Design elements for supply network resilience – A unified reference framework for quantitative simulation modelling

Patrick Doege (patrick.doege@zhaw.ch)
ZHAW Zurich University of Applied Sciences
Institute of Sustainable Development (INE)
Switzerland

Joel Niklas Weingart (joelniklas.weingart@zhaw.ch)
ZHAW Zurich University of Applied Sciences
Institute of Sustainable Development (INE)
Switzerland

Maike Scherrer (maike.scherrer@zhaw.ch)
ZHAW Zurich University of Applied Sciences
Institute of Sustainable Development (INE)
Switzerland

Abstract
Existing research on supply network resilience is predominantly qualitative, with limited attention given to quantitative methods such as simulation and optimisation techniques. Based on an exploratory search of the literature, this paper proposes a novel framework for capturing interdependencies and dynamics among different components leading to increased supply network resilience. The framework serves as reference for building quantitative resilience models and is essential for understanding how different design elements contribute to overall network resilience. It further advances the understanding of supply network resilience and serves as comprehensive guide for researchers and practitioners when building quantitative supply network resilience models.

Keywords: Supply chain network resilience, quantitative modelling, resilience framework

Introduction
The concept of *Supply Chain Resilience* was formed in the early 2000s (Rice & Caniato, 2003; Christopher & Peck, 2004; Ponomarov & Holcomb, 2009) and is referred to as the *ability of a supply chain to withstand disruptions and quickly recover to normal operations or adapt to changing conditions* (Ribeiro & Barbosa-Povoa, 2018). Since then, supply chain resilience gained increasing attention, displayed by an almost exponentially growing number of literature contributions over the past 20 years (Ali & Gölgeci, 2019; Bier et al., 2020; Ivanov, 2021). Modern supply chains are complex networks (Li & Zobel, 2020) and research on resilience has evolved from observing individual supply chains towards the investigation of multiple interlinked supply chains (Ivanov & Dolgui,

2020), which we denote as *supply chain networks* or short *supply networks*. The importance of building *supply network resilience* was recently underlined by the Covid-19 pandemic and the Russian war against Ukraine, as well as the subsequent sanctions against Russia (Farrell & Newman, 2022; Korn & Stemmler, 2022), reshaping globalisation and supply chains (Ruta, 2022) at an unprecedented scale and pace. Over the past 20 years, supply chain resilience literature produced a plethora of definitions (see Orlando et al., 2022; Ribeiro & Barbosa-Povoa, 2018), and differentiations (i.e., versus agility see Gligor et al., 2019), identified resilience dimensions, developed frameworks and concepts, conceived ways of measuring resilience capacity, detected the ripple effect (Liberatore et al., 2012; Ivanov et al., 2014), and so forth.

From reviewing the literature, we conclude that existing research is predominantly qualitative. Quantitative research on supply network resilience (i.e., performing experiments on a virtual system by using digital twins, agent-based simulation, system dynamics, discrete-event simulation, Monte Carlo simulation, artificial intelligence, linear and mixed-integer optimisation, etc.) has received little attention to date. As literature is only opening this novel research avenue towards simulation and optimisation methods, there is no contribution mapping out a common basis (i.e., contributing factors for increased resilience of networks, a reference framework, or a common language) for quantitative supply network resilience modelling (Bier et al., 2020; Katsaliaki et al., 2022). In contrast, literature displays a growing interest in quantitative methods and a strong need for the deployment of quantitative methods to further advance supply network resilience literature (Ali & Gölgeci, 2019; Ivanov & Dolgui, 2020; Pimenta et al., 2022; Sawik, 2022). For academia to continue exploring this research avenue, a common understanding and framework for quantitative resilience modelling are essential.

The purpose of this research is to identify existing supply chain design elements that lead to increased resilience in supply networks, subsequently denoted as *design elements for supply network resilience*. We recognise that there is currently no consistent definition of what to include or exclude in the design elements for supply network resilience and that a *complete picture of mechanisms creating resilience through supply network design is yet missing*. Consequently, we conduct an exploratory literature review to identify such design elements in the literature and subsequently derive a unified and comprehensive conceptual framework linking supply chain design elements to supply network resilience, considering the ripple effect and potential trade-offs and interaction effects that exist among such resilience-building measures.

Scope of paper

We present the results of an exploratory search of the literature, where we first identify design elements for supply network resilience that are commonly found in literature. These design elements are then mapped in a theoretical model that provides a framework for classifying, managing, and operationalising the design elements. This framework serves as reference for building quantitative supply network resilience models and is essential for understanding how different design elements contribute to the overall resilience of supply networks. It further advances the understanding of supply network resilience and serves as comprehensive guide for researchers or practitioners when building quantitative supply network resilience models.

It is important to note that while the research paper at hand focuses on above-mentioned components, other aspects are not within the scope of this paper (see Figure 1).

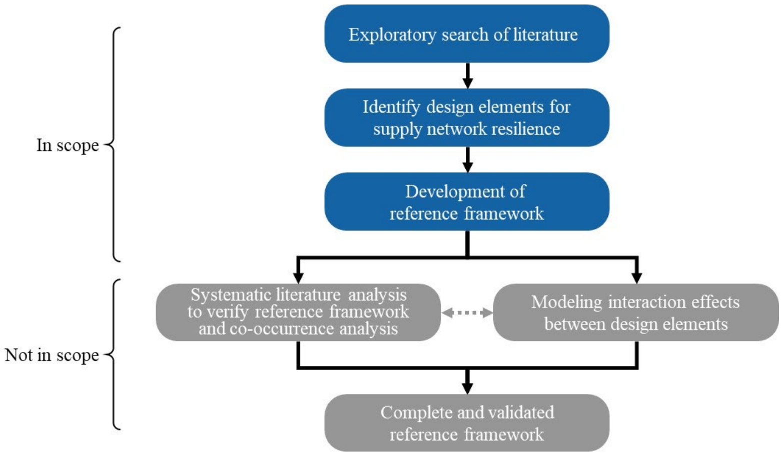

Figure 1 – Scope of the research paper at hand

Methodology

Our research approach is based on a comprehensive, exploratory scan of state-of-the-art literature using Google Scholar with search strings "supply resilience" and "resilient supply." This approach was deemed more appropriate than conducting a systematic literature review. As the design elements were unknown initially, we chose this approach to efficiently select relevant literature on the design elements from literature. For each search string, the top 100 results were screened based on their title and short description to identify papers that potentially addressed design elements of supply network resilience. Keywords such as *drivers*, *capabilities*, *dimensions*, *components*, *constructs*, *strategies*, *principles*, *abilities*, *enablers*, *elements*, *aspects*, and *antecedents* were used as indicators of relevant content. We assigned a subjective rating to each paper based on title and the short Google Scholar description, with a focus on identifying papers that were most likely to contain information on design elements of supply network resilience. The more likely a paper seemed to present content on design elements, the higher the assigned rating. 40 contributions received the highest rating and were consequently selected for further analysis to dig deeper into the literature quickly. The selected papers were analysed in full to extract information on design elements and their impact on resilience. Additionally, we reviewed promising references that were made in those contributions. The identified design elements were collected, sorted, and aggregated in a table. This approach allowed for a comprehensive review of the literature and facilitated the identification and analysis of relevant design elements and dimensions related to supply network resilience.

Dimensions that set the framework for resilience analysis

During the analysis process, a set of *dimensions* emerged from several contributions, which differ in their nature from the previously introduced *design elements*. Instead, these dimensions define the general structure for resilience analysis and may be used for the segmentation of the large space of design elements. The identified dimensions are presented in Table 1.

Table 1 – Dimensions for supply network resilience analysis

Dimension	**Description**	**Authors**
Proactive / reactive	Refers to the temporal aspect of design elements and resilience analysis. Proactive measures are taken in advance to prevent disruptions and focus on risk assessment, preparedness, and robustness. Reactive measures are implemented in response to disruptions and focus on response, recovery, and adaptation.	Adobor & McMullen, 2018; Ivanov, 2021

