



Uncertainty–Dependency Interactions in Supply Chains: A Flow-Based Perspective on Planning, Control, and Resilience

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Abstract. Supply-chain performance depends critically on how flows are structured and managed under uncertainty. This paper examines how dependencies, both along and across flows, interact with different types of uncertainty to create fundamental flow challenges for planning and control. Building on a theory-driven, conceptual analysis, the study distinguishes between fluctuations (frequent, low-impact variation) and disruptions (rare, high-impact events) and analyses their implications for three established planning and control approaches: lot-based, repetitive-based, and bottleneck-based. The findings show that while these approaches effectively manage fluctuations through embedded redundancy mechanisms such as safety buffers, they are structurally limited when facing disruptions, as such events expose and amplify underlying dependencies. This leads to a convergence of flow challenges across different control logics under disruptive conditions. The paper contributes a flow-based conceptualisation that integrates dependency structures with uncertainty typologies and resilience capabilities, demonstrating that disruptions require resilience-oriented responses, combining agility and robustness, rather than traditional buffer-based control. The results provide a foundation for rethinking planning and control design in increasingly volatile supply-chain environments.

Keywords: Disruption · Fluctuations · Disturbances

1 Introduction

The performance of production and supply systems depends critically on the behaviour of the flows that connect activities across time and space. Although each activity can be described by its local characteristics, the dependencies between activities, both along and across flows, play a decisive role in determining how systems respond to variation. Under stable conditions, these dependencies are often masked by well-designed buffers and established planning routines. However, when uncertainty increases, the same dependencies can amplify disturbances in ways that challenge conventional planning and control.

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Recent supply-chain research highlights this shift. Reviews of supply-chain risk management point to a growing range of uncertainties affecting modern networks, including operational variability, environmental and geopolitical pressures, information distortions, and global disruptions such as pandemics. At the same time, research on risk dependencies shows that risks seldom operate in isolation. Instead, their effects propagate across interconnected supply-chain structures, making dependence itself a key driver of systemic behaviour during disruptions. Complementary work examining contemporary uncertainty sources reinforces that modern supply chains are exposed to increasingly volatile and interlinked conditions, making it necessary to revisit how planning and control systems operate when both fluctuations and disruptions are present [1–3].

Against this backdrop, this paper examines how dependencies and uncertainty interact to create flow challenges, and how different planning and control approaches, namely, lot-based, repetitive-based, and bottleneck-based, perform under such conditions. While these approaches were developed with certain assumptions about variability and controllability, contemporary environments expose them to a wider and more severe spectrum of uncertainties. Understanding the implications of these interactions is thus essential for designing planning and control systems that are both effective and resilient. To support this analysis, the paper also draws on the supply chain resilience perspective (e.g. [4].) as a means of characterising the capabilities needed for systems to cope with uncertainty, interpreting the strengths and limitations inherent in established planning and control logics. By integrating insights on uncertainty, dependencies and resilience, the paper provides a clearer conceptual foundation for explaining flow behaviour under fluctuating and disruptive conditions, and for understanding how planning and control methods can be aligned with the demands of modern operating environments.

Hence, the purpose of this paper is to demonstrate that fluctuations and disruptions represent fundamentally different categories of uncertainty yielding flow challenges, and that while traditional planning and control approaches are effective for managing fluctuations through redundancy, they are structurally ill-suited for disruptions, which require resilience-based responses.

The rest of this article is based on redundancy and resilience [4] to manage different types of uncertainty that, in combination with dependencies, constitute flow challenges. Flow challenges are then illustrated to clarify how dependencies and uncertainty interact in a flow. It is then clarified how different methods for planning and control manage fluctuations in different ways. However, disruptions mean that the different methods' strategies for managing the combination of dependencies and uncertainty are insufficient, and regardless of the chosen method, disruptions pose a challenge that requires resilience.

2 Method

The paper develops its contribution through a theory-building logic grounded in conceptual analysis, aimed at deepening understanding of how dependencies and uncertainty interact to shape flow behaviour. Rather than beginning from empirical findings, the study works from established principles in planning and control and synthesises them to expose the causal structure behind flow challenges. This type of reasoning is well-suited

to research in which existing constructs are well-known individually, but their combined implications remain under-articulated.

