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Uncertainty regulation and adaptable supply chain planning

Sourav Sengupta
Trinity Business School, Trinity College Dublin, Dublin, Ireland
Patrik Jonsson
Department of Technology Management and Economics, Chalmers University of Technology, Gothenburg, Sweden
Heidi Dreyer
Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, Trondheim, Norway
Riikka Kaipia
VTT Technical Research Centre of Finland Ltd, Espoo, Finland, and
Thomas Y. Choi
Department of Supply Chain Management, Arizona State University, Tempe, Arizona, USA

Abstract

Purpose – Supply chain planning (SCP) as an important management intervention is highly relevant to operations and supply chain practice. While SCP processes have developed over time with the use of integrative and advanced analytics tools, the essential foundation and focus on restoring stability remain unchanged and limit the capacity of SCP to adapt to uncertainty. We aim to address this limitation and the way forward in research and practice of SCP through adaptable supply chain planning (ASCP).
Design/methodology/approach – Drawing on the current discourse on uncertainty regulation and SCP foundations and assumptions, a typology of SCP uncertainty and respective planning strategies are conceptualized.
Findings – To elevate SCP to account for today's volatile environment, we put forward various forms of uncertainty that organizations face with respect to their awareness and understanding of threats from uncertainty. We also consider how conditions require simultaneously using different planning strategies and navigating between the strategies to regulate the uncertainty, not only to mitigate it but also to create opportunities for progress and growth.
Originality/value – We propose a new ASCP paradigm with foundational principles, planning strategies and layers of potential research avenues.

Keywords Supply chain planning, Complex adaptive system, Uncertainty, Adaptable supply chain planning, Planning strategies

Paper type Research article

1. Introduction

For decades, supply chain planning (SCP) has aimed at matching supply with demand (e.g. Jonsson and Holmström, 2016) through forecasting the right quantity, ensuring timely delivery, and possessing the right capacity. The goal of SCP has been to establish stability and proactiveness in supply chain operations. However, as supply chains are evolving with globalization, with emerging dependencies and incidents beyond the visibility or control of any single organization, stability is largely non-existent since the system is in a constant state

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of flux under the dynamic and volatile planning environment (e.g. Christopher and Holweg, 2011; Sengupta *et al*., 2025). The COVID-19 pandemic exposed the limitations of traditional SCP, as firms with rigid systems struggled to respond, while those with more adaptive and integrated planning capabilities showed stronger performance and resilience (Swink *et al*., 2025). While traditional planning has focused on creating predictable and controlled operations, both practice and research now increasingly recognize *adaptability* as a critical capability for coping with uncertainty (e.g. Schoenherr and Swink, 2015; Roh *et al*., 2025). A growing body of literature demonstrates mechanisms to increase adaptability in supply chain management (SCM) through, for example, increased technology use or building supply chain flexibility (Jonsson and Holmström, 2016). Still, much of this work views adaptability primarily as a reactive risk-mitigating response (Ivanov, 2010; Dittfeld *et al*., 2021). What remains unexplored is the potential for planning to also serve as a proactive intervention – one that not only absorbs uncertainty but also shapes and regulates it intentionally (Griffin and Grote, 2020) or even creates new strategic possibilities by design (Pil *et al*., 2024).

Traditional planning practices that focus on optimizing responses to known and predictable uncertainty may fall short in addressing emergent and unforeseen challenges. In dynamic environments, this can undermine confidence in planning, trigger frequent capacity replanning, and reduce planning efficiency (De Kok and Inderfurth, 1997; Kaipia *et al*., 2006). Consequently, there is growing interest in making SCP more adaptable and resilient to change (Sengupta *et al*., 2025; Swink *et al*., 2025). The SCP focus needs to go beyond pure forecasting future development trajectories (Lapide, 2022; Sengupta *et al*., 2025) by addressing contextualized planning solutions (Jonsson and Holmström, 2016; Kaipia *et al*., 2017), innovative solutions to rapidly deal with emergent situations (Lapide, 2022; Xu *et al*., 2023), and new possibilities for growth and competitiveness (Pil *et al*., 2024). Adaptability can be framed as a reinterpretation of resilience in today's unpredictable, dynamic and complex social-ecological supply chain systems (Feizabadi *et al*., 2023; Wieland *et al*., 2023; Phadnis, 2024), and the role of planning can be viewed as an intervention to build adaptability. Planning for adaptability thus requires understanding the different forms of uncertainties, supporting dynamic decision-making, fostering learning, and developing strategies aimed at regulating uncertainty.

The world with highly integrated supply chains and rugged business landscapes (Choi *et al*., 2001) adds uncertainty and calls for continuous adaptations to the changes. This requires an increased focus on the consideration of SCP as an emerging system of decisions for building planned flexibility and dynamic rescheduling, so that such capabilities and resources can deal with different types of uncertainties. This discussion directs toward a new paradigm in SCP research and practice, assuring capability for evolutionary tinkering in planning and decision-making (Packard *et al*., 2017; Kauffman *et al*., 2018). In this paper, we call for the development of an adaptable supply chain planning (ASCP) approach, extending SCP to incorporate adaptability and energize new research avenues.

2. Perspectives on SCP uncertainty

2.1 SCP and uncertainty

Effective SCP utilizes accurate and timely information and rigorous decision-making to define plans for execution. Following Oliva and Watson (2011) and Jonsson and Holmström (2016), we define SCP as an implemented operations planning and control framework with a supply chain scope. It aims to coordinate and synchronize supply-facing and demand-facing activities to generate supply chain value through collaboration and optimization. SCP has evolved from its roots in inventory management, forecasting, and production scheduling into an integrated framework of planning and control processes with a supply chain scope. This framework spans multiple layers of business planning, through strategic, tactical and operational considerations to execute and control of operations and supply (see, e.g. Stadtler and Kilger, 2008; Olhager, 2013; ASCM, 2025).

The strategic-tactical-operational level alignment inherent in hierarchical SCP plays a critical role in building resilience and adaptability (Duchek, 2020; Phadnis, 2024) and managing uncertainties. This requires incorporating business strategy and financial perspectives, such as business-value optimization (e.g. Pereira *et al*., 2020; Schlegel *et al*., 2021). Furthermore, risk management practices, such as contingency planning and what-if scenario planning (e.g. Dittfeld *et al*., 2021) or the allocation of resources and development of capabilities for adjusting planning processes (Kaipia and Holmström, 2007), enable organizations to proactively identify the need for risk preparedness and build capacity flexibility into their operations and supply chains (e.g. Van Mieghem, 2003; Sengupta *et al*., 2025). Such proactive strategies support more efficient and effective control and execution under uncertain conditions.

Furthermore, the multi-level structure of SCP allows for sensing disruptions for faster and more coordinated and reactive responses (e.g. Ivanov *et al*., 2010; Dittfeld *et al*., 2021; Sengupta *et al*., 2025). Research has assessed the proactive and reactive value of sharing planning information in uncertain environments (e.g. Petersen *et al*., 2005; Jonsson and Mattsson, 2013; Kaipia *et al*., 2017; Saarinen *et al*., 2025). As such, SCP contributes to supply chain transparency and visibility (e.g. Budler *et al*., 2024). For example, the sharing of proactive demand and capacity data, with built-in alerts, warning systems, and escalation structures, can support the detection of disruptions. These capabilities also enable more coordinated and optimized responses to prioritization, rescheduling and expediting.

Moreover, SCP contributes to managing uncertainties by constituting a platform and infrastructure for collaboration. For example, sales and operations planning (S&OP) can contribute to cross-functional engagement and coordination of demand and supply (e.g. Kaipia and Holmström, 2007; Oliva and Watson, 2011; Tuomikangas and Kaipia, 2014) and inter-organizational visibility and collaboration (e.g. Jonsson and Holmström, 2016; Laari *et al*., 2023). Supply chain collaboration of inventory management has been used in concepts such as vendor managed inventory, quick response (QR), efficient consumer response and collaborative planning, forecasting, and replenishment (CPFR) (Williams and Tokar, 2008).

Even though literature to some extent has discussed the fit between SCP and the planning environment (e.g. Kaipia and Holmström, 2007; Kristensen and Jonsson, 2018), empirical studies that explore planning solutions are rare, especially when focusing on adapting SCP to uncertain environments. Kaipia (2009) and Kaipia and Holmström (2007), for example, suggest matching tactical planning efforts to the organizations' ability to execute, to avoid over-frequent plan changes and wasted planning resources. Additional examples of SCP adaptation to uncertainty include temporary QR and task force planning (Lapide, 2022), mini-S&OP structures (Wallace and Stahl, 2008; Kaipia *et al*., 2017; Dittfeld *et al*., 2021), modifying planning scope (Wu *et al*., 2025) and adapting planning parameters and dynamic modeling (Ivanov *et al*., 2010).

The literature on SCP uncertainty draws on diverse theoretical foundations, with a predominant emphasis on control and risk perspectives. The need to align planning approaches with contextual uncertainty has led scholars to consider contingency theory (e.g. Kristensen and Jonsson, 2018; Wu *et al*., 2025) and information processing theory (IPT) (e.g. Schlegel *et al*., 2021; Laari *et al*., 2023; Harju *et al*., 2025; Swink *et al*., 2025). There is literature on specific SCP processes and uncertainty, for example, S&OP (Fakhry *et al*., 2025; Jonsson *et al*., 2021). A large body of literature focuses on analytics, simulation and artificial intelligence (AI)-based modeling to enhance planning under uncertainty (e.g. Gupta and Maranas, 2003; Peidro *et al*., 2009; Ivanov *et al*., 2010; Perreira *et al*., 2020), complemented by technology-oriented studies on advanced planning and scheduling systems (e.g. Stüve *et al*., 2025; Swink *et al*., 2025), big data, AI (e.g. Xu *et al*., 2023; Jazairy *et al*., 2025), and emerging technologies (e.g. Sengupta and Dreyer, 2023; Hajian *et al*., 2025). Human- and organization-centered research examines the role of human-technology interaction, modified planning models, and decision interfaces (e.g. Jackson *et al*., 2004; Berglund and Karltun, 2007; Jazairy *et al*., 2025). Emerging work on organizational adaptability further explores coordination mechanisms (Roh *et al.*, 2025) and planning culture and decision-making (Tuomikangas and Kaipia, 2014; Stentoft *et al.*, 2021; Lapide, 2022).

2.2 Epistemic and aleatory uncertainty

What the literature on SCP informs us is the focus on uncertainty and adaptability. Dealing with uncertainties has often led to inefficiencies such as overreactions, unnecessary interventions, second-guessing, and irrational decision-making (Childerhouse and Towill, 2004). Uncertainty can be understood as the lack of certainty and predictability regarding events and conditions (Van der Vorst and Beulens, 2002). Various factors stemming from uncertainty influence the supply chain performance, where their occurrence and impact are unknown or unpredictable. A supply chain manager would have to contend with unknown frequency of events and disturbances, fluctuating demand and supply volumes and timing, varying material yield in different operations, and external events causing disturbance.

Uncertainty arises from multiple sources (Simangunsong *et al.*, 2012). Demand, supply, and operations suffer from various uncertainties. Common sources of uncertainty are market and economic volatility, epidemics, geopolitical aspects, armed conflicts and tensions, changing environmental conditions, and natural disasters. For example, there is consensus that the level of uncertainty has intensified in the aftermath of the COVID-19 pandemic (Chen *et al.*, 2024; Tiwari *et al.*, 2024).

The extent to which uncertainty and its probability distribution is knowable affects the choice of SCM strategies. This affects planning in terms of when and to what extent the future can be predicted and when and to what extent it could be intervened in an adaptive way. There may be uncertainty because some features are fundamentally unknown, but uncertainty could also exist because of the lack of available knowledge about the world. The former cannot be understood, while the latter can because events and associated uncertainty are knowable.

Packard and Clark (2020) elaborate on whether true stochasticity exists or if perceived randomness simply is ignorance of the underlying causal inputs to an outcome (i.e. knowledge that is knowable in principle). The extent of knowledgeability and immitigability of the uncertainty determines "whether and when predictive and planning strategies are preferable to nonpredictive approaches" (Packard and Clark, 2020, p. 774). When there are observational and procedural limits to prediction, but input is knowable in principle, then uncertainty is categorized as *epistemic*. Holmes and Westgren (2020) further explicate that "uncertainty is epistemic if and only if (a) it concerns ignorance about a causally deterministic process such that (b) acquiring further information about this process and mitigating the ignorance would be cost effective for the agent." Such uncertainties are like what is referred to as "knowable unknown-unknowns" in project management literature – uncertainties that could have been anticipated or foreseen (Ramasesh and Browning, 2014). Consequently, there is a pragmatic implication to what knowledge to acquire. In contrast, if we are surrounded by indeterminacy and unknowability, we face *aleatory* uncertainty (e.g. Kauffman *et al.*, 2018; Packard and Clark, 2020). Aleatory uncertainty is comparable to how uncertainties are framed as "unknowable unknown-unknowns" by Ramasesh and Browning (2014). However, unknowable unknown-unknowns are described as uncertainties that may be unforeseeable or regarded as unlikely to occur, but, like a tsunami or earthquake, their effect or nature may be understood, as opposed to what is referred to as more fundamental or "absolute uncertainty" (Loch *et al.*, 2011; Packard *et al.*, 2017). For the latter, nature or outcome is not understood, the desired state or paths are uncertain, planners are completely unaware of the events' possibilities, and the plan seems like fiction (DeMeyer *et al.*, 2002; Loch *et al.*, 2011).

2.3 The concept of uncertainty regulation

Uncertainty can undermine supply chain performance through increased costs, disruptions, factory closures, unpredictable demand, or transport delays. Yet, for organizations adept at coping with uncertainty, it can also serve as a catalyst for innovation, enhanced responsiveness, and competitive advantages, unlocking opportunities for growth in sales and market share. Uncertainties, therefore, can result in both positive and negative outcomes. The positive outcomes to firm's goals present opportunity and the negative outcomes present risks (Hubbard, 2009). In uncertainty lie opportunities, and balancing the risks and opportunities by investing in feasible solutions becomes a critical task (Ramasesh and Browning, 2014; Lu *et al*., 2024). Managers are responsible for identifying what outcomes are feasible and which actions the firm should undertake (Packard *et al*., 2017). SCP is an important managerial mechanism to respond to uncertainties as "reducing" and "coping" strategies (Gupta and Maranas, 2003; Simangunsong *et al*., 2012). This, for example, corresponds to an information processing capability in the IPT literature (Galbraith, 1973).

Reducing strategies identify and address the source of uncertainty, bridging the gap between knowable and known, reducing the need for buffers (Field *et al*., 2006; Ramasesh and Browning, 2014). Coping strategies in contrast "mitigate the negative effects of uncertainty without addressing the underlying uncertainty itself" (Field *et al*., 2006, p. 154). This would be, for example, to add buffers (i.e. inventories, resources, or time) (Hopp and Spearman, 2008). Supply chain managers may also use better algorithms to enhance information exchange through digitalization between supply chain partners (Choi *et al*., 2024), to add visibility across the chain (Budler *et al*., 2024), enhance collaboration (Laari *et al*., 2023), and to build flexibility, adaptability and responsiveness (Christopher and Holweg, 2011; Merschmann and Thonemann, 2011). For uncertainty regulation, however, it is difficult to decouple the two strategies. SCP primarily seeks for ways to cope with uncertainty, but the choices employed along the way could eventually reduce the uncertainty. The nature of coping with uncertainty and subsequently reducing uncertainty, in fact, would depend on the form of uncertainty. To cope with unknowable uncertainty, plans can focus on residual risk management aimed at improvising and control and fast response aimed at avoiding the unknown altogether by reacting to deviation rapidly (Loch *et al*., 2011). A supply chain manager may diversify supply sources by maintaining multiple parallel suppliers, selecting suppliers from different geographical areas, and maintaining parallel distribution channels to avoid dependency on a single solution (Polyviou *et al*., 2023). Scenario planning, risk management strategies, and contingency plans are also used to minimize the impact of supply chain disruptions.

These methods for managing uncertainty, however, ignore the possibilities for discovery and creation of opportunities especially for absolute (aleatory) uncertainty. That is, uncertainty has traditionally been regarded as aversive, and hence the potential opportunities that uncertainty brings have received little attention (Griffin and Grote, 2020; Pil *et al*., 2024). To cope with absolute uncertainty, which is regarded as immitigable, exploring creative possibilities for positive outcomes in SCP may offer a way forward. Approaches such as "iterate and learn approach" and "selectionist approach" of creating a variety of solutions to choose from are suited for regulating such uncertainties (Loch *et al*., 2011). We posit that SCP contributes to the discovery and creation of opportunities. We use the term, *uncertainty regulation*, to refer to the approach that combines uncertainty reduction and exploration of new possibilities and opportunities. This perspective elevates SCP to ASCP and positions SCP as an intervention that not only mitigates uncertainty but also embraces uncertainty to promote progress and growth through new opportunities.

2.4 Scoping SCP uncertainty to a typology

2.4.1 Uncertainty dimensions. To plan for uncertainty and adapt to emerging situations, it is critical to be aware of potential threats. From a planning perspective, being aware refers to an ability to perceive, anticipate, and continuously analyze the status of plans in relation to a variety of uncertainties. Epistemic uncertainty arises from a lack of knowledge caused by ignorance of events and behaviors that would otherwise be known. One example of epistemic uncertainty is the launch of a new product, where limited or non-existent historical sales data renders demand forecasting highly uncertain. Likewise, engaging with a new overseas supplier introduces uncertainty due to insufficient knowledge of the supplier's supply chain processes and network, financial stability, or capacity. Expanding into unfamiliar markets also entails significant uncertainty, particularly when organizations lack a comprehensive understanding of local regulations and policy frameworks. Much of the planning literature discusses and revolves around such uncertainty.

In contrast, there are uncertainties in planning that are indeterminable or a result from stochastic events. Such aleatory uncertainty must be addressed differently. Many of these uncertainties may be caused by environmental factors such as international conflicts and wars that disrupt transportation infrastructure or energy and commodity price volatility driven by global market dynamics. Similarly, unpredictable variations in lead time caused by shortage or climate conditions also fall into this category. In contrast, uncertainties that originate from within the supply chain itself can be caused by stochastic production yields resulting from machine wear, operator variability, inconsistencies in raw materials, supplier network instability, and demand fluctuations influenced by internal marketing actions, promotions, or pricing strategies.

In Figure 1, awareness and understanding are shown as orthogonal dimensions. The former involves knowledge, and the latter deals with causal patterns. In this regard, knowledge relies on empirical evidence, while causal patterns come from theoretical explanations. Awareness based on the result of data and analysis is not always assured. Companies must be prepared for threats that are both knowable and unknowable. But their understanding of how these manifest, whether ambiguous or not, determines how well they can plan for the knowable and unknowable uncertainty. Knowing or predicting an occurrence is not enough for planning. One also needs to understand how it might play out and what is its impact on future decisions.

2.4.2 The typology. The combinations of *awareness* of uncertainty events (i.e. knowable or unknowable uncertainty) and *understanding* of how these manifest (i.e. ambiguous or unambiguous) lead to a potential typology of SCP uncertainty (see Figure 1). It offers us four quadrants of known-known (K-K), known-unknown (K-U), unknown-known (U-K), and unknown-unknown (U-U). The simultaneous regulation of all the four combinations

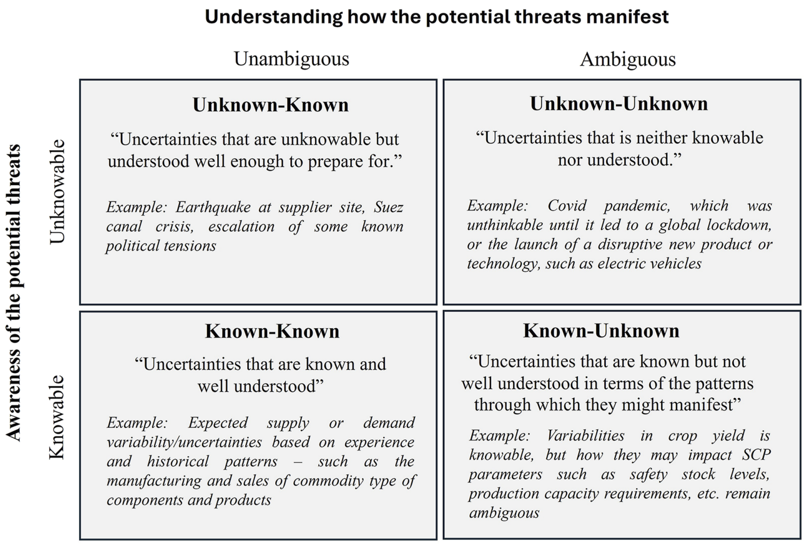

Figure 1. A typology of SCP uncertainties. Source: Authors' own work

characterizes the different forms of uncertainty that firms face using planned adaptability and brings us to ASCP.