Short- / medium- / long-term	Relates to the time horizon of design elements and resilience analysis. Short-term resilience design elements focus on immediate responses to disruptions, while medium-term and long-term resilience analysis considers longer timeframes, including recovery, adaptation, and transformation strategies.	Azadegan & Dooley, 2021; Ivanov, 2021; Lee, 2004
Individual- / firm- / system-level scope	Defines the unit of analysis, which may range from individual entities, such as single employees or factories, to firms with multiple locations, or the entire system, such as a supply network, or region.	Adobor, 2019
Internal / external orientation (based on the scope)	Refers to the focus of resilience analysis, whether it is internal or external to the unit of analysis. Internal resilience analysis focuses on the entity's or system's own capabilities, resources, and strategies. External resilience analysis focuses on external factors, such as the environment, collaborators, or external support.	Cohen et al., 2022
Corporate / non-profit or NGO / governmental affiliation	Defines the corporate, non-profit or NGO, or governmental affiliation of the unit of analysis. Resilience analysis can vary depending on the type of organisation or entity being analysed, as their objectives, capabilities, and resources may differ.	Azadegan & Dooley, 2021

A dimension that is not fully in line with the previous dimensions but relevant for resilience analysis is the categorisation of design elements in *supply network configuration and supply network coordination measures* (Scherrer & Deflorin, 2017), as referred to by other authors as supply network structure (i.e. configuration measures) and supply network control protocols (i.e. coordination measures), as seen in, e.g., Levalle & Nof (2017). In the following, we mainly rely on the configuration and coordination dimension to categorise the design elements.

Design elements for supply network resilience

Within the literature, design elements are denoted as, e.g., *drivers*, *capabilities*, *dimensions*, *components*, *constructs*, *strategies*, *principles*, *abilities*, *enablers*, *elements*, *aspects*, or *antecedents*, among other terms. Our exploratory literature review delivered 22 design elements. Some of which were more often *directly* referred to than others, suggesting that these are more commonly understood design elements. Nearly all design elements were also referred to *indirectly* in the literature. For instance, supply chain collaboration was also referred to as risk and revenue sharing between partners or collaborative planning, both implicitly suggesting collaboration. Table 2 presents the aggregated results of our literature review, including literature from both direct and indirect references. Please note that the table contains parent dimensions, all of which maintain further sub-dimensions.

Table 2 – Design elements for supply network resilience

Design element	References[1]	Literature
Supply chain collaboration	Direct: 20 Indirect: 21	Adobor, 2019; Adobor & McMullen, 2018; Ali & Gölgeci, 2019; Barroso et al., 2010; Belhadi et al., 2022; Brusset & Teller, 2017; Carvalho & Machado, 2007; Christopher & Peck, 2004; Donadoni et al., 2019; Dubey et al., 2019; Gligor et al., 2019; Jain et al., 2017; Kochan & Nowicki, 2018; Lee, 2004; Namdar et al., 2021; Pettit, 2008; Ponis & Koronis, 2012; Ponomarov & Holcomb, 2009; Schneider-Petsinger, 2021; Scholten et al., 2014; Wicher & Lenort, 2012; Yadav & Samuel, 2021
Redundancies in the supply chain	Direct: 16 Indirect: 14	Ali & Gölgeci, 2019; Barroso et al., 2010; Belhadi et al., 2022; Christopher & Peck, 2004; Donadoni et al., 2019; Ivanov, 2021; Namdar et al., 2021; Ponis & Koronis, 2012; Ponomarov & Holcomb, 2009; Purvis et al., 2016; Schneider-Petsinger, 2021; Scholten et al., 2014; Sheffi & Rice Jr., 2005; Tang, 2006; Wicher & Lenort, 2012; Yadav & Samuel, 2021; Zavala-Alcívar et al., 2020
Preparedness / anticipation	Direct: 15 Indirect: 15	Ali & Gölgeci, 2019; Belhadi et al., 2022; Christopher & Peck, 2004; Donadoni et al., 2019; Gligor et al., 2019; Gunasekaran et al., 2015; Ivanov, 2021; Kochan & Nowicki, 2018; Levalle & Nof, 2017; Namdar et al., 2021; Pettit, 2008; Schneider-Petsinger, 2021; Scholten et al., 2014; Sheffi & Rice Jr., 2005; Yadav & Samuel, 2021; Zavala-Alcívar et al., 2020
Supply chain flexibility	Direct: 15 Indirect: 13	Ali & Gölgeci, 2019; Belhadi et al., 2022; Brusset & Teller, 2017; Christopher & Peck, 2004; Donadoni et al., 2019; Gligor et al., 2019; Gunasekaran et al., 2015; Ivanov, 2021; Jain et al., 2017; Mensah & Merkuryev, 2014; Namdar et al., 2021; Pettit, 2008; Ponomarov & Holcomb, 2009; Purvis et al., 2016; Sheffi & Rice Jr., 2005; Tang, 2006; Wicher & Lenort, 2012; Yadav & Samuel, 2021; Zavala-Alcívar et al., 2020
Risk mgmt. culture / resilience culture	Direct: 14 Indirect: 10	Adobor, 2019; Ali & Gölgeci, 2019; Barroso et al., 2010; Belhadi et al., 2022; Christopher & Peck, 2004; Donadoni et al., 2019; Ivanov, 2021; Jain et al., 2017; Kochan & Nowicki, 2018; Mensah & Merkuryev, 2014; Namdar et al., 2021; Pettit, 2008; Ponomarov & Holcomb, 2009; Purvis et al., 2016; Scholten et al., 2014; Sheffi & Rice Jr., 2005; Yadav & Samuel, 2021