The conceptualisation builds on established principles in operations management and strategy, where production and supply systems are commonly understood in terms of process flows, capacity structures, and planning and control mechanisms e.g [5, 6]. These literatures recognise the importance of process sequencing, resource constraints, and flow coordination but typically treat them through separate constructs such as process design, capacity planning, and supply network configuration. In this paper, these principles are synthesised by distinguishing explicitly between dependencies **along flows** (process sequencing) and **across flows** (shared resources), thereby making explicit a combined dependency structure that is implicit in existing theory but not systematically articulated.

The analytical strategy unfolds in three phases. First, the paper formalises two primary building blocks, dependencies along and across flows and uncertainty in the form of fluctuations and disruptions and clarifies how they jointly influence the behaviour of production and supply networks. This involves isolating core relationships and making explicit the conditions under which familiar planning mechanisms (e.g. safety buffers, materials coordination, resource alignment) lose effectiveness. By doing so, the analysis brings visibility to mechanisms that are normally implicit in operational practice.

Second, the study positions these mechanisms within a broader capability perspective, drawing on resilience research that distinguishes between robustness, agility, leanness, and flexibility (RALF) [4] as complementary means of coping with disturbances in supply systems. This RALF lens provides a vocabulary for characterising the strategic posture embedded in different planning and control logics and allows the paper to contrast the resilience profiles implied by lot-based, repetitive-based, and bottleneck-based approaches. The purpose is not to evaluate any method empirically but to show analytically why each approach offers a distinct balance of strengths and vulnerabilities when disruptions occur.

Third, the explanatory logic is illustrated through stylised flow representations. These schematic examples, moving from isolated to interdependent processes, serve to demonstrate the mechanisms in operation without requiring empirical generalisation. The illustrations highlight how uncertainty propagates, how buffers are breached, and how dependency structures amplify or dampen the effects of disturbances. Their role is pedagogical, to clarify the conceptual arguments by placing them in observable patterns of system behaviour.

The overall aim of the methodological approach is to provide a coherent theoretical structure that unites flow-based planning concepts with resilience thinking. As a theory-building effort, the work does not attempt empirical validation. Instead, it offers a platform for subsequent empirical inquiry by articulating testable implications, clarifying boundary conditions, and revealing underlying causal pathways that have remained fragmented across prior literature.

3 Flow Challenges

The concept of flow indicates that there is a context from the beginning to the end of the flow. It may include several sub-flows that are dependent on each other to “move” the flow from start to finish. There may also be dependencies between sub-flows in different

flows because they are performed by the same resource. An event in one part of the network can therefore affect other parts of the network through these dependencies, like the ripple effect [7]. If these events also involve uncertainty in terms of when they occur and their extent, this results in a combination of dependencies and uncertainty that is very challenging to manage, referred to here as flow challenges.

3.1 Dependencies

Planning and control typically focus on materials (in terms of inventory/shortages and order book) and capacity (in terms of load). In practice, materials and capacity interact, and these two must be considered simultaneously in balancing resources. Both materials and capacity are closely linked to dependencies, and there are mainly two types of dependencies:

- Dependencies **along-flow** concern materials since the network reflects the material flow, so the arcs in a network consist of connections between different materials. Considering along-flow dependencies is therefore a matter of finite materials. The network can also represent operations performed to create different materials. A node in the network can thus be seen as a processing step, and items define a state after several processing steps.
- Dependencies **across-flow** concern capacity since operations performed in parallel flows may appear independent from a network perspective, but if they use the same resources through the operations, they are dependent. Considering across-flow dependencies is therefore linked to what is known as finite capacity.

Balancing availability with requirements is generally a difficult problem with many aspects to consider. It is theoretically possible to simultaneously consider both finite materials and finite capacity, as in the bottom right corner of Table 1, but in practice finite materials and finite capacity are usually considered in two-phase sequential planning. Phase 1 then often involves material planning based on the availability of finite materials to assess when work can begin (“earliest start” with forward scheduling) or must be completed (“latest finish” with backward scheduling). This sets the framework for material availability. This is done in principle as the top right corner, considering limited materials and infinite capacity, but planned queue times are used to include that resources still have limited availability in practice and that queues can therefore arise. Additionally, the time required by the resource, e.g., in setup and processing, is included. Phase 2 is then to consider finite capacity under the assumption that incoming materials are available at the start time and that the resulting materials must be ready at the finish time, applying in principle the bottom left corner of the table for the resources that will process the materials. Infinite materials mean that no material planning is needed; materials are assumed to be immediately available. Note that an important distinction between infinite materials and infinite capacity is that while materials can be assumed to be immediately available and delivered directly, capacity can be assumed to be immediately available, but it still takes time to perform the work, such as an operation, meaning that capacity is immediately available to perform the operation, which takes a certain amount of time. Infinite capacity should therefore be interpreted as a resource being able to perform an unlimited amount of activities simultaneously, not that an activity takes

no time to perform. The top left corner thus constitutes a special case where materials do not pose a limitation, and capacity is assumed to be available, possibly using planned queues as a safety buffer as an alternative to safety capacity.

Table 1. Effect of dependencies on flow

	Infinite Materials	Finite Materials
Infinite Capacity	Input materials are assumed to be available in inventory, and planned queues represent capacity	Material planning without regard to capacity but with planned queue times
Finite Capacity	Input materials are assumed to be available in inventory, and finite capacity planning	Simultaneous planning regarding finite input materials and finite capacity

Using capacity can create across-flow links because different flows may require the same resources. Regardless of whether capacity is finite or infinite, activities take a certain lead time, so capacity planning must account for activity timing. With infinite capacity, expected lead times can be used and across-flow dependencies disappear. With finite capacity, resources may be busy, causing queue times and requiring across-flow planning.

Finite materials create along-flow dependencies, requiring time-ordered planning through forward or backward scheduling. Infinite materials remove these dependencies because material-producing and material-consuming activities no longer need explicit coordination. When materials are assumed unlimited, they become decoupled, and no material-linked planning is needed.

3.2 Uncertainty

Flows can be relatively complex, with many different types of dependencies as described above. Another property that challenges flow management is different types of disturbances or perturbations. Disturbances are phenomena that deviate from the normal or expected and thus constitute uncertainty, causing the conditions for a flow to change in unexpected ways. There are mainly two types of disturbances [8–10]:

- Uncertainty in the form small disturbances are often localised and of high frequency, easily absorbed via buffers. These **fluctuations** involve frequent changes in some part of the flow or external influence on the flow (such as demand).
- Uncertainty in the form of large disturbances are less frequent in nature. Such **disruptions** may lead to systemic failures that interrupt operations.

Both types of disturbances affect a part of the flow, but it is in combination with dependencies that they can also affect other parts of the flow. A common tool for isolating disturbances is to introduce safety buffers in various ways. For example, safety stock can be used to avoid shortages if demand is higher than expected when deliveries are from finished goods inventory, safety lead time can be used for temporary late deliveries

from a supplier, and safety capacity can be used to avoid delays if an order is tardy and requires capacity at the same time as another order is to be executed. However, safety buffers should not be too large because they drive costs, and therefore safety buffers are not large enough to handle disruptions (e.g [11].). This is summarized in Table 2, which covers how the two types of disturbances (fluctuations and disruptions) can be managed with safety buffers to avoid the ripple effect.

Table 2. Effect of uncertainty on flow

	Fluctuations	Disruptions
Without Safety Buffers	Rippling disturbances	Rippling disturbances
With Safety Buffers	Isolated disturbances	Rippling disturbances

Safety buffers represent redundancy in the flow and thus only serve a function for fluctuations but not for disruptions. Disruptions require resilience, i.e. the ability to manage the disruption rather than isolate it, as can be done with safety buffers and fluctuations.

4 Fundamental Mechanism for Flow Challenges

Supply is often performed in some kind of network, which means many different types of dependencies along and across the flow. If these dependencies are combined with uncertainty in the form of different types of disturbances, it quickly becomes a flow challenge that is a major challenge for planning and control. To understand what this means, a simpler system, inspired by [12], can be analysed to better understand causality. The analysis is performed in four steps. First, a system without dependencies and without uncertainty is illustrated. Then, uncertainty is introduced but still without dependencies. Both these cases are based on an Atomic flow system. This is followed by including dependencies and analysed in terms of a Simple flow system as illustrated on the right in Fig. 1. The Simple flow system introduces dependencies and this is analysed both without uncertainty and with uncertainty. In both cases the flow system has inventory points for input and output. The flow system can be interpreted as a flow that delivers either products (physical goods), services or a combination of the two.

4.1 Analysis of an Atomic Flow System

The simplest form of a flow system consists of a single process that converts input into output. This type of system can therefore be called “atomic,” meaning indivisible. An atomic flow system means there are no dependencies between processes. The single process in the atomic flow system is isolated from other parts of the flow by an inventory point on the input side and an inventory point on the output side. A plan for this flow system can look like the one bottom left in Fig. 1, which corresponds to a capacity of 6 units/h, meaning each job takes 10 min.

If there is variation in the time each job takes, it could look like the outcome in top left of Fig. 1. Even there, the average is 6 units/h, and the variations can be managed by the inventory points on the input and output sides of the process, supplying sufficient material and being able to receive what is completed. A conclusion is therefore that uncertainty is relatively easy to manage if there are no strong dependencies with other processes, but rather a delimitation with buffers, in this case inventory points on the input and output sides. By analysing uncertainty using, for example, probability theory, the inventory points can be dimensioned so that there is enough safety stock to handle the uncertainty.

4.2 Analysis of a Simple Flow System

The next step is to introduce dependencies, compared to the atomic system, where Process 1 supplies Process 2. The expanded system is a simple composite system with two processes in sequence and involves entirely new conditions. Note that there is no buffer between the processes. They are dependent along the flow in the sense that Process 1 can be “blocked” if Process 2 cannot receive output from Process 1, and similarly, Process 2 can be “starved” if it does not receive jobs from Process 1. Just as with the atomic flow system a plan can be created based on the average capacity of 6 units/h. The plan for the flow through the two processes can then look like the one bottom right of Fig. 1 if there is no uncertainty. In this case, the dependency is simple with two processes in sequence, but even if there were more dependencies, a good plan can often be determined with the support of optimisation theory if there is no uncertainty.

If Process 1 also has variations in the time per job, the effect is significantly more extensive than in the case of the atomic flow system. Jobs that take longer than planned in Process 1 can result in starvation in Process 2, and if jobs take less time than expected in Process 1, it can lead to blocking from Process 2, as illustrated in the outcome on the top right in Fig. 1. Starvation occurs in this example, for instance, when the red job #1 is supposed to enter Process 2. Since it took longer than planned (uncertainty compared to the plan) in Process 1, Process 2 has to wait for job #1 to be available, representing that Process 2 is dependent on what Process 1 delivers. When Process 2 must wait for job #1, it is called starvation. Blocking occurs, for example, when Process 1 finishes job #3 faster than expected, but Process 2 is not ready to receive the job because it is busy with job #2. Then, Process 1 becomes blocked.

4.3 Conclusions from the Analysis of Flow Systems

The examples above, illustrating the role that dependencies and uncertainty can play in a flow, is summarized in Fig. 1. The horizontal axis represents the degree of dependency, ranging from low (left) to high (right). Similarly, the vertical axis is based on uncertainty, with a scale from low to high. This means that the bottom-left corner represents relatively easy decision making, indicated by the green colour, without uncertainty and without dependencies. The top-left corner represents with uncertainty but without dependencies, while the bottom-right corner represents with dependencies but without uncertainty. Finally, the top-right corner represents the combination with uncertainty and

with dependencies. This corner is marked in red, indicating difficult decision making related to flow management.

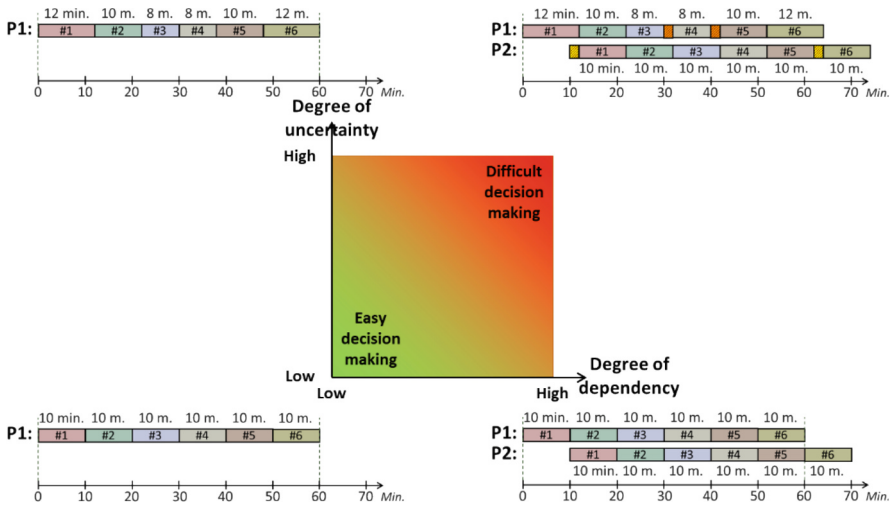


Fig. 1. Summary of the example of flow challenges as a combination of degree of dependency and degree of uncertainty

This illustrates one of the most important reasons why problems in flows are a consequence of a combination of uncertainty and dependencies between different steps in the flow. Key challenges in flow management can therefore be seen a result of the combination of dependencies and uncertainty. Dependencies can essentially be of two types as illustrated in Sect. 3.1:

- Along-flow dependencies between activities simply mean that activities are performed in a specific sequence. To enable their separation over time, they can be decoupled using buffers.
- Across-flow dependencies mean that different flows can share the same resource. In this case, flows can be decoupled through flow orientation, which means that different flows do not need to share resources, but to some extent they can also be decoupled through safety buffers if total requirements is less than total availability.

Stochastic variations are typically referred to as uncertainty, and they can have two different origins as illustrated in Sect. 3.2:

- Uncertainty in demand means that the drivers of the flow include stochastic variations, such as uncertain demand.
- Uncertainty in supply is instead linked to the unpredictability of the flow, which can, for example, be due to uncertain lead times.

5 Redundancy and Resilience

Managing uncertainty in flows has a long history rooted in different ways of using safety buffers. This has involved creating flows capable of withstanding disturbances. The focus has been on fluctuations, where safety buffers in the flow have been used to create redundancy. Typical examples are safety stock, safety lead time, and safety capacity (see, e.g. [13].), used to create resistance to fluctuations in demand and supply related to redundancy in line with [4]. Major disturbances, or disruptions, have been particularly noted in connection with dynamic effects such as the bullwhip effect in supply chains (see, e.g., [14]). Disruptions are characterized by the fact that they cannot be isolated in a single part of the supply network but affect the entire flow. In this case, redundancy is not enough; resilience is required, the ability to adapt and recover to return to a functioning state. The properties of redundancy and resilience (see, e.g., [4]) can be summarized as:

- Redundancy is having resistance to fluctuations to minimize the impact on the flow.
- Resilience is having the ability to adapt to disruptions so that the flow can recover.

6 Managing Fluctuations–Redundancy

Uncertainty in the form of fluctuations refers to disturbances of a more frequent nature with less impact on the flow. Since disturbances are frequent, it is important to build redundancy into planning and control so that disturbances can be mitigated, managed and countered, in a good way on a regular basis. A fluctuation can be a minor deviation from what is expected, such as a forecast deviation in demand or a delay in delivery. To avoid impacting the flow, safety buffers are needed, integrated into the flow so that the ripple effect of disturbances is avoided.

6.1 Flow Challenges and Redundancy

Based on the idea that planning and control aim to balance the flow in terms of materials and capacity; two main types of safety buffers can be identified: safety stock and safety capacity. Safety stock in the flow reduces along-flow dependencies by dividing the flow into different segments that affect each other to a lesser extent. Safety lead time serves a similar function as safety stock in this context. A stoppage in one segment does not need to significantly impact the subsequent segment if there is safety stock available to supply the next step during the stoppage. Safety capacity can play a similar role in that a resource would have more time slots available in case there is an upstream delay. In a corresponding fashion safety capacity can be used to disconnect different flows in terms of across-flow dependencies since capacity will then be available when needed. This means that introducing safety buffers in a flow can be used to reduce dependencies both along and across flows, as indicated by the arrow at the top of Fig. 2.