These combinations might appear similar to the Rumsfeld Matrix [1] and other such uncertainty and risk management frameworks developed in entrepreneurship, project management, SC structural adaptability, and environmental dynamism literature (Ramasesh and Browning, 2014; Packard *et al*., 2017; Roh *et al*., 2025), highlighting known-, knowable-, and unknown-unknowns. However, they differ in purpose and perspective, focusing on how planning should account for them and their dynamics depending on the understanding of other aspects such as context, complexity, and severity/impact noted by DeMeyer *et al*. (2002), Craighead *et al*. (2007) and Lu *et al*. (2024).

K-K denotes uncertainties that are knowable and understood. This essentially illustrates the uncertainties that arise from traceable or predictable variations in supply and demand. This category would include random and systematic demand, lead time and capacity utilization, and variations in operations and material flows that are affected by campaigns or seasons. Similarly, the gradual decline in demand for a product at the end of its life cycle being replaced by a newer product (i.e. an older smartphone followed by the release of a newer model) with the extent of the decline depending on the significance of improvements in the new model's functionality.

K-U denotes uncertainties that are knowable but not well understood in terms of the patterns through which they might manifest. For example, with effort and viable investment, it is possible to obtain data about crop yield during harvest or even real-time feedback on a promotional campaign. However, it may still be unclear how such variables will influence SCP parameters such as safety stock levels, replenishment timing, or production capacity requirements.

U-K represents uncertainty, which, although unknowable, is understood well enough to prepare for. Incidents such as blockages of the Strait of Hormuz or the Suez Canal, natural disasters like earthquakes and volcanic eruptions, or cyber-attacks targeting critical data, computer systems and infrastructure, for example, are unknown. Still, their implications are widely understood and could be considered in planning.

Finally, U-U denotes uncertainty that is neither knowable nor understood. For example, the impacts of COVID-19 pandemic were unthinkable until they led to a global lockdown. No one knows the exact consequences of, say, the launch of a disruptive new product or technology, such as electric vehicles, AI and machine learning, and autonomous vehicles. No one understood how drones might be adopted during the early stages of the Ukraine-Russian war. A shift in global trade and industrial structure or sustainability policy may also denote U-U uncertainty.

Both U-K and U-U are aleatory uncertainties, presumably caused by factors beyond the focal firm's control. K-K and K-U are epistemic uncertainties that can emerge from both internal and external/environmental factors. Nonetheless, each has distinct planning objects that must be addressed at different planning levels and parameters.

3. Uncertainty regulation through SCP

Different strategies are appropriate for regulating various forms of epistemic and aleatory uncertainty. Regardless of the uncertainty type, the interplay between what is planned *ex ante* and what is executed *ex-post* is significant, as capabilities for ex-post execution must be planned *ex ante*. As we theorize, ASCP is about looking into this interplay while searching for new possibilities within uncertainty by associating with, combining, and navigating between different regulation strategies suited for the four forms of uncertainty which are expected to simultaneously exist in companies and supply chains. We elaborate on ASCP strategies in the following subsections, guided by two foundational principles:

Principle 1. ASCP regulates epistemic and aleatory uncertainty and considers discovery and creation of opportunities.

Principle 2. ASCP considers the interplay between ex ante and ex-post planning.

3.1 Supply chain planning for known-knowns – predictive strategy

In the K-K category of uncertainty, variations may be significant. Still, they are understood and can be predicted and quantified. This type of uncertainty fits within a stochastic context, where both the option and outcome sets are closed, and the relationships between each are defined by known probabilities (Packard *et al*., 2017). An example is planning seasonal food sales to respond to peak demand ahead of holidays (Ivert *et al*., 2015). The focus of SCP under these conditions is on accessing and improving utilization of available data and applying structured planning processes, appropriate and advanced methods, and competent people to predict and improve plan accuracy. This planning strategy here is aimed at coping with and subsequently reducing uncertainty by essentially building predictive capabilities through structured processes using forecasting and optimization models and tools. We refer to this as the *Predictive* strategy of uncertainty regulation.

SCP in this context targets the optimization and balancing of financial, demand and supply plans through well-established, cross-functional and hierarchical multi-level SCP frameworks and models (e.g. manufacturing resource planning) to plan on different object aggregation, frequency and time horizon (e.g. Jacobs *et al*., 2011; ASCM, 2025). This includes business planning, S&OP, master production scheduling, material requirements planning (MRP), sales and operations execution (S&OE), and monitoring, execution and control of operations. As the uncertainty is knowable and understood, *ex ante* solutions involve fitting appropriate planning methods to the specific planning environment and to coping with the uncertainty by time fence management and quantity and time buffers (Jacobs *et al*., 2011; ASCM, 2025) in order to improve plan accuracy and to optimize outcome (Jonsson and Mattsson, 2003). Examples of planning environment simplification include product complexity reduction, lead time reduction, process stabilization, pooling or postponement decisions, and information visibility. SCP practices involve structured demand and supply planning, using, for example, S&OP to assess and make tactical decisions about demand shaping, inventory positioning, and supply flexibility investments. Organizations can use optimization models and scenario planning in what-if analysis (Dittfeld *et al*., 2021). Well-established stochastic methods (i.e. safety stock calculations, order quantity models, multi-echelon inventory systems, and predictive tools like machine learning forecasting) are typically applied (Peidro *et al*., 2009).

Ex-post planning mechanisms focus on monitoring and adjusting for deviations between plans and actual demand and supply. This includes root cause analysis to improve the accuracy of input variables and corrective actions such as prioritizing, expediting and rescheduling to efficiently and effectively execute operations within the frames of *ex ante* plans. Execution is guided by structured processes like S&OE, which ensure alignment between tactical plans and operational performance.

3.2 Supply chain planning for known-unknowns – proactive strategy

In the known-unknown (K-U) situation, we know where the uncertainty is but cannot understand it in a way that allows us to model and assess it using data and models. Since we are aware of the potential consequence and threat, focus is on experiencing and learning about it, preparing for it before it may occur, and monitoring the conditions. While we may know where the uncertainty lies (i.e. specific technologies, policies, or sectors), we lack understanding to delineate the relationships with outcomes in probabilistic terms. According to Packard *et al*. (2017), this refers to a situation where the option and outcome sets are closed, but the probabilistic relationships between them remain unknown. This awareness enables a planning approach focused on proactive capabilities [2] – that is, monitoring, preparing and learning. We call this a *Proactive* strategy of uncertainty regulation.