[1] Multiple indirect references to a design element by same author are possible.

Visibility	Direct: 13 Indirect: 5	Ali & Gölgeci, 2019; Belhadi et al., 2022; Christopher & Peck, 2004; Donadoni et al., 2019; Dubey et al., 2019; Ivanov, 2021; Jain et al., 2017; Pettit, 2008; Ponis & Koronis, 2012; Ponomarov & Holcomb, 2009; Scholten et al., 2014; Yadav & Samuel, 2021; Zavala-Alcívar et al., 2020
Agility	Direct: 13 Indirect: 4	Ali & Gölgeci, 2019; Belhadi et al., 2022; Christopher & Peck, 2004; Gligor et al., 2019; Ivanov, 2021; Jain et al., 2017; Lee, 2004; Ponis & Koronis, 2012; Ponomarov & Holcomb, 2009; Purvis et al., 2016; Scholten et al., 2014; Wicher & Lenort, 2012; Yadav & Samuel, 2021
Information sharing	Direct: 10 Indirect: 2	Ali & Gölgeci, 2019; Barroso et al., 2010; Belhadi et al., 2022; Dubey et al., 2019; Jain et al., 2017; Namdar et al., 2021; Ponomarov & Holcomb, 2009; Wicher & Lenort, 2012; Yadav & Samuel, 2021; Zavala-Alcívar et al., 2020
Adaptability	Direct: 10 Indirect: 2	Adobor & McMullen, 2018; Ali & Gölgeci, 2019; Belhadi et al., 2022; Carvalho & Machado, 2007; Ivanov, 2021; Jain et al., 2017; Lee, 2004; Pettit, 2008; Yadav & Samuel, 2021; Zavala-Alcívar et al., 2020
Supply chain re-engineering	Direct: 8 Indirect: 12	Adobor, 2019; Ali & Gölgeci, 2019; Barroso et al., 2010; Belhadi et al., 2022; Carvalho & Machado, 2007; Christopher & Peck, 2004; Ivanov, 2021; Namdar et al., 2021; Ponomarov & Holcomb, 2009; Scholten et al., 2014; Wicher & Lenort, 2012; Yadav & Samuel, 2021
Velocity	Direct: 8 Indirect: 3	Ali & Gölgeci, 2019; Christopher & Peck, 2004; Gligor et al., 2019; Gunasekaran et al., 2015; Ponis & Koronis, 2012; Scholten et al., 2014; Wicher & Lenort, 2012; Yadav & Samuel, 2021; Zavala-Alcívar et al., 2020
Trust / security	Direct: 8 Indirect: 3	Donadoni et al., 2019; Dubey et al., 2019; Jain et al., 2017; Kochan & Nowicki, 2018; Pettit, 2008; Schneider-Petsinger, 2021; Wicher & Lenort, 2012; Yadav & Samuel, 2021; Zavala-Alcívar et al., 2020
Efficiency	Direct: 7 Indirect: 8	Christopher & Peck, 2004; Gunasekaran et al., 2015; Kochan & Nowicki, 2018; Mensah & Merkuryev, 2014; Namdar et al., 2021; Pettit, 2008; Purvis et al., 2016; Schneider-Petsinger, 2021; Scholten et al., 2014; Wicher & Lenort, 2012
Robustness	Direct: 7 Indirect: 1	Adobor & McMullen, 2018; Ali & Gölgeci, 2019; Belhadi et al., 2022; Gligor et al., 2019; Namdar et al., 2021; Purvis et al., 2016; Scholten et al., 2014
Knowledge management	Direct: 6 Indirect: 6	Ali & Gölgeci, 2019; Belhadi et al., 2022; Carvalho & Machado, 2007; Namdar et al., 2021; Ponomarov & Holcomb, 2009; Scholten et al., 2014; Sheffi & Rice Jr., 2005; Zavala-Alcívar et al., 2020
Dispersion	Direct: 5 Indirect: 6	Carvalho & Machado, 2007; Donadoni et al., 2019; Dubey et al., 2019; Jain et al., 2017; Kochan & Nowicki, 2018; Pettit, 2008; Ponis & Koronis, 2012; Schneider-Petsinger, 2021; Wicher & Lenort, 2012; Yadav & Samuel, 2021
Capacity	Direct: 4 Indirect: 2	Pettit, 2008; Ponis & Koronis, 2012; Schneider-Petsinger, 2021; Wicher & Lenort, 2012
Financial strength	Direct: 3 Indirect: 6	Belhadi et al., 2022; Kochan & Nowicki, 2018; Namdar et al., 2021; Pettit, 2008; Schneider-Petsinger, 2021; Tang, 2006; Yadav & Samuel, 2021
Management support	Direct: 3 Indirect: 2	Ali & Gölgeci, 2019; Namdar et al., 2021; Zavala-Alcívar et al., 2020
Supply chain innovation	Direct: 3 Indirect: 0	Ali & Gölgeci, 2019; Yadav & Samuel, 2021; Zavala-Alcívar et al., 2020
Recovery	Direct: 2 Indirect: 3	Namdar et al., 2021; Pettit, 2008
Market position	Direct: 2 Indirect: 1	Kochan & Nowicki, 2018; Pettit, 2008

Table 3 presents how each design element contributes to increasing supply network resilience. Additionally, we introduce the categorisation of design elements into configuration and coordination, as this helps not only to get a better overview of the 22 design elements, but this concept is also a key element of the subsequently proposed reference framework.

Table 3 – Impact of design elements on supply network resilience

Design element	**Possible impact on supply network resilience**	**Config. / Coord.**
Supply chain collaboration	Collaboration fosters exchange of information and thus creates visibility in the network. This provides a longer disruption lead time for other entities and consequently allows for better preparation and increased robustness.	Coordination
Redundancies in the supply chain	Excess capacity, inventory and sourcing alternatives allow the supply chain to handle larger fluctuations without performance loss; increases flexibility.	Configuration
Preparedness / anticipation	Preparation of e.g., contingency plans and backup capacities reduces response time as well as impact of the disruption.	Coordination
Supply chain flexibility	Increased flexibility enables the supply chain to better absorb fluctuations without impact on performance without the expense of redundancies.	Configuration / Coordination
Risk mgmt. culture / resilience culture	Organisational drive towards risk awareness, aversion and assessment impacts planning and decision making to reduce risk and/or its impact.	Coordination
Visibility	Reduces the probability of an unexpectedly occurring disruption.	Coordination

Agility	Quick decision making and fast response to disruptions minimise impact.	Coordination
Information sharing	Creates visibility along the supply chain and helps to take better decisions.	Coordination
Adaptability	Fosters quick accommodation to fluctuations helps maintain performance.	Configuration / Coordination
Supply chain re-engineering	Restructuring the supply chain to adjust to longer-term or structural trends allows to keep up with change instead of being challenged by it.	Configuration
Velocity	A high organisational pace supports agility and thus helps minimise impact.	Coordination
Trust / security	Enables supply chain collaboration and reduces expense from redundancies.	Coordination
Efficiency	Generally supports to remain operational in times of uncertainty and crisis.	Configuration
Robustness	Increased robustness allows to withstand major fluctuations unscathed.	Configuration / Coordination
Knowledge management	Generally supports preparedness, absorptive capacity during a disruption as well as in the recovery phase to rebuild operational performance.	Coordination
Dispersion	Supports to overcome locally contained disruptions more easily.	Configuration
Capacity	Generally supports in recovery phase to rebuild operational performance.	Configuration
Financial strength	Allows for a swift return to the original performance during recovery.	Configuration
Management support	Can support preparedness and helps taking right decisions during recovery.	Coordination
Supply chain innovation	Increased innovation leads to better solutions in preparation prior to disruptions as well as when reconfiguring the supply chain.	Configuration / Coordination
Recovery	General ability to better rebound from disruptions.	Coordination
Market position	Possibly leads to better pre-event preparation and increased recovery.	Coordination

