THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

# **Balancing Demand and Supply in Complex Manufacturing Operations**: Tactical-Level Planning Processes

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CHALMERS UNIVERSITY OF TECHNOLOGY

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## Abstract

By balancing medium-term demand and supply, tactical planning enables manufacturing firms to realize strategic, long-term business objectives. However, such balancing in engineer-to-order (ETO) and configured-to-order (CTO) operations, due to the constant pressure of substantial complexity (e.g., volatility, uncertainty, and ambiguity), induces frequent swings between over- and undercapacity and thus considerable financial losses. Manufacturers respond to such complexity by using planning processes that address the business's needs and risks at various medium-term horizons, ranging from 3 months to 3 years. Because the importance of decision-making increases exponentially as the horizon shrinks, understanding the interaction between complexity and demand-supply balancing requires extending findings reported in the literature on operations and supply chain planning and control. Therefore, this thesis addresses complexity's impact on planning medium-term demand-supply balancing on three horizons: the strategic–tactical interface, the tactical level, and the tactical–operational interface.

To explore complexity's impact on demand–supply balancing in planning processes, the thesis draws on five studies, the first two of which addressed customer order fulfillment in ETO operations. Whereas Study I, an in-depth single-case study, examined relevant tactical-level decisions, planning activities, and their interface with the complexity affecting demand–supply balancing at the strategic–tactical interface, Study II, an in-depth multiple-case study, revealed the cross-functional mechanisms of integration affecting those decisions and activities and their impact on complexity. Next, Study III, also an in-depth multiple-case study, investigated areas of uncertainty, information-processing needs (IPNs), and information-processing mechanisms (IPMs) within sales and operations planning in ETO operations. By contrast, Studies IV and V addressed material delivery schedules (MDSs) in CTO operations; whereas Study IV, another in-depth multiple-case study, identified complexity interactions causing MDS instability at the tactical–operational interface, Study V, a case study, quantitatively explained how several factors affect MDS instability.

Compiling six papers based on those five studies, the thesis contributes to theory and practice by extending knowledge about relationships between complexity and demand–supply balancing within a medium-term horizon. Its theoretical contributions, in building upon and supporting the limited knowledge on tactical planning in complex manufacturing operations, consist of a detailed tactical-level planning framework, identifying IPNs generated by uncertainty, pinpointing causal and moderating factors of MDS instability, and balancing complexity-reducing and complexity-absorbing strategies, cross-functional integrative mechanisms, IPMs, and dimensions of planning process quality. Meanwhile, its practical contributions consist of concise yet holistic descriptions of relationships between complexity in context and in demand–supply balancing. Manufacturers can readily capitalize on those descriptions to develop and implement context-appropriate tactical-level planning processes that enable efficient, informed, and effective decision-making.

**Keywords:** tactical planning, complexity, engineer-to-order, configure-to-order, sales and operations planning, order fulfillment, material delivery scheduling, organizational information processing

# List of appended papers

This thesis is based on research reported in six research papers. Each research paper is included in full after the cover paper.

| Paper | Author(s) | Title and Journal | Responsibility of the thesis author |
|---|---|---|---|
| I | Shurrab, H., Jonsson, P. and Johansson M. | "A tactical demand–supply planning framework to manage complexity in engineer-to-order environments: Insights from an in-depth case study," *Production Planning & Control* | Main author: Primary responsibility for planning the related study, collecting and analyzing data, and writing the paper |
| II | Shurrab, H., Jonsson, P. and Johansson, M. | "Managing complexity through integrative tactical planning in engineer-to-order environments: Insights from four case studies," *Production Planning & Control* | Main author: Primary responsibility for planning the related study, collecting and analyzing data, and writing the paper |
| III | Shurrab, H. and Jonsson, P. | "Managing information processing needs in engineer-to-order organizations: A prerequisite for demand–supply balancing," *submitted to a scientific journal* | Main author: Primary responsibility for planning the related study, collecting and analyzing data, and writing the paper |
| IV | Shurrab, H. and Jonsson, P. | "Information processing mechanisms of tactical planning to address demand–supply balancing uncertainty in engineer-to-order organizations," *submitted to a scientific journal* | Main author: Primary responsibility for planning the related study, collecting and analyzing data, and writing the paper |
| V | Shurrab, H. and Jonsson, P. | "Untangling the complexity generating material delivery 'schedule instability': Insights from automotive OEMs," *submitted to a scientific journal* | Main author: Primary responsibility for collecting and analyzing data and writing the paper, while all authors jointly planned the related study |
| VI | Jonsson, P., Shurrab, H., Öhlin, J., Bystedt, J., Sheikh, M. A., and Verendel, V. | "Explaining causes to delivery schedule inaccuracies in supply chains," *submitted to a scientific journal* | Second author: Mutual responsibility with all authors in conceptualizing the problem, analyzing the data, and writing the paper |

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Hafez Shurrab

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# 1. Introduction

This thesis addresses tactical demand–supply balancing in complex manufacturing operations by focusing on the strategic–tactical interface, the tactical level, and the tactical–operational interface. The following sections in this chapter introduce the background of the research and describe the problem of demand–supply balancing for tactical-level planning activities in complex manufacturing operations. The remaining sections of the chapter present the purpose of the thesis and describe the three guiding research questions (RQs), the scope of the research, and the outline of the thesis's content.

## 1.1. Background

Bringing customer demand and supply capacity into balance is an ultimate business objective that can afford a sustainable competitive advantage (Stank et al., 2012). Demand–supply balancing is also a planning objective for capturing target customer demand and meeting such demand with minimal missed business opportunities and swinging between over- and undercapacity (Coker & Helo, 2016). Firms seek to reach and maintain a balanced demand–supply state by predicting demand and establishing corresponding supply requirements within the short, medium, and long term (Jonsson & Mattsson, 2009). To that purpose, they dedicate strategic-level planning activities to addressing generic long-term needs, typically beyond 3 years. They also perform operational-level planning activities to address detailed short-term (i.e., daily or weekly) requirements. For those reasons, planning activities generally entail decisions associated with various horizons and levels of uncertainty. Integrating such decisions across the various horizons is often referred to as *hierarchical production planning* (e.g., Bitran & Hax, 1977; Sitompul & Aghezzaf, 2011).

Rich, diverse, and extensive, the literature on strategic management describes strategic planning for numerous businesses and operations in various industries (Durand et al., 2017). Likewise, an abundance of literature on operational planning describes specific areas of planning demand and supply, including marketing (Pulendran et al., 2003), transportation (SteadieSeifi et al., 2014), the supply chain (Power, 2005), scheduling (Pinedo, 2016), and capacity (Wu et al., 2005). However, the literature describing planning activities addressing medium-term demand and supply requirements (e.g., from 3 months to 3 years)—most frequently labeled "tactical planning"—is thin and fragmented and lacks consensus compared with the literature associated with strategic and operational planning (Pereira et al., 2020). The lack of structure in literature on tactical planning especially applies to work concerning complex environments such as engineer-to-order (ETO) and configure-to-order (CTO) operations (Kristensen & Jonsson, 2018).

Balancing demand and supply in ETO and CTO operations is challenging at the tactical level (Carvalho et al., 2015). To address the considerable variety, volatility, uncertainty, and ambiguity embedded in ETO and CTO operations, this thesis adopts complexity as a theoretical lens (e.g., Bozarth et al., 2009; Dittfeld et al., 2018; Senge, 1998). From that perspective, firms combat the impact of complexity on tactical demand–supply balancing by performing planning activities both at the tactical level and at the interfaces between the strategic and operational levels. Figure 1.1 presents a pyramid whose downward-expanding base represents the disaggregation of information that guides long- to short-term plans. Accordingly, tactical-level planning processes can be positioned at the strategic–tactical interface, tactical level, and tactical–operational interface. The following three subsections describe the corresponding practical and theoretical problems of demand–supply balancing that serve as the foundation for the thesis's purpose, as described in Section 1.2.

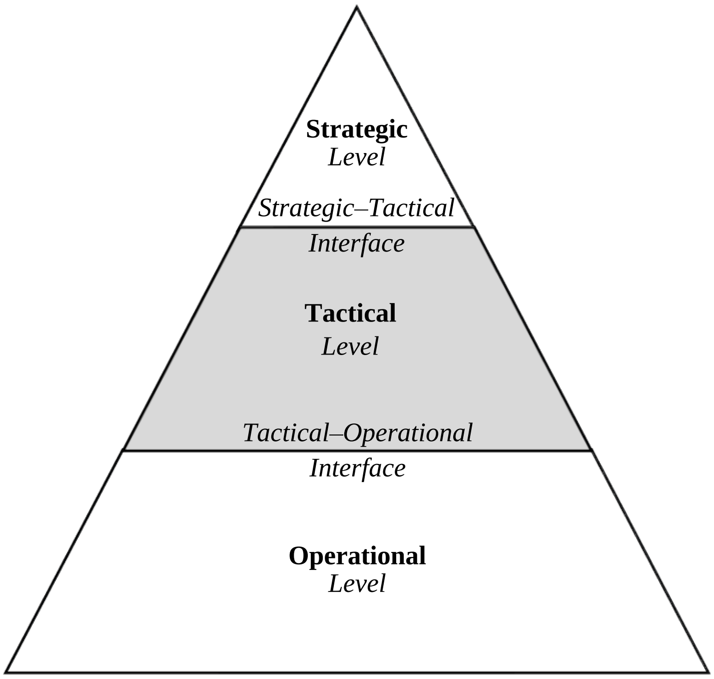



**Figure 1.1.** Levels of tactical planning activities addressed in the thesis

### 1.1.1. Balancing demand and supply at the tactical level

Fulfilling demand in ETO businesses requires engineering and production readiness to meet potential requirements for customization, which are seldom visible until customers issue their order requests (Gosling et al., 2017). Such uncertainty challenges demand–supply balancing (Birkie & Trucco, 2016), which is critical in ETO operations, wherein profit margins can quickly vanish if demand falls behind supply capacity (Olhager, 2010). Beyond that, a slight mismatch between demand and supply perpetuates a devastating bullwhip effect (Lee et al., 1997).

Different forms of variation and uncertainty also affect how demand and supply are balanced. In general, ETO product architectures allow significant customization and modular configurations and thus require substantial flexibility in production (Carvalho et al., 2015). Such customizability increases as the freedom given to internal functions to propose and design solutions to customers increases as well (Cannas et al., 2020). Moreover, because ETO firms typically serve tender-based markets (Hicks et al., 2000), winning customers' orders for ETO operations is not certain. Added to that, customers vary in the size of their organizations, their tendency to request post-agreement changes, and their familiarity with technical and functional specifications (Cannas et al., 2020). Such variations can challenge demand–supply balancing because estimating capacity requirements and related timelines is subject to significant uncertainty.

Technological advancements have increased competition within ETO-oriented industries in the arenas of lead times and prices (Buer et al., 2020; Cannas et al., 2020). Such competition has reduced the tolerance for slack resources and system inefficiencies, privileges that many ETO manufacturers benefited from for decades (Hinckeldeyn et al., 2015). In addition, customers' expectations for customization continue to steadily rise (Birkie & Trucco, 2016; Cannas et al., 2019; Tiedemann et al., 2020). Leading manufacturers seek to capture and manage the uncertainty caused by frequent engineering changes introduced by customers' incoming orders as soon as possible. Such proactive behavior helps to prevent unbalanced demand–supply scenarios and minimize associated costs (Shurrab et al., 2020a).

For those reasons, engineering changes requires the regular involvement of various engineering competencies necessary to compete for contracts (e.g., upon tendering) and to deliver orders as expected (Shurrab et al., 2020b). Any lack of such competencies constrains the intake of customers' orders, which typically translates into a high opportunity cost given the relatively large budgets required to fulfill customers' orders in ETO markets (Hicks et al., 2001). On the other hand, having excess engineering competencies is costly. Engineering hours and engineers' recruitments come with high costs, and for newly hired engineers to keep up satisfactorily, extended learning periods apply (Duchi, 2017).

Identifying the gap between demand and supply over a medium-term horizon—usually 24 months (Wallace & Stahl, 2008)—requires intensive information processing across functions and layers of management (Feng et al., 2008). The tactical planning level is where planning processes explicitly address medium-term demand–supply balancing as an objective, which in a manufacturing context applies to sales and operations planning (S&OP; Jonsson & Holmström, 2016; Pereira et al., 2020). S&OP is a monthly planning process through which demand-facing functions (e.g., sales and marketing) and supply-facing functions (e.g., operations and procurement) attempt to reach a consensus concerning the medium-term demand that the firm needs to fulfill (Wallace & Stahl, 2008).

Research touching upon S&OP has grown noticeably in the last decade as increasingly more firms across all manufacturing industries have begun to implement S&OP. However, evidence from several studies shows that many firms continue to struggle with gaining the appropriate effect of demand–supply balancing from S&OP due to mismatches in the design of processes (Kreuter et al., 2021a; Kreuter et al., 2021b; Kristensen & Jonsson, 2018; Tuomikangas & Kaipia, 2014). Such a problem lacks empirical evidence for effect practice, especially in complex environments such as ETO operations. S&OP has a simple process design that begins with demand planning, followed by supply planning, and ends with demand–supply plan reconciliations (Ling & Goddard, 1988). However, in practice, S&OP implementers encounter countless challenges concerning process designs that need to effectively and efficiently balance demand and supply, especially in complex manufacturing operations (Kristensen & Jonsson, 2018). Those challenges represent the practical problem at the tactical level addressed in this thesis.

According to Gosling et al. (2017), ETO environments vary in the intensity of engineering activities required for customization after customers place their orders. Therefore, to be effective, managerial approaches adopted in ETO operations need to align with the degree of customization (Cannas et al., 2019). The degree of customization determines the number of engineering and production hours required before and after customers' orders are received; thus, designing an S&OP process that manages uncertainty in its particular context is critical even when considering ETO businesses independently from other types of planning environments.

### 1.1.2. Balancing demand and supply at the strategic–tactical interface

At the strategic–tactical interface, long-term business plans that shape a firm's future demand, competence, and capacity are subject to substantial uncertainty (Carvalho et al., 2017). After all, those plans are merely guesses about realities far into the future. Such uncertainty often makes long-term demand–supply balancing activities such as strategic planning inaccurate and risks significant costs associated with lost opportunities and the underutilization of capacity (Coker & Helo, 2016). Because aggregate plans are not profitable when capacity utilization is low (Gansterer, 2015), most businesses implement a customer order fulfillment process (Cannas et al., 2020). Customer order fulfillment is a decision-making process that addresses customers' incoming orders and the consequent impact on a firm's medium-term to long-term capacity (Kingsman et al., 1996). The process seeks to balance medium-term demand and supply while at once contributing to strategic business objectives. The process enables such performance by aligning with promising markets and accumulating competence and expertise that allow taking the lead in the market (Cooper & Budd, 2007).

In industries offering changes in product design at the moment when customers place their orders (e.g., ETO operations), the customer order fulfillment process is standard practice. The uniqueness within the influx of ETO customers' orders entails regular extensive adaptations to the underlying production infrastructure (e.g., machinery, equipment, facility layouts, and material handling). Because such transformations have extended lead times, production planning at the aggregate strategic–tactical interface is necessary to detect in advance any potential shortage in, for instance, critical competencies (Giebels et al., 2000). Critical competencies are often challenging to secure on short notice (Cooper & Budd, 2007); therefore, failing to identify the types and timing of critical capacity constraints in ETO settings often leads to demand–supply imbalance. Thus, operational complexity in ETO contexts is substantial, as is uncertainty, and makes demand–supply balancing at the strategic–tactical interface (i.e., within the customer order fulfillment process) crucial despite being challenging to manage. That practical problem is also addressed in this thesis.

Another problem concerning planning within a customer order fulfillment process in complex environments such as ETO operation is applying effective cross-functional integration. According to Oliva and Watson (2011), demand–supply balancing requires intensive cross-functional integration between demand- and supply-facing functions. The customer order fulfillment process needs extensive cross-functional integration in ETO operations in order to effectively and consistently balance demand and supply (Adrodegari et al., 2015). One reason for that dynamic is fierce competition to win contracts, which requires tight delivery lead times that are often attainable via increased concurrency. Concurrency, entailing increasing interdependencies across functions and between activities, calls for substantial cross-functional integration (Mello et al., 2015), and such pressure to integrate is yet another practical problem addressed in this thesis.

### 1.1.3. Balancing demand and supply at the tactical–operational interface

The success or failure of planning at the tactical level appears more clearly as variations emerge at the operational level (Okongwu et al., 2016). Therefore, demand–supply imbalances frequently translate to increased schedule variations at the operational level (Shurrab et al., 2019).

To ensure a stable, efficient production environment, most manufacturing firms plan their production schedules based on a fixed capacity level with a certain degree of short-term flexibility. In other words, manufacturers can increase or reduce their production capacities only to a limited extent on short notice, typically within a few months (Deif & ElMaraghy, 2006). Manufacturers thus tend to avoid designing overly ambitious levels of production capacity at the expense of missing demand opportunities (Nejad & Kuzgunkaya, 2014). The costs of overcapacity can be harmful in cases of market stagnation, especially in contexts in which heavy investments are required to increase capacity. Because production capacity is fixed below market demand levels in order to minimize the effect of demand variations on a production schedule (Olhager et al., 2001), production schedule instability is often not attributed to poor planning performance, particularly the failure to accurately capture medium- and long-term variations in demand. Such instability is, however, usually a consequence of internal factors such as machine failures, labor shortages, and problems with quality (Inman & Gonsalvez, 1997).

Unlike disruptions in production schedules, many researchers attribute disruptions in material delivery schedules to demand–supply imbalances at the tactical level (e.g., Li & Disney, 2017; Pujawan, 2004). Understanding the causality of variations in material delivery schedules affords possibilities to prevent the propagation of instability upstream in the supply chain (Herrera et al., 2016; Pujawan & Smart, 2012). To determine effective procedures, manufacturing firms downstream in the chain have to identify and explain how underlying factors cause schedule instability (Atadeniz & Sridharan, 2019).

Procurement in high-mix, low-volume manufacturing environments such as ETO operations is often tender- or project-based and thus decentralized. Because delivery lead times are relatively long in those environments, the information about material deliveries appears early in the fulfillment process (Moretto et al., 2020). By contrast, in medium-mix, high-volume manufacturing environments such as configure-to-order (CTO) operations delivering complex products (e.g., automobiles), such information is subject to substantial uncertainty. The automotive supply bases are massive and require intensive coordination and synchronization, and such substantial complexity generates material delivery schedule variations within the supply chain (Lalami et al., 2017; Moetz et al., 2018), which is another practical problem addressed in this thesis.

In the last decade, the automotive industry yielded an average turnover accounting for 4% of the world's gross domestic product (Saberi, 2018). Automotive supply chains are complex networks of manufacturers; original equipment manufacturers (OEMs) maintain large supply bases in terms of breadth (e.g., number of first-tier suppliers) and depth (e.g., number of supply chain echelons; Doran, 2004). In turn, automotive supply chains generate more than 50% of the product value (Lee & Oakes, 1996). In such environments, competition between supply chains is thus more important than competition between constituent firms (Li et al., 2015; Stock et al., 1998).

Automotive supply chains need to maximize efficiencies through synchronous production, zero-defect quality, and constant engineering (Harrison, 2004). OEMs synchronize material flows through a material delivery scheduling process that generates and revises future material requirements, typically using material requirements planning systems. Material delivery schedules include forecasted and fixed (i.e., frozen) delivery orders distributed over a specific horizon to fulfill future demand (Ho et al., 1992). A material delivery schedule is unstable when planned quantities experience frequent revisions (Carlson et al., 1979; Steele, 1975).

Material delivery schedule instability features substantial complexity, especially dynamic complexity (Sivadasan et al., 2013). Increased unnecessary complexity in operations can harm businesses by requiring increased coordination costs and narrower managerial attention spans (Holweg et al., 2018). Dynamic complexity is observable in several settings, including when variations in a process generate short- and long-term effects in local and global systems, when obvious interventions produce ambiguous consequences, and when minor changes in inputs or parameters produce significant changes in behavior (Senge, 2014). In material delivery, minor schedule variations may generate imperfectly understood short- and long-term instability effects in a plant and in the supply chain (Pujawan & Smart, 2012). Understanding such causality affords possibilities to prevent the propagation of instability upstream in the supply chain. A causal factor can affect schedule variations in two principally different ways: through different planning horizons and through different levels of schedule inaccuracy. Some factors can significantly impact shorter horizons, whereas others can affect extended horizons; some factors may substantially impact minor schedule variations, whereas others influence significant variations. Understanding whether and how factors affect inaccuracies along those dimensions is a precondition to generating predictive models.

## 1.2. Purpose of the thesis

The previous subsections describe practical and theoretical problems concerning demand–supply balancing using tactical-level planning processes in complex manufacturing environments. In high-mix, low-volume manufacturing environments such as ETO operations, demand–supply balancing is most frequently challenging at the strategic–tactical interface and tactical level. Material demand–supply balancing is especially challenging at the tactical–operational interface in such environments associated with complex products—for example, automotive CTO supply chains. At each level, manufacturing firms dedicate a specific planning process to demand–supply balancing: customer order fulfillment at the strategic–tactical interface, S&OP at a tactical level, and material delivery scheduling at the tactical–operational interface. In the literature, knowledge about various tactical-level planning processes integrated in managerial practices in complex manufacturing environments is fragmented at best (see Chapter 2). As a result, considerable gaps in knowledge exist concerning the interaction between the three tactical-level planning processes and demand–supply balancing. Manufacturing firms need such knowledge about their specific industry when designing, adapting, and implementing tactical planning for efficient, effective demand–supply balancing challenged by increased complexity. Considering all of the above, the purpose of this thesis is:

*To elucidate how complexity in manufacturing operations influences demand–supply balancing and planning at the tactical level.*

## 1.3. Scope

This thesis addresses demand–supply balancing in three tactical-level planning processes: customer order fulfillment, S&OP, and material delivery scheduling. Demand–supply balancing translates to generic activities in each of those process's frameworks that are needed to plan demand and supply capacity. Although the three processes are integrable and may interact with other planning processes, this thesis considered them independently.

The concept of the supply chain emerges in several places throughout the thesis, often to explain the importance of demand–supply balancing as a phenomenon and its associated far-reaching consequences. At the same time, the problem of demand–supply balancing is approached from a perspective focusing on the firm, not the dyadic or triadic network. Moreover, the thesis frequently refers to the term *supply* as a concept that embraces all supply-related activities: manufacturing, engineering, logistics, procurement, finance, and human resources. Accordingly, *supply capacity* refers to the internal and external capability to meet demand using available buffers of material and operational time and scale.

In this thesis, the term *design* refers to the configuration of activities, inputs, outcomes, organizations, methods, information systems, and performance measurements that form the planning processes examined. The focus on design does not involve providing a complete blueprint of the planning process but is limited to highlighting contextually relevant aspects of designing those processes.

The thesis does not associate tactical planning with traditional metrics of performance. Instead, it perceives demand–supply balancing as a high-level measure of performance indicating overcapacity and undercapacity. Those dimensions are quantifiable by comparing actual versus planned capacity and actual versus targeted demand.

The thesis addresses tactical planning in several contexts marked by substantial complexity, including the environments of ETO and CTO operations. However, those contexts do not represent all of the various planning settings of ETO and CTO operations. The term *context* is thus limited to the planning environment, especially the factors or variables that have a contingency effect on the relationship between the planning process and demand–supply balancing. Product complexity is a typical example of other aspects in the context considered in this thesis.

## 1.4. Research questions

This subsection introduces the three RQs addressed in the thesis, which align the research with the purpose presented in Section 1.2 and address the research area as broadly yet as precisely as possible.

As introduced in Section 1.1, tactical planning plays an essential role in demand–supply balancing and manifests as cross-hierarchical business processes, as shown in Figure 1.1. The three RQs presented in this subsection target three business processes that define the boundaries of the tactical domain.

Combined, the three RQs enable focused research studies. The studies address critical issues associated with demand–supply balancing in complex environments and build on the literature concerning operations planning and control. Answers to the RQs contribute to the research's purpose—that is, to elucidate how complexity in manufacturing operations influences demand–supply balancing and planning at the tactical level.

Each of the following subsections presents an RQ preceded by a summary of the motivation for the question based on the literature. Figure 1.2 illustrates the RQs and the purpose of the thesis, while Chapter 2 more comprehensively reviews the literature about the topics and presents the theoretical framework of the thesis.

**Purpose:** *To elucidate how complexity in manufacturing operations influences demand–supply balancing and planning at the tactical level*

**RQ1.** *How does complexity in engineer-to-order operations influence demand–supply balancing within the customer order fulfillment process?*

**RQ2.** *How does complexity in engineer-to-order operations influence sales and operations planning?*

**RQ3.** *How does complexity in configure-to-order operations influence material delivery schedule instabilities?*

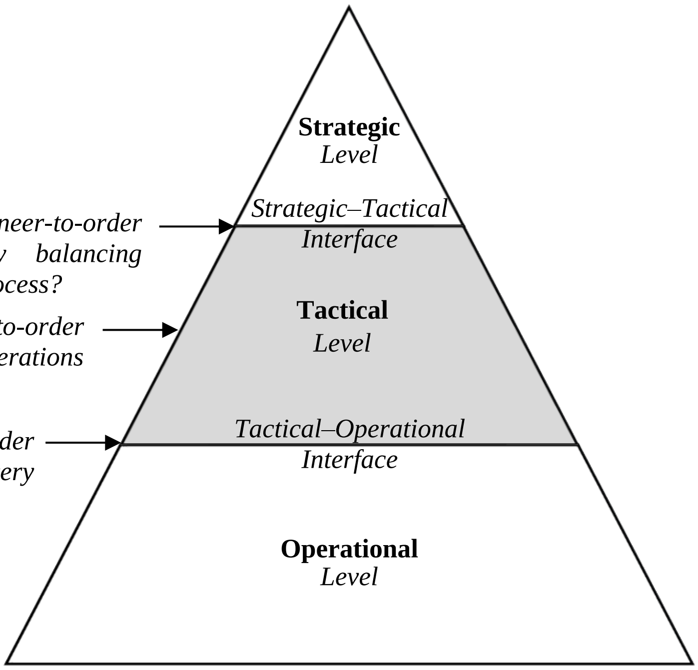



**Figure 1.2.** Purpose and research questions addressed in the thesis

### 1.4.1. Research Question 1

As mentioned, ETO operations feature substantial complexity, which places pressure on demand–supply balancing. Because the associated lead times are long (Gosling & Naim, 2009), ETO firms need to early and systematically plan for and build capacity that fulfills future medium-term to long-term demand (Cannas et al., 2019). Such a planning interface requires a hybrid planning focus that aligns medium-term fulfillment with strategic business objectives (Carvalho et al., 2015). Hierarchically, this thesis positions such hybrid planning at the strategic–tactical interface.

To date, various studies have together partly explained how a similar planning setting affects demand–supply balancing in ETO environments. The contributions of such research have included testing objective functions that minimize costs (e.g., Gademann & Schutten, 2005) or timespans (e.g., Nobibon et al., 2015) or that maximize revenues (e.g., Alfieri et al., 2011). More recently, Carvalho et al. (2015) conducted a study with a broader scope and more variables. Such quantitative contributions provide valuable but nevertheless fragmented insights into limited scopes of planning. Often, they have simplified the planning problem by concentrating on disjointed activities and decisions.

Meanwhile, other studies have proposed four processes that can be associated with planning at the strategic–tactical interface: order acceptance, rough-cut capacity planning, procurement, and macro-level process planning (Hans et al., 2007). Again, however, the literature on those individual processes does not comprehensively describe the cross-functional coordination reflected by the underlying planning activities and decisions associated with demand–supply balancing. According to Fleischmann & Meyr (2003), establishing integrated planning processes requires clear descriptions of alternatives, objectives, constraints, and suitable optimization algorithms.

In another stream of research, generic models of the customer order fulfillment process have been developed for ETO-oriented firms (e.g., Adrodegari et al., 2015; Weber et al., 2000). Although the models provide rich insights into detailed activities and decisions, from tender requests to final cost assessment upon the completion of orders, they do not distinguish operational-level from tactical-level activities. However, that distinction is pivotal for tactical-level planners to appropriately delineate problems in medium-term demand–supply balancing from near-term problems (Jonsson & Mattsson, 2009). Therefore, comprehensively capturing planning activities and decisions at the strategic–tactical interface is crucial for appropriate medium-term demand–supply balancing. For that reason, a holistic conceptualization of the process needs to be developed to describe ways of managing and coordinating demand–supply balancing in ETO environments. In response, the thesis contributes to that gap by addressing RQ1:

**RQ1:** *How does complexity in engineer-to-order operations influence demand–supply balancing within the customer order fulfillment process?*

### 1.4.2. Research Question 2

As described in Subsection 1.1, ETO operations represent complex contexts for demand–supply balancing downward to the tactical level, where S&OP is a typical process for such balancing. The degree of customization varying across ETO operations determines the number of engineering and production hours required before and after customers' orders are received (Gosling et al., 2017). Therefore, designing a planning process that manages uncertainty in its context is critical even when considering ETO operations independently from other types of planning environments (Cannas et al., 2019).

Drawing on the contingency and complexity theories, several studies have shown that a prerequisite for effective S&OP is a process designed to adequately address uncertainty in its environment (see literature review of Kristensen & Jonsson, 2018). However, literature addressing uncertainty's effect on S&OP design is nearly devoid of examples from ETO environments (Kristensen & Jonsson, 2018; Tuomikangas & Kaipia, 2014). The few works that have explicitly discussed and related ETO-oriented characteristics to S&OP have focused on a few contextual differences that make available-to-promise capacity drive supply planning instead of inventory (Ling & Goddard, 1988; Olhager, 2010; Wallace & Stahl, 2008). As such, those works provide insights into some basic principles for S&OP in ETO operations, which lack the level of guidance required for configuring a context-fitted S&OP design.

Although context-fitted S&OP design is an information-processing problem at its core, no study concerned with S&OP has adopted an information-processing perspective. Taking such a perspective can nevertheless help to identify the information-processing needs (IPNs) generated by the environment in which S&OP operates. An exception was a study conducted by Schlegel et al. (2020); however, it explores only the enabling role of big data analytics. Several studies have highlighted information-processing mechanisms (IPMs) generated by S&OP in the form of coordination (e.g., Goh & Eldridge, 2019; Tuomikangas & Kaipia, 2014) and cross-functional integration (e.g., Oliva & Watson, 2011). However, S&OP problems concerning contextually unfit process designs remain unresolved, and only limited knowledge is available concerning the logic that determines how to adapt the design to meet the context's requirements (Kreuter et al., 2021b; Kristensen & Jonsson, 2018). Therefore, another RQ was developed for the thesis:

**RQ2:** *How does complexity in engineer-to-order operations influence sales and operations planning?*

### 1.4.3. Research Question 3

As also described in Section 1.1, high complexity in material demand–supply balancing manifests at the tactical–operational interface in medium-mix, high-volume manufacturing environments where products are complex, as typical in automotive CTO supply chains. In general, material delivery schedule instability is a classic problem that has received considerable attention in research on operations management since the 1970s (Steele, 1975). Most studies have focused on mitigating schedule instability by investigating how suppliers may temper frequently changing (i.e., nervous) schedules to maintain demand–supply balancing through, for instance, lot sizing, schedule freezing, and safety stock policies (e.g., Atadeniz & Sridharan, 2019; Ho, 2002; Krajewski et al., 2005; Li & Disney, 2017). By contrast, very few studies have addressed the root causes of such instability (Inman & Gonsalvez, 1997; Law & Gunasekaran, 2010; Pujawan et al., 2014; Pujawan & Smart, 2012), and the ones that have done so have not considered a complexity perspective to further clarify the phenomenon. Conceptually, Holweg et al.'s (2018) process theory implicitly connects complexity drivers and variations in processes at an generic level. Even so, its descriptions concerning how "dynamic interactions" may generate such variations are abstract and lack granular detail.

Schedule instability develops along with variations at organizations downstream in the supply chain, including OEMs. Understanding the causality of variations in material delivery schedules allows mitigating the propagation of instability upstream in the supply chain (Pujawan, 2008). However, OEMs are often not considered in relevant studies, even though instability to a great extent emanates from downstream in the chain. Sahin et al. (2013) have argued that advancing the understanding of material delivery schedule instability requires shifting toward empirical research and real-case data. In response to that need, the thesis's final RQ was:

**RQ3:** *How does complexity in configure-to-order operations influence material delivery schedule instabilities?*

## 1.5. Outline of the thesis

This chapter, Chapter 1 (i.e., Introduction), has introduced the research and its background. It has also described the research's purpose, its scope, and the three RQs addressed in the thesis, as well as provides this outline of the thesis's contents. Next, Chapter 2 (i.e., Frame of reference) reviews literature relevant to the thesis's purpose and RQs and highlights essential conclusions from the literature.

Chapter 3 (i.e., Method) describes the research method adopted in the thesis, including the processes, strategies, and methods used in the six research papers appended to the thesis. The chapter ends with a discussion of the research's validity and reliability. After that, Chapter 4 (i.e., Results) presents the results from the six research papers appended to the thesis as answers to the thesis's three RQs.

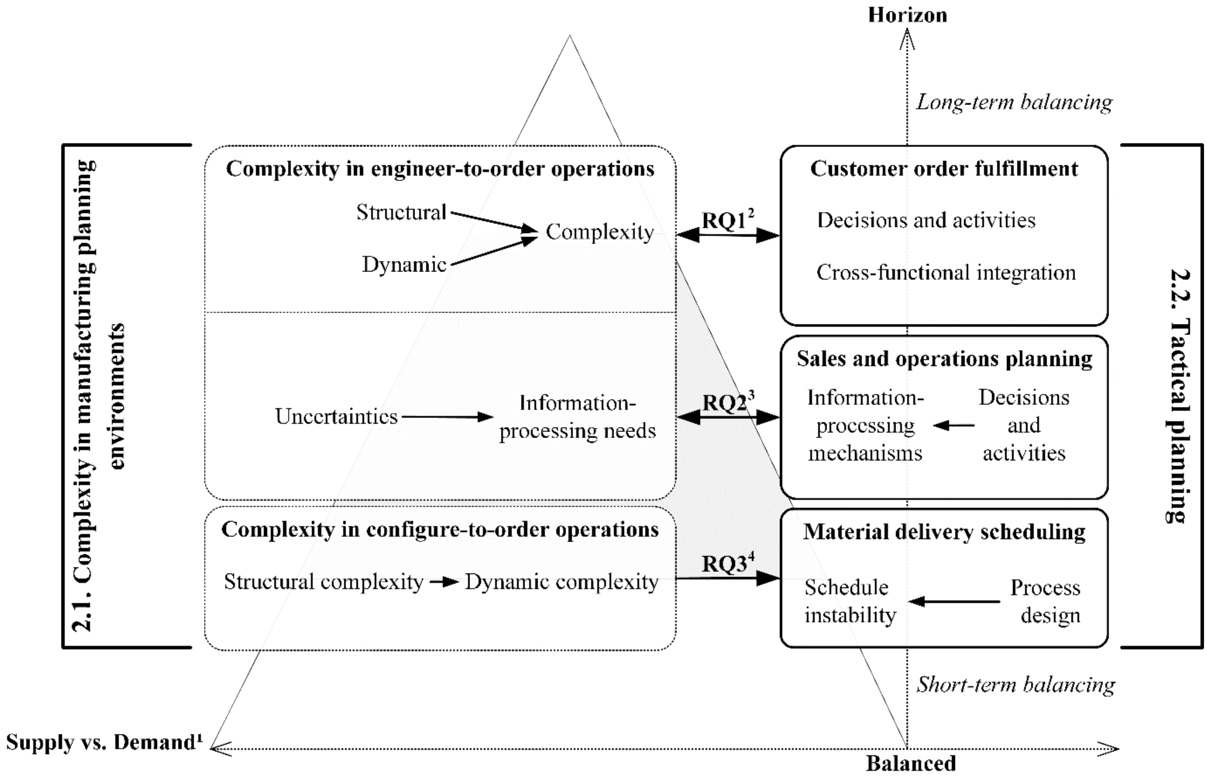
Chapter 5 (i.e., Discussion) discusses the thesis's results and highlights implications for future research. It also combines a discussion about the results' generalizability and how they apply to theory and practice. Last, Chapter 6 (i.e., Conclusions) presents the thesis's conclusions.

# 2. Frame of reference

The beginning of this chapter describes the thesis's conceptual framework. Figure 2.1 presents the framework at a generic level by showing tactical-level planning processes, manufacturing environments (i.e., ETO and CTO operations), and the focus of the RQs. In the figure, the x-axis represents the state of the relationship between demand and supply, with the y-axis intercepting the state of demand–supply balance. The y-axis represents the horizon, while the rectangles along the axis represent the three planning processes addressed in the thesis: customer order fulfillment, S&OP, and material delivery scheduling. The position of each rectangle represents the horizon that each process addresses, and arrows connecting the rectangles represent complexity-related constructs.

In what follows, Section 2.1 describes complexity in ETO and CTO operations and their generic impact on demand–supply balancing. Afterward, Section 2.2 defines *tactical planning* and describes the three processes, each of which was essential in at least one of the thesis's studies. The corresponding subsections describe generic steps of the processes and relevant insights from extant research.

Next, Section 2.3 presents the fundamental theories adopted in the thesis's studies as lenses for analyzing empirical data, including theories on cross-functional integration, organizational information processing, complexity, and processes. The section also describes concepts relevant to the thesis's purpose. Last, combining insights from Sections 2.1–2.3, Section 2.4 provides a comprehensive overview of the literature specific to the RQs and elaborates upon the discussion about gaps in the literature briefly presented in Chapter 1.




[1] Available capacity minus capacity required to fulfill targeted demand
[2] RQ1 (i.e., How does complexity in engineer-to-order operations influence demand–supply balancing within the customer order fulfillment process?)
[3] RQ2 (i.e., How does complexity in engineer-to-order operations influence sales and operations planning?)
[4] RQ3 (i.e., How does complexity in configure-to-order operations influence material delivery schedule instabilities?)

**Figure 2.1.** Overview of the theoretical framework of the thesis

## 2.1. Complexity in manufacturing planning environments

In manufacturing operations, demand refers to physical products, whereas supply refers to the machines, labor, material, and knowledge required to meet demand (Jonsson & Mattsson, 2009). Suitable approaches for planning demand and supply in manufacturing contexts vary depending on associated variables and the information available. The more complex the manufacturing system required to respond to demand, the greater the difficulty of planning (Serdarasan, 2013). Because such complexity in manufacturing imposes prerequisites for effective planning (Jonsson & Mattsson, 2003), identifying the complexity that characterizes contexts of demand and supply can shed light on what planning requires to achieve demand–supply balance.

In general, complexity theory lacks a consensus regarding the constructs and characteristics associated with complex systems (Stein, 1989). In the past decade, several studies have expanded on Simon's (1962) seminal work on complexity (e.g., Aitken et al., 2016; Bolaños & Barbalho, 2021; Bozarth et al., 2009; Dittfeld et al., 2018; Fernández Campos et al., 2019; Serdarasan, 2013). Among them, Senge (2014) has posited that complexity in a given system has a structural dimension and a dynamic dimension. Along those lines, supply chain complexity is a type of combined structural and dynamic complexity manifested in the chain's products, processes, and underlying relationships (Bozarth et al., 2009). On the one hand, Serdarasan (2013) has defined *structural complexity*, also called *detail complexity*, in supply chains as "the structure of the supply chain, the number and the variety of its components and strengths of interactions" between them. In other words, structural complexity represents a combination of numerousness and variety (Dittfeld et al., 2018).

On the other, Bozarth et al. (2009, p. 79) have defined *dynamic complexity* as "the unpredictability of a system's response to a given set of inputs." For Serdarasan (2013), the uncertainty related to time and randomness represents the essence of dynamic complexity. According to Galbraith (1977), *uncertainty* "is the difference between the amount of information required to perform the task and the amount of information already possessed by the organization." Therefore, higher uncertainty requires decision-makers to process more information in order to execute tasks and achieve a certain level of performance (Cooper et al., 1992). By extension, numerousness and variety are deterministic subdimensions of complexity characterizing "the level and type of interactions in the system," such that *uncertainty* refers to "the inherent noise and variations" therein (Vachon and Klassen, 2002, p. 220).

Past studies have provided evidence of key variables of complexity that influence manufacturing planning and control systems (Buer et al., 2018). For instance, Maccarthy and Fernandes (2000) identified general variables (e.g., enterprise size, repetitiveness of manufacturing, and level of automation), a product-related variable (i.e., bill of material complexity), a process-related variables (i.e., complexity of the production process), and assembly-related variables (i.e., types of assembly and types of work organizations. Added to that, Bozarth et al. (2009) developed a generic framework that captures complexity in supply chains, one that categorizes drivers of complexity into factors that increase structural and dynamic complexity in internal operations and across the supply chain, both down- and upstream. The key takeaways from the framework related to the thesis's scope are that the greater the detail of information required for decision-making, the greater the structural complexity, and the more ambiguous the causality in a context, the greater the dynamic complexity.

More recent research has associated the point at which customers' orders are decoupled from forecasted orders as a determinant of effective managerial practices considering the contextual complexity in question (e.g., Bertrand & Muntslag, 1993; Cannas et al., 2019, 2020; Earl et al., 2003; Giesberts & Tang, 1992; Gosling et al., 2017; Okongwu et al., 2016; Olhager, 2010; Olhager et al., 2001; Rudberg & Wikner, 2004; Wikner & Rudberg, 2005). The decoupling point reflects contrasting complexity that influences managerial approaches such as effective capacity management (Olhager et al., 2001) and production planning and control (Olhager, 2010).

The decoupling point in a product fulfillment process that separates forecast-driven activities from activities driven by customers' orders (Wikner & Rudberg, 2005). As such, the setting of the decoupling point influences the amount of production-related work that firms perform before and after receiving customers' orders (Giesberts & Tang, 1992; Hoekstra & Romme, 1992). On a scale from mostly forecast-driven to mostly order-driven, settings of generic decoupling points are make-to-stock (MTS) operations, CTO operations (also called "assemble-to-order operations"), make-to-order operations (MTO, also called "build-to-order operations"), and ETO operations (Olhager, 2010). Accordingly, in order-driven environments (i.e., MTO and ETO operations), planning processes have to manage greater variety and uncertainty (i.e., complexity). The increase in such complexity stems from increased production and engineering activities that do not occur until the corresponding actual demand is visible (Hicks et al., 2000).

### 2.1.1. Complexity in high-mix, low-volume engineer-to-order operations

As clarified earlier, an increase in engineering and production complexity associated with order fulfillment activities after customers' place orders entails greater planning complexity in ETO operations. Several recent studies on complexity management have adopted constructs from Bozarth et al. (2009) (e.g., Aitken et al., 2016; Birkie & Trucco, 2016; Fernández Campos et al., 2019; Serdarasan, 2013; Turner et al., 2018) for the comprehensive overview that their framework offers, which organizes the drivers of complexity based on their source. Such an overview enables researchers and practitioners to relate the impact of complexity to demand–supply balancing.

According to Bozarth et al. (2009), the drivers of supply chain complexity are either downstream drivers, internal manufacturing drivers, or upstream drivers. Because this thesis addresses demand–supply balancing from the perspective of focal firms, it relates drivers of downstream complexity to demand because they primarily emanate from the demand side. By contrast, the thesis associates drivers of upstream and internal complexity with the supply side. In that way, it assumes that drivers of complexity are assumed to stem from either demand or supply. Therefore, the way in which tactical planning is organized and performed depends on the degree of structural complexity and dynamic complexity originating from customers' demands and the capacity of supply.

Demand-related drivers of complexity include the number of customers, heterogeneity in customers' needs, and variability in demand. A larger number of customers requires more customer relationship management and order management tasks, which only increase the associated structural complexity (Berry et al., 2011). Responding to increasingly diverse order specifications distracts operations from fulfilling their strategic priorities due to the consequent proliferation of order winners and qualifiers. According to da Silveira (2005), such variety especially increases the potential for conflicts in manufacturing tasks and misalignment with customers' needs. For an antidote, the operational scope should align consistently with the solutions representing the firm's highest levels of technology readiness in areas of core competence (Mankins, 2009). Variability in demand may increase uncertainty upstream in supply chains. For example, a lack of coordination and visibility upstream in ordering policies generates the so-called bullwhip effect (Chen et al., 2000).

Supply-related drivers concerning internal operations include the number of products and product parts, low-volume batch production, and manufacturing schedule instability (Bozarth et al., 2009). An increase in the number of products and their unique components increases the variety of manufacturing tasks (Closs et al., 2008; Salvador et al., 2002), which consequently increases structural complexity. Meanwhile, low-volume batch production or one-of-a-kind production raises the number of unique jobs in manufacturing, which also increases structural complexity. In turn, increasing cross-job uniqueness entails increased variability in the underlying manufacturing tasks, which eventually leads to higher dynamic complexity (Duray et al., 2000; Hill, 2017). Instability in a production environment, often driven by unexpected absenteeism and machine failure, increases the uncertainty of production schedules, which also increases dynamic complexity (Berry et al., 2011). Manufacturers dedicate hierarchical planning and control systems to handle the uncertainty associated with such unpredictability and with nonlinear impacts on operational production and material plans.

**Table 2.1.** Supply chain complexity drivers in engineer-to-order settings

| **Source** | **Driver** | **Description** |
|---|---|---|
| Demand | Number of customers | More customers lead to more tasks involved in managing the increased detail in relationships, demand, and orders. |
| | Size of customers | Fulfilling orders of larger organizations entails increased details and uncertainties in coordination tasks. |
| | Heterogeneity in customers' needs | A variety of customers' needs leads to a variety of order winners and qualifiers, which leads to increased potential for conflicts in manufacturing tasks and misalignment with bundles of customers' needs. |
| | Customers' product knowledge | Customers' relatively limited technical and functional knowledge of the specifications needed entails increased uncertainties. |
| | Customers' order change behavior | Higher probabilities of customers' requests for changes after receiving orders entail increased uncertainties in manufacturing and engineering tasks. |
| | Demand variability | Depending on the demand levels, supply chain actions can lead to different outcomes (e.g., stockout), and the resulting variability in demand increases uncertainties upstream in the supply chain. |
| Supply | Number of products and components | More unique products and more unique components lead to more details in manufacturing tasks. |
| | Technology maturity | Incorporating less mature technology in early stages of the life cycle of products entails increased uncertainties in engineering tasks. |
| | Breadth of customizable product structure | Product structures offering a broader scope of customizability entail increased details and uncertainties in engineering tasks. |
| | Degree of design modularity | Product structures offering less modularity entail increased details in engineering tasks. |
| | Number of external contributors | More external contributors lead to more information and physical flows and more relationships to manage. |
| | Sales and engineering process structures | Providing greater freedom to sales and engineering resources in proposing solutions entails increased uncertainties in sales and engineering tasks. |
| | One-of-a-kind or low-volume batch production | Low-volume batch or one-of-a-kind production increases manufacturing details as the number of unique jobs increases, and increasing uniqueness across jobs causes task variability and consequently more significant uncertainties. |
| | Manufacturing schedule instability | Uncertain production disruptions lead to unpredictable and nonlinear impacts on lower-level production and material plans. |
| | Cross-functional interfaces | Needing to involve more functions after receiving orders entails increased details and uncertainties in coordination tasks. |
| | Reliability and length of supplier lead times | Long, unreliable supplier lead times prolong planning horizons and increase uncertainties in manufacturing and delivery dates. |
| | Supply base globalization | The increased globalization of a supply base leads to more uncertainties in import and export regulations, fluctuations in currency valuations, cultural differences, and longer, more uncertain lead times. |

Supply-related drivers concerning complexity upstream in the supply chain include the number of suppliers, suppliers' long lead times, suppliers' unreliable lead times, and globalized supply bases

(Bozarth et al., 2009). Adding external contributors to the supply bases increases the flows of information, physical flows, the relationships that firms need to manage, and the overall uncertainty of lead times for material delivery. Long, unreliable supplier lead times require longer planning horizons and greater levels of detail, which increases the underlying uncertainty of the supply chain (Berry et al., 2011). On top of that, the growing globalization of any supply base increases the uncertainty in, for instance, import and export laws, fluctuations in currency valuations, cultural differences, and longer and eventually more uncertain lead times (Cho & Kang, 2001).

In addition to Bozarth et al.'s (2009) generic framework, more recent studies have highlighted variables specifically relevant to managerial practices in ETO operations. Cannas et al. (2020), for instance, have described what this thesis positions as complementary contextual (i.e., market-, product-, and process-related) variables in order to determine the effectiveness of order fulfillment in ETO settings. In general, those variables expand the list of drivers. Table 2.1 shows a synthesized overview of drivers of operations complexity that shape demand–supply balancing activities.

ETO-oriented businesses vary considerably from the perspective of decoupling (Gosling et al., 2017). To elucidate that dynamic, Cannas et al. (2019) have suggested a two-dimensional decoupling framework that presents engineering and production configurations as separated process flows with underlying subflows. Combining insights from the frameworks of Cannas et al. (2019) and Gosling et al. (2017), Table 2.2 describes basic configurations of engineering decoupling. By some contrast, generic configurations of production decoupling refer to the initial production activities after customers have placed their orders—that is, the purchase of raw materials, the production of components and subassemblies, the use of some components in stock and making or purchasing the customized components to finalize assembly, the final assembly using components and subassemblies in stock, and the delivery of finished products from stock (Cannas et al., 2019).

**Table 2.2.** Configurations of engineering decoupling

| Decoupling point | Activities after order entry | Starting point after order entry | Typical input from customers |
|---|---|---|---|
| Research | Concept development | Math or science: Academic results | Feasibility specifications with an open brief |
| | | Engineering: Problem briefs and codes | Constraint specification and approvals |
| Development | Development of codes, standards, and principles | Development or integration of codes: Updating of or departure from codes or standards | Tendering documentation and negotiation |
| Design | Designing detailed product specifications | Codes, standards, and case studies | |
| Modification | Major or minor modifications of existing designs to change technical, functional, or superficial characteristics | Adapted design: Building systems | Requirements and technical approvals |
| Combination | Combining a set of predefined design options | Finalized design: Modular or approved designs | Order with project documentation |

### 2.1.2. Complexity in medium-mix, high-volume configure-to-order operations

Unlike ETO operations, CTO operations proceed after customers place orders specifying their desired product configurations (Gosling & Naim, 2009). However, this thesis postulates that ETO operations are not necessarily more complex for planning processes than CTO operations in absolute terms. ETO operations are typically high-variety, low-volume production environments (Cannas et al., 2019).

Demand fulfillment along shorter horizons in such settings is less uncertain than in CTO environments because the focus is on large, parallel projects well planned before contracting (Moretto et al., 2020). ETO businesses also enjoy larger profit margins and considerably longer lead times, both of which impose costs that customers are usually willing to pay. Thus, the challenge for planning processes in ETO environments primarily concerns demand–supply balancing along longer horizons (Olhager, 2010), in which the primary factor is the long lead times of engineering activities after orders are received (Cannas et al., 2019).

In contrast to ETO environments, market competition in typical CTO businesses in, for example, the automotive and electronic industries is usually higher than in ETO businesses, and the profit margins are thus far narrower (Olhager, 2010). Therefore, CTO operations need to maintain higher efficiency and synchronization throughout the supply chain as competition between supply chains becomes fiercer than competition between constituent firms (Li et al., 2015; Stock et al., 1998). Manufacturers need to manage greater complexity along shorter horizons in specific CTO environments, namely medium-variety, high-volume production environments, than in ETO operations. CTO operations in such environments need to respond to noticeably higher volumes of highly complex products and, at the same time, a wide-ranging variety of product configurations. The number of first-tier suppliers is thus typically enormous in such a production environment (Rezapour et al., 2017). For manufacturers, especially OEMs, those characteristics represent increased complexity that causes challenges for demand–supply balancing within relatively shorter periods (Gansterer, 2015; Lalami et al., 2017; Simchi-Levi et al., 2015).

Stability in operational plans is a key indicator of effective medium-term demand–supply balancing (Coker & Helo, 2016). The higher the accuracy of medium-term plans, the lower the instability in short-term production and material delivery schedules and executions (Sahin et al., 2013). Several factors influence schedule stability. Examples of demand-related factors are demand variability (Xie et al., 2003), late changes to orders (Atadeniz & Sridharan, 2019), and information inaccuracy (Sivadasan et al., 2013). Examples of supply-related factors also include information inaccuracy (Inman & Gonsalvez, 1997) as well as changes in master production schedules and bills of material (Pujawan et al., 2014).

Regarding demand-related factors, customers' orders typically proceed through multiple stages. In later stages, manufacturers freeze orders to ensure schedule stability, and in that way, they temper the impact of the instability of some demand-related factors—for instance, forecasting errors, demand variability, and the quality of coordination with customers (e.g., access to relevant and accurate information) and across internal functions (e.g., marketing, sales, supply chain, engineering, and production). Higher-quality coordination often reduces schedule instability (Law & Gunasekaran, 2010; Pujawan & Smart, 2012). At the same time, to maintain good business–customer relationships (Krajewski et al., 2005), manufacturers need to be flexible with requests for changes from critical customers even if they arrive in the frozen stage.

As for supply-related factors, disruptions to the master production schedule in production—for example, machine breakdown, tooling issues, material loss, labor absenteeism and strikes, and unplanned plant shutdowns—represent the primary source of instability even for frozen orders (Lalami et al., 2017; Pujawan et al., 2014). Other reasons for changing the master production schedule could be discrepancies in inventory stock, variability in production lead times, and transfers between manufacturing plants (Inman & Gonsalvez, 1997). Discrepancies in stock occur due to the failed real-time synchronization of the available item counts and the registered records (Pujawan & Smart, 2012). Such deviations develop as the invisible, unreported, or untraceable disappearance, misappropriation, misplacement, and scrapping of material.

Variabilities in production entail overproduction, overshipment, underproduction, and undershipment. Manufacturers lose material when they have to refuse shipments from suppliers due to problems with quality. Material losses also occur due to unscheduled disbursements for internal projects and programs, damages during transit, scrapping, and theft (Inman & Gonsalvez, 1997). Underproduction and undershipment result in higher costs, both opportunity costs and sometimes steep penalties (Xie et al., 2003).

Other supply-related factors that influence frozen orders include coordination with suppliers (Law & Gunasekaran, 2010), end-product complexity, the variety of related configurations (Pujawan & Smart, 2012), suppliers' transport lead times, packaging sizes, lot sizing (i.e., batching) policies (Inman & Gonsalvez, 1997), and production system constraints (Atadeniz & Sridharan, 2019; Meixell, 2005). Examples of constraints that moderate schedule instability include limited access to excess capacity in space, equipment, labor, material, and time (Pujawan et al., 2014; Rice & Caniato, 2003), high sensitivity to timing (e.g., the need to sequence flows and thus the need for safety lead times; Blackburn et al., 1985), the limited effectiveness and flexibility of planning parameters (e.g., length of the planning horizon, frozen period, freezing policy, and replanning periodicity) and time-fencing systems (Pujawan & Smart, 2012), and differences in operational calendars across the supply chain—for instance, national holidays (Inman & Gonsalvez, 1997).

Last, product design modifications and the manufacturer's cost structure (i.e., ordering costs, handling costs, material costs, and setup costs) generate instability before orders are frozen (Inman & Gonsalvez, 1997). Manufacturers need to regularly modify the products' bills of material as part of research and development programs concerning new and existing products. During release periods, many items are subject to in-phasing and out-phasing. As for the cost structure, manufacturers need to optimize the quantity and frequency of material deliveries to ensure cost-effectiveness. Such optimization sometimes results in approving large orders without regard for schedule instability. In that sense, there is a trade-off between total cost, service level, and schedule instability (Meixell, 2005).

## 2.2. Tactical planning

A central concept in this thesis is *tactical planning*, a term consisting of two words, each with a specific meaning. Subsection 2.1.1 clarifies the term by first defining *planning* in general before describing the impact of adding the term *tactical* to the definition of *planning*. Next, Subsections 2.1.2–2.1.4 respectively describe three planning processes associated with the tactical domain: customer order fulfillment, S&OP, and material delivery scheduling.

### 2.2.1. Definition and role

In basic terms, *planning* is "the act of deciding how to do something" (Walter, 2008, p. 1080). In a business context, it is "the process of deciding the activities or events in an organized way so that they are successful or happen on time" (Combley, 2011, p. 633). That is to say, planning involves deciding what activities to perform in the future, how and when the execution of those activities will happen, and which resources need to be used to achieve which goals.

Planning frequency, planning horizon, and planning object are parameters in the generic planning set-up in manufacturing contexts (Jonsson & Mattsson, 2009). *Planning frequency* refers to how often the respective decision-making process occurs; the *planning horizon* describes the period into the future that a plan may cover; and the *planning object* is the entity that most decisions address (e.g., final products, product families, stock-keeping units, or combinations). Because managerial decisions vary in impact along different horizons, they shape how hierarchical production planning is organized

(Anthony, 1965). Whereas decisions with a clear long-term impact are the domain of strategic planning, decisions with shorter impact horizons are the domain of tactical and operational planning.

Strategic decisions are generally concerned with developing managerial policies and competencies that help to satisfy target markets over the long term and thus usually involve significant investments (Liberatore & Miller, 1985). Thus, strategic decisions shape a firm's competitiveness and growth as means to achieving long-term business success. By contrast, operational decisions concern day-to-day challenges and thus require predefined objectives at higher levels to be disaggregated entirely into equivalent objectives of operational performance (Jonsson & Mattsson, 2009).

Decisions related to tactical planning focus on resource utilization, and the planning object is typically aggregated into product families (Bitran & Tirupati, 1993). For the reason, several studies on operations management (e.g., Kristensen & Jonsson, 2018; Thomé et al., 2012; Tuomikangas & Kaipia, 2014), operations research (e.g., Aghezzaf et al., 2010; Carvalho et al., 2015), and supply chain management (e.g., Jonsson & Holmström, 2016; Oliva & Watson, 2011) have agreed that demand–supply balancing is *the* focus of tactical production planning. Demand–supply balancing helps to achieve business objectives by ensuring that operations over a medium-term horizon (i.e., 1 month to 2 years) deliver the desired results. Achieving those outcomes requires fulfilling strategic objectives and continually updating those objectives to be consistent with the firm's operational capabilities. Therefore, tactical-level planners need to control variables such as output rates, utilization levels, and subcontracting to meet predictable demands at the lowest possible cost (Aghezzaf et al., 2010).

In practice, planning at the tactical level manifests as processes that overlap with the strategic and operational levels. In that way, those processes also determine decisions associated with the requirements of long- and short-term demand and supply. The following subsections describe three of those processes: customer order fulfillment, S&OP, and material delivery scheduling. Customer order fulfillment and material delivery scheduling are tactically adjacent planning processes; customer order fulfillment overlaps with the strategic level (Day, 1994), while material delivery scheduling is primarily operational but overlaps with the tactical level nonetheless (Sahin et al., 2013). Last, S&OP is explicitly a tactical planning process (Pereira et al., 2020).

### 2.2.2. Planning at the strategic–tactical interface: Customer order fulfillment

Customer order fulfillment is the primary process by which ETO operations responds to customers' inquiries regarding lead time agreements and capacity constraints (Olhager, 2010). Customer order fulfillment begins with order generation before order entry and order prioritization, which are three strategic steps concerned with marketing, segmentation, and resource base development. Accordingly, manufacturers select customers' inquiries for later available-to-promise assessments in the order acceptance phase (Giebels et al., 2000).

Order acceptance is equivalent to order entry and prioritization in Day's (1994) generic customer order fulfillment process, a widely recognized process model for market-driven organizations such as ETO operations. After accepting customers' orders that strategically fit the overall long-term business plan (Easton & Moodie, 1999), three central planning activities are initiated to identify consequent aggregate needs of capacity, material, and technology: multi-project rough-cut capacity planning, multi-project procurement planning, and macro-level process planning (Giebels, 2000; Hans et al., 2007). The outcomes of those activities represent the baseline for order scheduling (Day, 1994), which in ETO operations is primarily operational and concerned with detailed short-term requirements for individual customers' orders. Figure 2.2 combines an adapted hierarchy of the structures proposed by Hans et al. (2007) and Giebels (2000) and Day's (1994) order fulfillment process model into a conceptual framework showing the most critical tactical-level planning activities within customer order fulfillment in ETO operations.

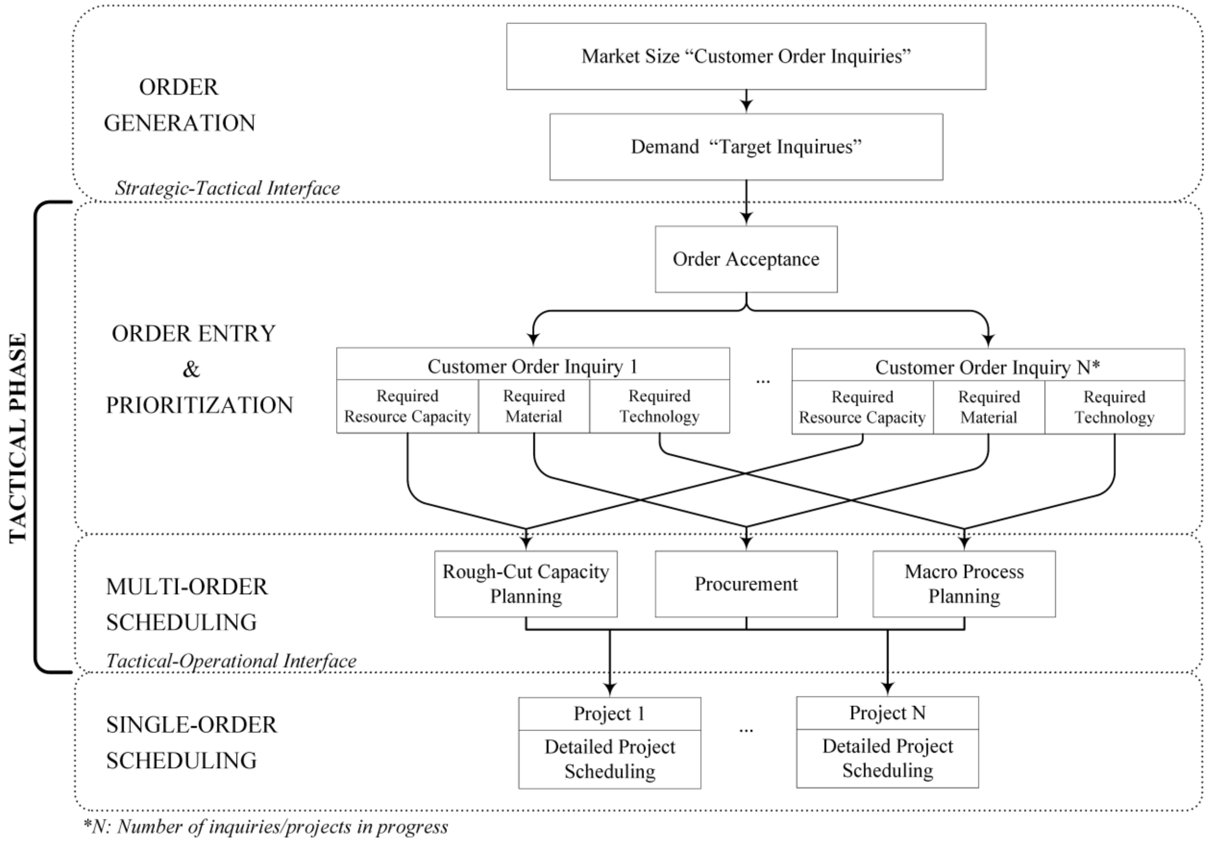



**Figure 2.2.** Tactical planning within the customer order fulfillment process

ETO manufacturers accept customers' orders carefully in order to ensure profitable returns on investment considering unexpected costs for overtime work, tool wear, and material usage, among other things (Giebels et al., 2000). Commonly, ETO manufacturers tend to accept as many inquiries as possible and strive to promise early-as-possible delivery dates in order to win tenders (Hans et al., 2007). In that context, the ability to quickly price tight, reliable due dates affords an outstanding competitive advantage. Therefore, manufacturers need to screen, select, prioritize, and eventually accept or reject inquiries (Carvalho et al., 2015). