: Assess the competitive advantage gained from innovations in terms of differentiation, market positioning, and barriers to entry for competitors. (3) Long-Term Sustainability: Consider the long-term sustainability and resilience of innovations in addressing emerging market trends, technological disruptions, and regulatory changes.
Social and environmental impact	(1) Social Responsibility: Evaluate the social impact of innovations in terms of job creation, community development, and societal well-being. (2) Environmental Sustainability: Assess the environmental impact of innovations on resource conservation, pollution reduction, and carbon footprint mitigation.
Qualitative assessment	(1) Stakeholder Feedback: Gather qualitative feedback from stakeholders, including customers, employees, investors, and partners, to understand their perceptions of the value created by innovations. (2) Case Studies and Success Stories: Document and share case studies, success stories, and testimonials that highlight the tangible and intangible benefits of innovations for stakeholders.

Source: Nuerk (2024)

Tab. 7: Ambidexterity dimensions and the study contributions to mastering those (Nuerk, 2024)

Dimension	Challenge to balance	Study contribution to respond to the challenge
Efficiency vs. flexibility	Balancing efficiency in operations with the necessity to adapt and flexible response to changing market demands & disruptions. This involves process optimization for cost-effectiveness while agility adjusts to new circumstances.	The study delivers a holistic simulation and evaluation framework for agile response to market and context changes. It enables the identification of adversities in time and the most suitable response. Collaborative SC resilience engineering enables high adaptiveness and efficiency. The evaluation methods and simulation methods enable the designing of effective capabilities and dynamic capabilities for fast and flexible responses to business change.
Strategic alignment	Ensuring alignment between strategies and SC models with organizational goals, enabling synergy between exploitation and exploration.	The study's evaluation method deliverables support value-oriented and focused developments of transformation roadmaps and scoping of transformation and capability alignment activities. The simulation methods enable focused design, transformation processes, and capabilities alignment, for the agile flexible, and responsive design of SCM IT infrastructure. Finally, the evaluation methods provided by the study enable the effective development of dynamic capabilities by SE-driven capability engineering and strategic capability alignment.
Adaptive capacity	The ability to quickly respond to changes in markets, customer preferences, or disruptions by adjusting SC capabilities.	
Technological exploration and exploitation	*Technological exploration:* drive innovation and adapt to changing market demands. This includes activities such as R&D and prototyping exploring emerging technologies. *Technological exploitation:* leveraging existing capabilities to optimize operations, enhance productivity, and deliver value to customers. This involves process optimization and continuous improvement initiatives to exploit the full potential of established technologies and practices.	*A holistic view design, transformation, evaluations, and simulations:* The SE model delivered by the study enables holistic engineering, evaluation, and simulations along the life cycles and respective technology curves of the SC business model, capabilities, products, and services of a company. *A holistic view on all phases of lifecycles:* The model provides an integrated view of sensing innovations, their transformation and convergence processes, and their optimization and value exploitation. *Optimized emergence processes (value exploration):* Practising the evaluation of sensing and value exploitation developed by the study provides deep insights into the emergence of value enablers and value exploitation processes by the business model components. *Optimized convergence (value exploitation):* Capability fit evaluations as demonstrated by the study enable highly effective transformation roadmaps and optimized value exploitation.
Business model innovation (BMI) vs. operational efficiency	*In Industry 4.0, BMI* involves experimenting with novel approaches such as product-as-a-service, platform-based business models, and ecosystem partnerships. *Operational efficiency* emphasizes optimizing internal processes to enhance productivity, reduce costs, and improve agility. This includes lean manufacturing, just-in-time production, and demand-driven logistics to streamline operations and increase competitiveness.	The evaluation method delivered by the study enables the identification of value potentials and conditions that foster emergence and help to create knowledge to improve innovation productivity. The digital twin-based SC model facilitates virtual testing and prototyping, reducing the time and cost associated with physical experiments and accelerating the development of new solutions. By optimizing processes and reducing downtime through predictive maintenance, digital twins contribute to significant cost savings. They help in resource optimization by providing detailed insights into asset utilization, leading to more efficient use of resources and reduced waste. DTWs provide a shared platform for collaboration among organizations. This shared visibility encourages innovation and continuous improvement.
Innovative product and service development	Explore new product & service offerings that address evolving customer needs & market trends, while exploiting existing capabilities for profit & service levels.	Collaborative product development and life cycle engineering supported by smart cycle business models were enabled by digital twin-based meta-modelling and simulations. Vertical integration for data collection from products in use will provide fast insights into product strengths and necessary improvements.
SC resilience and risk management	Managing risks associated with SC disruptions, such as natural disasters, or supplier failures, while also fostering innovation and experimentation to stay competitive and seize new opportunities.	A comprehensive proposal and concept have been delivered by the study enabling SC ecosystem partners to master the urgent topic of increased SC visibility by collaborative SC resilience processes. A robust and holistic SC meta-modelling concept including holistic evaluations and simulations has been worked out and empirically evaluated and validated by case studies.

Source: Nuerk (2024)

Tab. 8: Activities for linking quantitative KPI measures with qualitative measurements

Activity	Description
Define KPIs and Likert scale metrics	Identify the relevant KPIs to assess performance. These could include metrics such as productivity, efficiency, quality, customer satisfaction, or financial performance. Define the Likert scale metrics or criteria that will be used to assess performance qualitatively.
Establish weighting and importance	Assign importance scores to each KPI and Likert scale metric based on their relative significance to the overall performance evaluation. Determine the relative contribution of KPIs and Likert scale metrics to the overall performance score or evaluation criteria.
Collect data	Collect data for both KPIs and Likert scale metrics through several sources, for instance, performance reports, surveys, feedback reports, and direct observation. Ensure that data collection methods are consistent, and aligned with the defined KPIs and Likert scale criteria.
Normalise data	Normalize the data collected for KPIs and Likert scale metrics to ensure that they are on a consistent scale and can be compared directly. Convert KPI measurements into a standardized format, such as percentages, ratios, or indices, if necessary. Standardize Likert scale responses into numerical values (e.g., 1 to 5) to facilitate quantitative analysis and comparison.
Aggregate scores	Aggregate individual scores or measurements for each KPI and Likert scale metric across periods, projects, or organizational units. Calculate composite scores or weighted averages for KPIs and Likert scale metrics based on their respective weights and importance scores.
Integrate data	Combine quantitative KPI scores with qualitative Likert scale assessments to create a holistic performance profile.
Analyse results	Analyze the data for needed corrections and possible optimization. Benchmark KPI-based scores with Likert scale evaluations to identify correlations, discrepancies, and areas of alignment between quantitative and qualitative assessments.
Provide feedback and recommendations	Provide feedback to stakeholders based on the integrated performance evaluation results. Offer recommendations for improving performance based on insights from both KPIs and Likert scale assessments, focusing on areas of strength and opportunities for development.
Iterate and refine the evaluation Process	Iterate on the performance evaluation process based on feedback from stakeholders, changes in organizational priorities, and evolving performance objectives. Refine the weighting, criteria, and integration methods for linking KPI-based evaluations with Likert scale assessments to enhance the effectiveness and relevance of the evaluation system over time.

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