Unified reference framework

We conceive design elements as intangible and overarching constructs that cannot be directly acquired or created, nor can they be measured. Supply network *flexibility*, for instance, cannot be bought or built as such, or measured. Instead, we suppose that specific actions are required to achieve flexibility eventually. Gerwin (1993) labelled these flexibility strategies and split them into four possibilities, namely adaptation, reduction, banking, and redefinition. Such actions could be, e.g., to establish multiple sourcing for a given material (reduction), to reduce changeover times in manufacturing (adaptation), or to hold idle capacity (banking) for the ability to quickly react on disruptions. Another example is *security and trust*, which, as well, cannot be bought or built directly, nor can it be measured. Instead, the use of, e.g., blockchain technology in the supply chain creates data redundancy and in turn adds to the security and trust of the supply network. In line with the above, we consequently note that the *specific actions* are tangible constructs that eventually help to achieve intangible constructs, i.e., the *design elements*, which in turn add to supply network resilience and thus add to the performance of the supply network. An illustration of this concept is presented in Figure 2.

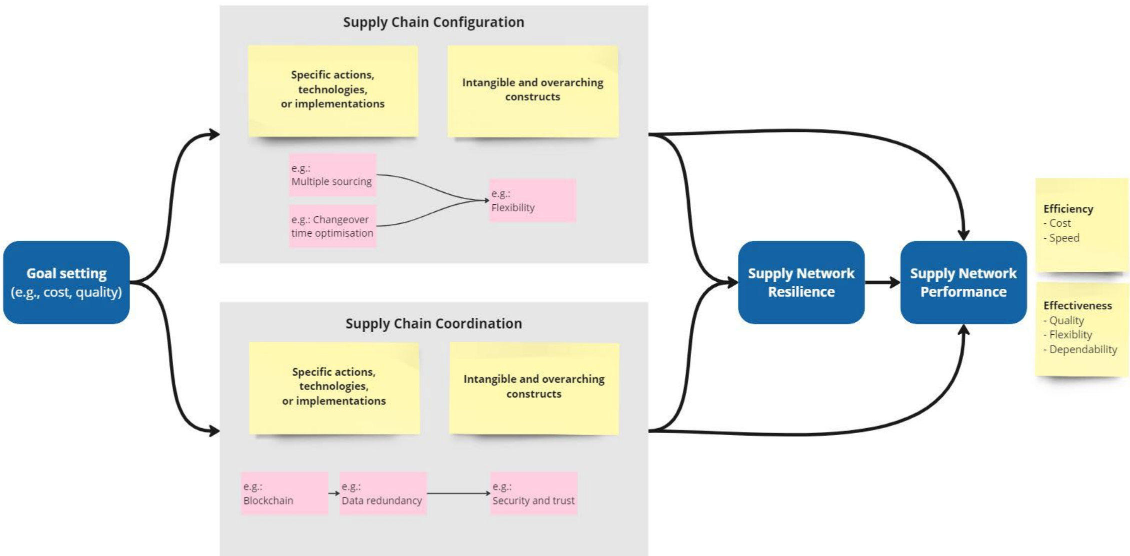

Figure 2 – Proposed conceptual framework

The conceptual framework in Figure 2 consists of multiple interconnected layers that capture the key mechanisms of building resilience. These layers are organised in a hierarchical structure, with the outer layers representing the broader context, displaying that supply network resilience can be achieved through supply network configuration and coordination. The inner layers represent the more specific elements that contribute to resilience. Tangible, specific actions (e.g., multiple sourcing) are required to achieve intangible design elements (e.g., flexibility). Arrows indicate cause-effect relationships within the framework, highlighting the dynamic nature of resilience and performance of supply networks.

It is easily conceivable that the design elements do not act exclusively on resilience, but also interact with each other. The same applies to the preceding specific actions. Figure 3 presents a causal loop diagram that integrates specific actions, design elements, and resilience, to explicitly model their interactions. It is a more formalised and more conceptual version of the above and shall provide a complete theoretical foundation for quantitative resilience research. As it encompasses and supersedes previous attempts of explaining supply network resilience, as it includes not only those factors relevant for the respective research paper but integrated all found factors in a holistic view, it is denoted as *unified reference framework*.

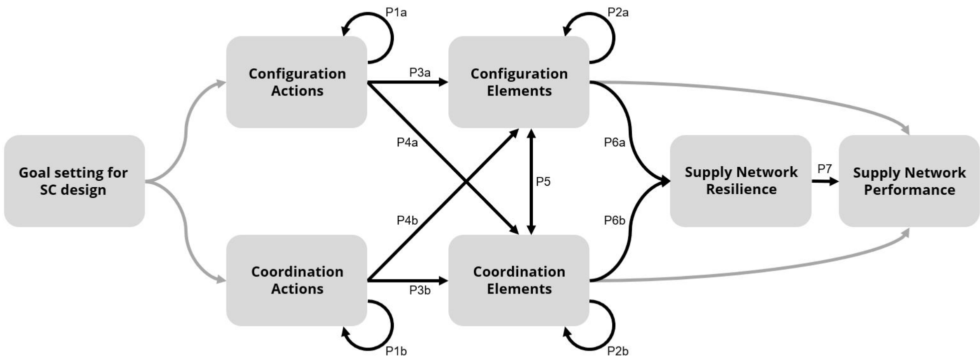

Figure 3 – Unified reference framework

The causal loop diagram in Figure 3 displays all conceivable interactions in the conceptual framework (see Figure 2). Black arrows indicate relevant interactions that act on supply network resilience, whereas grey arrows are out of scope. Consequently, we propose the following:

- P1a: *Configuration actions are interrelated with other configuration actions.*
- P1b: *Coordination actions are interrelated with other coordination actions.*
- P2a: *Configuration design elements are interrelated with other configuration design elements.*
- P2b: *Coordination design elements are interrelated with other coordination design elements.*
- P3a: *Configuration actions are required to achieve config. design elements.*
- P3b: *Coordination actions are required to achieve coord. design elements.*
- P4a: C*onfiguration actions are interrelated with coordination design elements.*
- P4b: C*oordination actions are interrelated with configuration design elements.*
- P5: C*onfiguration and coordination design elements are interrelated.*
- P6a: *Configuration design elements positively influence resilience.*
- P6b: *Coordination design elements positively influence resilience*.

- P7: *A higher degree of resilience leads to higher supply network performance.*

Conclusion

The proposed framework offers a systemic approach that facilitates the integration of *concrete actions*, *design elements*, *dimensions*, and *mechanisms of action* into a coherent framework. It serves as a foundation for developing quantitative resilience models that capture the interdependencies and dynamics among different components of resilience. This contribution shall further open the research avenue toward quantitative research in supply network resilience and increases accessibility to building, e.g., system dynamics, Bayesian network, or multicommodity network flow models. The framework consequently enables a deeper understanding of resilience dynamics. Practitioners may utilise our framework as guidance to systematically identify resilience potential in their company's supply networks and take action to achieve higher resilience levels.

The unified reference framework breaks new research grounds as it establishes a much-needed theoretical foundation for quantitative research on supply network resilience. With our contribution, we close the research gap identified by Bier et al. (2020) and Katsaliaki et al. (2022) regarding the development of a common understanding and a standardised reference framework for quantitative modelling-based resilience research. We further address the research gap noted by Li and Zobel (2020) and Bier et al. (2020) that a better understanding of the interactions of the different resilience aspects is needed. Additionally, we connect the concept of coordination and configuration measures in supply chains (Scherrer & Deflorin, 2017; Levalle & Nof, 2017), which is typically linked with performance, to the domain of resilience.

Future Research

From the insights gained during the exploratory search we define concise and meaningful keywords for a systematic literature review, which is to be performed following this work to empirically validate the proposed unified reference framework. Furthermore, it is planned to comprehensively model potential trade-offs and interaction effects that exist among design elements and thus complete the reference character of the framework (see Figure 1). Additionally, the framework shall be operationalised by building quantitative models to empirically support decision making in building resilient supply networks.

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