ASCP under this strategy concentrates on engaging stakeholders for developing integrative and collaborative processes and information channels to better understand and respond to potential disruptions before they occur. The aim is not to eliminate uncertainty but to engage it actively, develop the depth in understanding the severity, context, complexity, and consequently build the capacity to respond. For example, the strategy is suited to emerging circular economy regulations, such as extended producer responsibility (European Parliament and Council, 2008), which may drive entire industries toward reuse-oriented and circular supply chain models and the need for robust reverse logistics systems, new tracking and reporting mechanisms for product take-back, and partnerships for recycling and remanufacturing. See, for example, Harju *et al*. (2025) on the impact of uncertainty on greenhouse gas emissions reporting. There are also business and supply chain specific uncertainty which we are aware of but we cannot estimate the probabilities and effects. Extreme weather events affecting agriculture are examples of known threats, but their likelihood and consequences are difficult to assess.

Ex ante solutions focus on what-if contingency and scenario planning and building processes like integrated business planning (IBP) and CPFR that leverage external collaboration. These plans predefine response directions for specific known threats, enabling organizations to develop some preparation and act swiftly when they materialize. Specific preplanned responses can, however, not be prepared because we do not understand the implication of the uncertainty and how to best respond to it. For example, planning for buffer stock and capacity, pooling or postponement material flow design, subcontractor capability and dual sourcing, are example of tactical responsiveness. Monthly and weekly S&OP and S&OE processes are important SCP processes which should be complemented with more targeted initiatives, such as temporary demand- and supply-oriented monitoring and management programs, as well as activities or task forces focused on specific areas of threat.

Ex-post, organizations must utilize responsiveness that leverages built-in flexibility to develop solutions quickly. This may include reallocation of stocks, product redesign, sourcing from spot markets and building flexibility to supply base and prioritizing or offering substitutes to customers.

3.3 Supply chain planning for unknown-knowns – reactive strategy

In the U-K uncertainty category, the triggering event is unpredictable or unknowable in advance, but its consequences are well understood and can be anticipated and planned for. According to Packard *et al*. (2017), this refers to situations where the outcome set is closed, but the option set is open. We know what the impact could be, but we do not know when, how, or through which specific pathway the disruption will occur. Consequently, there is inherent tension between the inability to predict the timing or nature of the disruption and the need to reactively allocate capacity, design contingencies, and coordinate the response in advance. The aim, consequently, is to build a reactive capability [3] to be able to respond to the threats without getting disrupted. This might involve allocating buffer capacity, building redundancy and structural flexibility, and collaborative coordinated arrangements in the supply chain. Thus, we call this the *Reactive* strategy of uncertainty regulation, which aligns with improvision strategies that involve approaches such as “residual risk management,” that enables improvisation to accommodate alternative paths to stability, as well as “control and fast response” approach for quickly avoiding the uncertainty altogether and building a breadth of knowledge.

An example is the 2000 fire at Philips´semiconductor plant in Albuquerque, New Mexico (The Economist, 2006). Although the lightning strike that caused the fire was unexpected, the risk of relying on a single-source supplier was well known. Nokia responded swiftly by reallocating supply and collaborating with alternative suppliers. By doing so, they were able to maintain production with minimal disruption. In contrast, Ericsson, lacked similar flexibility and contingency arrangements and faced severe component shortages that significantly affected its operational performance (Norrman and Jansson, 2004).

Ex ante, SCP under Reactive strategy should focus on building structural flexibility and if-then contingency [4] planning to define and prepare measures that can be activated quickly. This includes creating and maintaining multi-supplier qualification and onboarding plans, flexible supply contracts with volume shifting clauses, and conducting scenario-based planning to test response options under various disruption scenarios. Building flexible manufacturing structures that can shift production across plants or regions can adjust production in response to unforeseen shortages. Investment in real-time supply chain visibility technologies and implementing collaborative planning processes with key suppliers, customers and logistics partners strengthens early detection of capacity disruptions and enables faster alignment on remedial actions.

Ex-post, SCP must enable the rapid activation of predefined if-then contingency measures once an unexpected event occurs. This may include deploying alternative sourcing channels, reallocating production capacity across sites, and dynamically repositioning inventory to address new constraints. Organizations should be prepared to invoke flexible supply chain contracts and activate standby agreements with backup suppliers. Cross-functional supply chain teams with clear roles and escalation paths can coordinate urgent supplier negotiations, customer order prioritization, and logistics rerouting. Real-time visibility tools and information sharing platforms are essential for aligning decisions across suppliers, logistics partners, and customers. Effective Reactive strategies ensure that, even when disruption strikes without warning, organizations can manage the consequences with deliberate, coordinated actions based on known consequences.

3.4 Supply chain planning for unknown-unknowns – adaptive strategy

Under unknown-unknown (U-U) conditions, the occurrence and the consequences of disruptive events are both unforeseeable and poorly understood. The organizations do not know what might happen, when it will happen or what the impact will be. According to Packard *et al*. (2017), this refers to situations where both the option and outcome sets are open, and the relationships between them are unknown. In this situation, traditional planning tools that rely on probabilistic forecasting, historical data, or predefined contingency plans become ineffective. The planning problem is the profound uncertainty combined with the potential for high-impact disruptions such as the emergence of radically new technologies, abrupt regulatory transformations, or unprecedented global crises that can threaten organizations competitiveness and existing supply chain structures, processes, or assets. Without reliable information about both the nature or impact of such disruptions, organizations cannot operate on prediction or static contingency plans alone. As result, they face a profound planning paradox – they must plan for situations that, by definition, cannot be addressed through conventional planning methods. The corresponding SCP strategy is *Adaptive*, emphasizing building adaptive capabilities [5] and transformation of processes/resources – for example, modular and reconfigurable supply chain structures, jury-rigging capabilities (Kauffman *et al*., 2018) or regionalizing procurement (Roscoe *et al*., 2022). This planning strategy for regulating absolute uncertainty is in line with the approaches such as “iterate and learn” and the “selectionist” approach noted in the project management literature.

Consider the electrical vehicles (EV). Most of us would agree that the trend toward electrification of automobiles is clear. Still, auto manufacturers have shown inconsistent behaviors. Ford and General Motors (GM) have gone back and forth about their transition to electrification (Reuters, 2025), Toyota has maintained that electrification is still quite far off (Reuters, 2024b), and Volvo Cars retains its electrification ambition but moderates the implementation (Reuters, 2024a). The level of awareness of electrification is uncertain, and its timing and nature cannot be anticipated (Liu *et al*., 2025). Disruptions may come from sudden technological leaps in battery technology, abrupt policy or regulation changes, and unexpected shifts in consumer behavior that traditional forecasting cannot anticipate. An unanticipated geopolitical shock affecting critical raw materials could rapidly render existing production assets and supplier arrangements obsolete. The development of technology making alternative drive-line options (e.g. fuel cells and renewable fuels) more competitive also affects the EV transition uncertainty, especially for heavy vehicles.

In such contexts, the role of planning shifts from prediction and optimization to building systemic adaptability and innovation capacity. *Ex ante*, SCP should support the design of modular, reconfigurable and adaptable supply chain networks. Flexible supply agreements, platform-based partnerships, clear contingency frameworks and real-options thinking ensure that organizations maintain open paths as conditions evolve. Embedding exploratory steps within planning cycles enables organizations to update assumptions and adjust plans proactively to shift direction when needed. Engaging in open innovation ecosystems, such as shared R&D initiatives, broadens the capacity for recognizing and responding to unknown situations.

Ex-post SCP must enable rapid and coordinated responses. This includes activating real-time visibility and advanced analytical tools, such as digital twins and AI-based scenario simulators, to assess emerging uncertainties in real time. Execution mechanisms need to be equally flexible, like dynamic reallocation protocols, rapid supplier onboarding procedures, and alternative sourcing arrangements should be embedded in operational planning. Collaborative platforms bring together supply chain actors, technology providers, and research institutions to co-create solutions when traditional plans no longer suffice. The Adaptive strategy, thus, transforms uncertainty into an opportunity for resilience, innovation and renewal, when facing unpredictable and poorly understood disruptions. The third principle of ASCP is (See ASCP summary in Table 1):

Principle 3. ASCP strategies for K-K, K-U, U-K, and U-U are, respectively, to be predictive, proactive, reactive, and adaptive.

3.5 The dynamics between the four uncertainty regulation strategies

Firms simultaneously face the four forms of uncertainty. The ASCP strategies must be considered together for uncertainty regulation. Further, uncertainty arising from a given situation does not remain static, but changes depending on evolving conditions and the environment. As such, the SCP strategies employed to regulate them must align to maintain contextual fit. Naturally, organizations must adjust their strategies as uncertain conditions change and understanding of its impact and complexity changes, rather than using the proposed matrix as a static decision framework.

A transition from proactive strategy to predictive strategy (see blue arrow in Figure 2) can happen. For example, cyber-attacks are known supply chain threats, but until a few years back, their likelihood and consequence were difficult to foresee, making them a K-U uncertainty (i.e. NotPetya cyber-attack in 2017 that hit Maersk). Consequently, a *proactive* strategy could be used to regulate such uncertainty of cyber-attack disruption. As a proactive strategy strives to develop information channels (e.g. Saarinen *et al.*, 2025) and ways to improve understanding and learning about the threat (Jeong *et al.*, 2025), it will gradually reduce the associated ambiguity, thereby transforming it over time into a K-K uncertainty that possibly then could be managed using the *predictive* strategy.

Furthermore, new knowledge regarding the impact of the uncertainty in supply chains may encourage organizations to investigate the possibility of developing new opportunities and innovations. For example, the cyber-attack vulnerabilities spurred pilot initiatives to disrupt traditional operations using blockchain solutions, such as Maersk and IBM's TradeLens program (Jensen *et al.*, 2019). However, while blockchain innovations like TradeLens were introduced to foster growth and address known supply chain challenges such as inefficiencies and security risk (i.e. K-U uncertainties), the platform's ambitious design and management structure introduced unforeseen challenges, becoming a source of new U-U uncertainties such as limited stakeholder engagement and trust issues. These emergent uncertainties ultimately

Table 1. Adaptable SCP for uncertainty regulation

Planned regulation strategy	Planning challenge	Aim of the strategy	Examples of what is to be planned	
			Ex ante	Ex-post
Predictive – *for known-known*	Accessing and utilizing available data, applying structured processes, appropriate methods and competent people to predict and ensure accurate plans	Building predictive capabilities (better prepare for shocks) through structured processes use of forecasting and optimization tools	Optimize plans within the limits of known uncertainty, MRP II, S&OP/ S&OE, inventory management	Monitor and adjust based on deviations between plans and actual demand/ supply
Proactive – *for known-unknown*	Insufficient understanding to define the relationships between uncertainty outcomes in probabilistic terms	Building proactive capabilities (prevent unprecedented shocks) through information channels strengthening preparedness monitoring and continuous learning creating integrated and collaborative processes for visibility, coordination, trust building, etc.	What-if contingency planning/scenario planning, collaborative planning, IBP, monitoring systems	Use built-in flexibility to develop and implement solutions quickly through task force
Reactive *-for unknown-known*	Inability to foresee when or how a disruption will occur, despite a solid understanding of the likely effects	Building reactive capabilities (event-specific reaction to shocks) allocate capacity to be able to absorb changes build structural flexibility and coordinate collaborative arrangements	If-then contingency planning, predefine measures and structural flexibility	Activate predefined contingency measures to manage known consequences when unexpected events occur
Adaptive *-for unknown-unknown*	The occurrence and the consequences of disruptive events are unforeseeable and poorly understood	Building adaptive capabilities (adapt and transform with the shocks) develop modular and reconfigurable supply chain structures developing jury-rigging capabilities possibilities of regionalization	Plan and design of modular, reconfigurable supply networks to enable rapid adaptation	Enable rapid, coordinated responses by activating real-time visibility and advanced analytical tools, such as digital twins and AI-based scenario simulators, to assess emerging uncertainties as they unfold

undermined adoption and led to the platform's discontinuation due to business model failure (Najati, 2025). As a result, rather than proactive, the *adaptive* strategy (see orange arrow in Figure 2) is required. However, the U-U uncertainty could take a different turn in other contexts, where organizations gradually learn more about the unknowns and the evolving environment. They may try new initiatives without success and then decide to go back to the

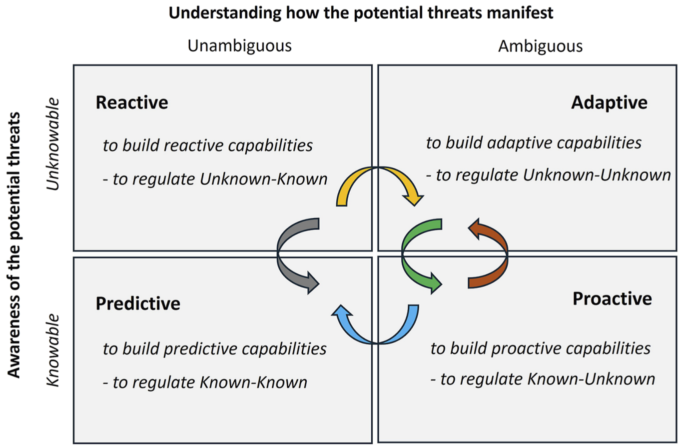

Figure 2. Dynamics in ASCP strategies. Source: Authors' own work

ways they did things when they were only faced with K-U uncertainty. For example, there was a trend among automakers like Volvo Cars to welcome the unpredictability of the launch of the disruptive electric vehicles by aiming for a total transformation for completely electric lineup (Reuters, 2024a). This represented an adaptive planning strategy. However, as market conditions evolved, Volvo Cars faced uncertain consumer demand, slower infrastructure rollout, and geopolitical complexities. The company then re-considered its approach, moderating its electrification ambitions to be less aggressive and to also focus on the hybrid lineup. This strategic adaptation is not unique to Volvo Cars; other major automakers such as GM, Ford and Honda have similarly scaled back their electrification goals, delaying model rollouts and reintegrating hybrid vehicles into their product mix. This involves some known production threats, but its impact, given the emerging fully electric vehicle category, shifting customer preferences, and climate policies, remains ambiguous, making it now suitable for the proactive planning strategy (see green arrow in Figure 2).

Similarly, U-K uncertainty is addressed through a *reactive* strategy, which focuses on increasing preparedness and structural flexibility, as well as discovering opportunities for regulating such uncertainty in due course. Like in the proactive strategy, this might in due course also bring out possibilities for creating new opportunities and value. For example, U-K uncertainty emerging from the prospect of closing the Strait of Hormuz due to escalating tensions between Iran and Israel could be regulated by building new partnerships for overland transport and pipelines. This might lead to the emergence of new opportunities but also create new U-U uncertainty from such new international collaborations and how geopolitics plays out, which subsequently would require the use of an adaptive strategy (see yellow arrow in Figure 2).

However, unlike K-U, U-K is typically expected to be a longer-term problem. Unless a new technology allows for acquiring the knowledge of previously unknowable events, or a disruption becomes extremely obvious (e.g. when sanctions are imposed due to war), the reactive strategy is maintained rather than shifts back to a predictive strategy (see grey arrow in Figure 2).

As we independently examined the various forms of uncertainty and the corresponding SCP strategies in the preceding sections and discussed how the uncertainties and strategies change over time, we argue that ASCP is best understood as a dynamic process of combining and shifting between these strategies for adaptation as uncertainty evolves (see Figure 2) in order to create and discover opportunities while also lowering uncertainties. This leads us to the fourth principle of ASCP:

Principle 4. ASCP simultaneously considers the K-K, K-U, U-K, and U-U uncertainties and dynamically combines and shifts between strategies, creating opportunities for progress and growth.

Figure 2 introduces the dominant strategy in each quadrant (predictive, proactive, reactive, and adaptive) and how these strategies could be considered in a dynamic way where a specific uncertainty could develop and move from one quadrant to another. Consequently, a company needs to map its uncertainties and combine SCP strategies for different forms of uncertainties, and also actively monitor and develop the uncertainties and adjust strategies accordingly.

4. Future research avenues to reach ASCP and closing

The emphasis on adaptability in SCP calls for research on topics that have been largely overlooked from its positioning in the field. These topics are listed in Figure 3 as layers in a research onion, which spans from high-level dimensions to basic planning challenges that must be addressed to transition from SCP to ASCP. Brief descriptions of underlying issues are shown in arrows pointing to the layers. We now visit each layer of the research onion with illustrations and examples.

4.1 Positioning SCP as a transdisciplinary field

Regulating aleatory uncertainty involves both discovering and creating new opportunities, while regulating epistemic uncertainty requires innovative ways of intervention. As such, to navigate through and explore across different planning strategies, a transdisciplinary approach becomes imperative. Take, for example, *cyber-attacks*. Understanding them may necessitate experts from computer science, behavioral science, and economics simultaneously (Anderson and Moore, 2009) alongside supply chain professionals since over 60% of all known cyber breaches come through supply chains (Rogers and Choi, 2018). Further, assessing the implications of international conflicts needs studying of geopolitics (Sheth and Uslay, 2023),

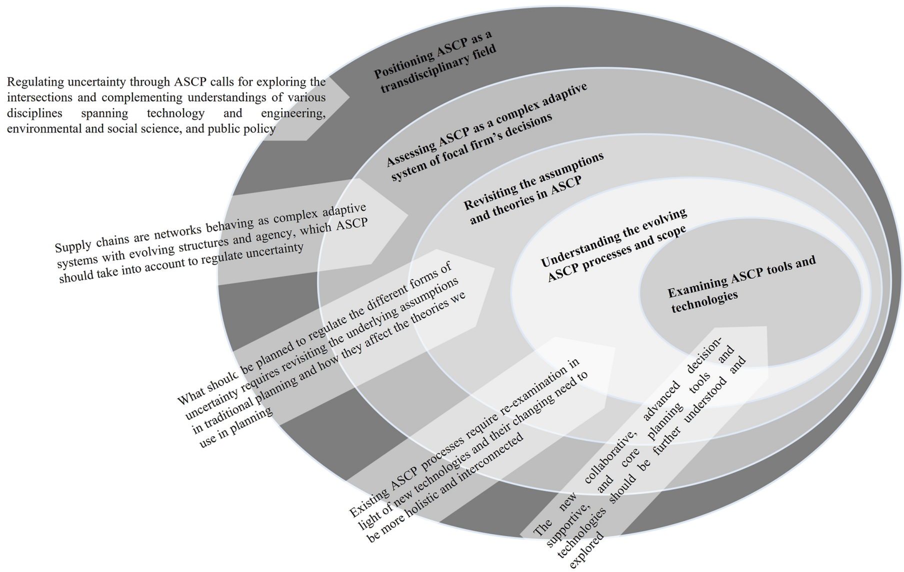

Figure 3. ASCP research onion – unpacking the layers in research and impact pathways. Source: Authors' own work

and finding flexibility options will require a deeper understanding of data science, product engineering and basic science (Nikolopoulou and Ierapetritou, 2012). ASCP to embrace new possibilities and continuously adapt to changes cannot be pursued effectively by conforming to the traditional SCP practices. Potentials can be attained at the intersections and complementing understandings of various disciplines spanning across technology, environmental and social science, and public policy. Consequently, a future research agenda should look into ASCP as a multi-disciplinary and transdisciplinary research stream and encourage researchers to collaborate with practitioners across various disciplines.

Prospect 1: How might breakthroughs and advancements in multiple disciplines (i.e. product engineering, operations, environmental science, and information systems and technology) within the context of changing geopolitics and ecological conditions benefit ASCP with uncertainty regulation?

4.2 Assessing SCP as a complex adaptive system of decisions

Recent supply chain literature suggests that uncertainty is not necessarily aversive (Griffin and Grote, 2020; Pil *et al*., 2024). As it reveals threats, it also offers possibilities for value creation and growth. We propose that the possibility theory lens regarding uncertainty is especially essential in the adaptive planning strategy (see Figure 2). Here, the basic assumption is that supply networks are complex adaptive systems (CAS) with evolving structures and agency (Choi *et al*., 2001). Planning must thus take this into account, including flexibility options such as incomplete contracts (Cummins *et al*., 2021) with suppliers that encourage evolutionary tinkering and emergence. This highlights the necessity for research into the capabilities that may be developed to promote emergence, as well as for firms to avoid becoming locked in rigid traps and instead be able to adapt to new emerging opportunities (Kauffman *et al*., 2018). As such, firms may embrace uncertainty and create solutions for growth and success. While CAS view differs from the classic control and risk-centric view of planning, it has not been much emphasized in the SCP literature and requires greater attention. To this, we have offered how the two perspectives of awareness (knowable vs. unknowable) and understanding (unambiguous vs. ambiguous) fit into the four types of uncertainty outlined and how they might be integrated for a multidimensional approach to ASCP.

Prospect 2: What should and should not be planned, at what levels, and what capabilities should be developed to facilitate evolutionary tinkering and emergence to regulate uncertainty?

4.3 Revisiting the assumptions and theories in SCP

SCP practices have usually been developed with the goal of ensuring stability and accuracy. As previously noted, assumptions in the SCP literature such as planning are aimed at ensuring or restoring stability and proactiveness. Here, uncertainty is framed as an aversive state, which may not always hold true today. Therefore, it becomes imperative to re-evaluate how we view uncertainty. We may begin with type of uncertainties that are better known and more understood. As we progress toward regulating more ambiguous and unknown uncertainties, we should investigate the underlying assumptions and patterns in our traditional planning and how these would affect the theories we use in planning. Long-standing assumptions in SCP may no longer hold, such as planners have complete visibility across the network, historical patterns provide a dependable basis for optimization, and decisions can be made sequentially within functional siloes (Sengupta *et al*., 2025). Thus, we must reflect on and challenge these assumptions and look for theoretical inconsistencies in SCP literature, considering today’s turbulent reality. This, therefore, brings forth the need to rethink how and what is planned to regulate the different forms of uncertainty to be adaptive.

Prospect 3: What assumptions and theories in traditional SCP need to be revisited and adjusted for creating new theories in ASCP to account for the opportunities emerging from expanding scope of uncertainty?

4.4 Understanding the evolving ASCP processes and scope

Traditional SCP processes, particularly tactical S&OP and operational inventory management have received considerable attention in the literature. The scope of SCP at the strategic, tactical, and operational levels has been distinct. However, as plans are now being developed for adaptability rather than stability, the distinctions between levels of planning are becoming increasingly blurred. To address the evolving need for ASCP, a more holistic and interconnected planning process must be devised. This is especially important because, with the introduction of new digital technologies, processes that were previously dependent on human collaboration and trust building are now technology dependent (e.g. Swink *et al*., 2025). Technology is also contributing to the widening of the planning scope (e.g. Jonsson and Holmström, 2016). Consequently, new technology is changing how we plan, what we plan, and the level of detail and accuracy with which planning is conducted, thereby enhancing our ability to adapt quickly to new situations (e.g. Sengupta *et al*., 2025; Swink *et al*., 2025). Consequently, the four different forms of uncertainty K-K, K-U, U-K and U-U must be re-assessed, as emergent technologies such as quantum computing, distributed leger technology, and real-time multi-tier visibility enable faster detection, richer simulation, and more adaptive responses. More than ever, research is required to evaluate existing SCP processes in light of new technology and analyze how the processes should be dynamically changed to be more efficient and more suited to the current needs and possibilities.

Prospect 4: Given that the traditionally distinct planning level are getting blurred with expanding scope of uncertainty, how can ASCP processes be dynamically changed according to the evolving needs?

4.5 Examining ASCP tools and technologies

Different functionalities offered by innovative technologies may be used as collaborative, advanced decision-supportive, and core planning tools. Understanding that is just as vital as assessing ASCP processes. We should know the micro foundations of shifting to a more technology-driven planning approach for ASCP and the potential barriers that these technologies may face in adoption. It concerns new human and organizational implications and barriers for such technology-driven planning (for example, see the discussions on the paradoxes in adopting AI in S&OP and the subsequent research directions identified by Jazairy *et al*., 2025). In addition, it is also crucial to understand how technology can help with the specific predictive, proactive, reactive and adaptive strategies, as discussed earlier, and integrating and navigating between them.

Prospect 5: What capabilities do firms need to develop in order to leverage the new technologies and their functionalities in ASCP, and what are the micro foundations of transforming to a technology-centered planning process?

4.6 In closing

Organizations face different forms of uncertainty simultaneously, and how they deal with uncertainty depends on their awareness and understanding of it. Different forms of uncertainty require different planning strategies and navigating between the strategies to mitigate it or to create opportunities for progress and growth. We propose an adaptable supply chain planning (ASCP) paradigm with foundational principles, planning strategies, and layers of potential research avenues. ASCP can be understood as a planning intervention for dynamic and emerging uncertainty. It ensures adaptability by the capability for evolutionary tinkering in planning and decision-making, while maintaining the basic elements of planning (i.e. to plan with distinct object, horizon, and frequency). Organizations must determine what they plan, for what time period, and how frequently the respective plan is updated. Foremost, we argue that planning is about managerial decision-making, which is realized when plans are generated, modified, and then executed. Furthermore, the goal of ASCP is still to provide stability, but not only by restoring but also by discovering and creating new balance among emerging constructs. We search across the various perspectives and understandings of uncertainty in project management, entrepreneurship, and operations and SCM literature in order to synthesize them in a coherent manner in relation to SCP. This enabled us to propose the typology of SCP uncertainty.

We consider the implications of SCP uncertainty for planning using four strategies and the dynamics of navigating between them for efficiency. Whereas in the K-K context the focus is on balancing specific demand with supply capacities, in the U-U context this balance must be created between adaptive and innovative capabilities and the requirements for responding to unknown event and their impacts. For example, in the U-U context, the purpose is to build capacity and capabilities for innovation and restructuring the supply chain to be prepared for unknown consequences (Kauffman *et al*., 2018). In sudden changes, or unforeseen events (e.g. as during the COVID-19 pandemic), timely planning is essential. Reactions must be fast, delays should be avoided, and stability can be created only for a short period of time. Given today's turbulent environment and continuous disruptions, organizations question the effectiveness of planning. This paper proposes a novel typology and SCP strategies that call for a shift in the scope and perspective of SCP to become ASCP, embracing uncertainty for new possibilities. Still, the scope of the discussions excludes implementation aspects, specific planning contexts, planning approaches, and an in-depth discussion of what is to be planned for. We shall look for these aspects in future studies.

Notes

1. https://www.theuncertaintyproject.org/tools/rumsfeld-matrix
2. "Capacity to take preventive measures before potential disruptions occur" (Zeng *et al*., 2025).
3. "Ability to respond to and recover from disruptions" (Zeng *et al*., 2025).
4. If-then contingency planning is different from what-if. The focus is on if some events (like an earthquake) that we understand well but whose occurrence is random and cannot be known before, occur, what would then be the consequence and suitable rules to respond and quickly recover.
5. Emergent ability to self-organize, evolve and tinker as a way to adapt to unknown-unknown uncertainty.

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Corresponding author
Patrik Jonsson can be contacted at: patrik.jonsson@chalmers.se