Safety buffers can, however, not only be used to separate two segments of a flow to reduce dependency between two flow segments but also be used to create preconditions for strong dependencies. Safety buffers can be used to isolate a segment from other segments and thus creating conditions where the impact of uncertainty is reduced

thus enabling dependencies inside the segment to be manageable. For example, on a larger scale safety buffers can be applied on finished goods inventory and raw materials inventory to isolate the internal flow from external uncertainty. In case needed capacity buffers can be used to reduce across dependencies in shared resources and the result would be a system with high level of dependencies but low level of uncertainty and this is the intended impact of safety buffers illustrated by the arrow on the right in Fig. 2.

6.2 Three Frameworks and Redundancy Planning and Control

The goal is to find a good match between the planning and control method and how flow challenges should be managed. Figure 1 summarized experiences of how dependencies and uncertainty affect flows. Figure 2 builds on this with the same starting point, where the degree of dependencies is represented by the x-axis and the degree of uncertainty is represented by the y-axis. The combination of these is represented by the colour on the surface, where green represents easier combinations and red represents more difficult combinations. Cases at the bottom left are easy to manage. Even cases with either a high degree of uncertainty or a high degree of dependencies are manageable with known methods. But, when there is a combination of both a high degree of dependencies and a high degree of uncertainty flow management is difficult.

Three approaches to flow planning and control have a clear strategy for managing flow challenges, which in Fig. 2 can be illustrated as moving away from the top-right corner illustrated by the wide arrows:

- *Lot-based Planning and Control (LbPC, e.g., MRP II – Manufacturing Resource Planning)*: This approach is based on reducing dependencies by using safety buffers and queue times to absorb uncertainty and thereby reduce the consequence of dependencies. The uncertainty itself is not affected; instead, the impact is reduced by isolating the effect with safety buffers between different parts of the flow, resulting in a shift to the left in Fig. 2.
- *Repetitive-based Planning and Control (RbPC, e.g., based on takt time as in e.g. lean)*: Minimizing uncertainty is important as a first step but then the focus can shift to reduce the impact of uncertainty as much as possible. Exogenous uncertainty is difficult to influence and therefore often mitigated through safety buffers, but endogenous uncertainty can be reduced through continuous improvement and striving for repetitiveness. By isolating the uncertainty in this way, dependencies can remain because the ripple effect of uncertainty is dramatically reduced as uncertainty decreases, resulting in a downward shift in Fig. 2.
- *Bottleneck-based Planning and Control (BbPC, e.g., DBR – Drum-Buffer-Rope)*: If a flow has a clear bottleneck, the critical point in the flow is known and can serve as the starting point. The impact of uncertainty on non-bottlenecks is not critical for the flow since they have a capacity buffer. The important thing is to minimize the impact of uncertainty on the bottleneck and the delivery itself. In this way, time-buffers are positioned to achieve this effect, which reduces uncertainty where it is critical and focuses on dependencies in critical parts of the flow, resulting in a combined downward and leftward shift in Fig. 2.

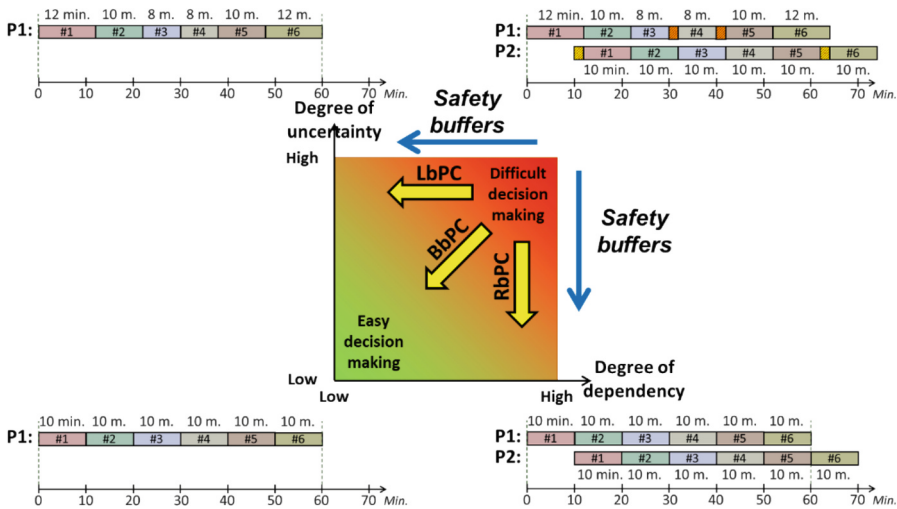


Fig. 2. Managing fluctuations with different planning and control methods involving safety buffers to reduce dependencies and uncertainty

Dependencies in combination with uncertainty make flows difficult to control, but by predicting uncertainty and absorbing uncertainty in parts of the flow, control is facilitated. To then plan and control the flow effectively, central properties of the flow can be in focus, and an appropriate planning and control method can be applied

7 Managing Disruptions–Resilience

Unlike fluctuations, disruptions involve major disturbances in the flow, and with disruptions, the strategy of reducing the effect of disturbances by positioning safety buffers to achieve redundancy is insufficient. Disruptions mean that safety buffers are not enough to mitigate the disturbances; dependencies along the flow become exposed and must be managed differently. This also includes that safety capacity (in terms of own capacity or supplier capacity) cannot absorb the disruptions and through the ripple effect they impact other parts of the flow. In both cases, this means coupling through depletion of safety buffers, linking flows together, thus creating a combination of dependencies and uncertainty where other means than redundancy must be applied.

7.1 Flow Challenges and Resilience

This means that the strategies with safety buffers (redundancy) are insufficient on their own. As illustrated in Fig. 3, safety buffers cannot mitigate the disruption but rather, the flow becomes exposed, requiring resilience to manage the disruption. The consequence is that regardless of the approach used previously, a disruption forces the system to confront the “red corner” of Fig. 1.

7.2 Three Frameworks and Resilient Planning and Control

As described earlier, different types of safety buffers are applied in the three planning and control methods illustrated in Fig. 2. The difference now is that, depending on the starting point of the various planning and control methods, disruptions cause a shift toward the top-right corner as illustrated in Fig. 3. The starting point is how different types of safety buffers have been used to manage fluctuations and address the challenge posed by the combination of dependencies and uncertainty.

- *Lot-based Planning and Control (LbPC, e.g., MRP/II)*: As previously described, this approach relies on reducing dependencies by using safety buffers and queue times to mitigate uncertainty. During disruptions, these safety buffers are insufficient, meaning disturbances cannot be isolated in different parts of the flow. Instead, because the safety buffer is inadequate to handle the disruption, the flow is exposed to the combination of uncertainty and dependencies, resulting in a shift to the right in Fig. 3.
- *Repetitive-based Planning and Control (RbPC, e.g., based on takt time)*: By minimizing fluctuations, dependencies can be managed by creating a repetitive flow. The safety buffer exists primarily to handle exogenous uncertainty. However, this also makes the system vulnerable to larger disruptions, as they can quickly affect large parts of the flow due to dependencies, causing an upward shift in Fig. 3.
- *Bottleneck-based Planning and Control (BbPC, e.g., DBR)*: Here, the focus is on flows with a clear bottleneck, which constitutes the critical point in the flow. The flow is constrained by the bottleneck, which is protected by safety buffers (in DBR, time buffers are used). These buffers reduce the bottleneck's dependence on non-bottlenecks. Non-bottlenecks, by definition, have a capacity buffer, and material buffers are in place to protect the bottleneck. This reduces dependencies and the impact of uncertainty, but if the safety buffers are insufficient to handle disruptions, a situation arises with both dependencies and uncertainty in combination, leading to an upward and rightward shift in Fig. 3.

In summary, regardless of which of these three approaches that is used for planning and control, disruptions present a similar challenge involving a combination of dependencies and uncertainty. This means that no matter which one of these three methods is used, resilience must be developed to handle this combination and redundancy on its own is not sufficient. In case of disruptions, additional means such as agility and/or robustness must be included to provide resilience [4].

8 Conclusions

This paper set out to demonstrate that fluctuations and disruptions represent fundamentally different categories of uncertainty that generate distinct flow challenges, and that while traditional planning and control approaches effectively manage fluctuations through redundancy, they are structurally ill-suited for disruptions, which require resilience-based responses.

The analysis has shown that the behaviour of supply-chain flows is fundamentally shaped by the interaction between dependency structures (along-flow and across-flow)

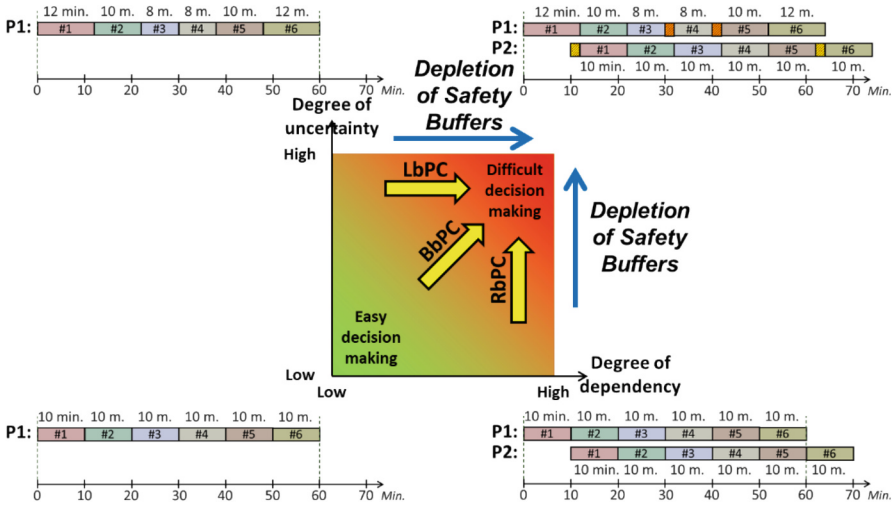


Fig. 3. The consequences of disruptions for different planning and control methods where depletion of safety buffers cause safety buffers to lose their effectiveness in reducing dependencies and uncertainty

and uncertainty. Under conditions of fluctuations, established planning and control methods, namely, lot-based, repetitive-based, and bottleneck-based, are able to maintain performance by embedding redundancy in the form of safety stock, safety lead time, safety capacity, and time buffers. These mechanisms either decouple dependencies or dampen variability, enabling stable flow execution.

However, the paper demonstrates that disruptions fundamentally alter this logic. When disruptions occur, safety buffers are depleted or rendered ineffective, thereby exposing the underlying dependency structure of the flow. This creates a systemic condition in which uncertainty and dependencies jointly propagate disturbances across the network, regardless of the original planning and control logic. As a result, previously distinct approaches converge in terms of their vulnerability, all facing the same “high-dependency/high-uncertainty” challenge.

The novel contribution of this work lies in its integrated, flow-based conceptualisation that brings together dependency structures (along and across flows), differentiated uncertainty types (fluctuations versus disruptions), and resilience capabilities (beyond redundancy), into a unified explanatory framework for flow behaviour. In particular, the paper clarifies why redundancy is sufficient for managing fluctuations but insufficient for disruptions, and why resilience, through agility and robustness, becomes the necessary response when disruptions occur. This provides a deeper theoretical explanation for observed limitations of traditional planning and control systems in volatile environments.

From a practical perspective, the findings imply that organisations should not view resilience as an extension of existing buffer strategies, but rather as a complementary design principle that becomes critical when disruptions exceed the buffering capacity of the system.

Future research should focus on laboratory testing (e.g. via optimisation and simulation) and empirically validating the proposed framework across different supply-chain contexts, particularly examining how dependency structures influence performance under varying degrees of uncertainty. Further work is needed to identify and quantify the thresholds at which fluctuations escalate into disruptions, as well as to operationalise resilience capabilities such as agility and robustness into measurable planning and control mechanisms. In addition, integrating the framework into decision-support tools and extending the analysis to multi-echelon and network-level systems would enhance its practical applicability and deepen understanding of disruption propagation in increasingly complex supply chains.

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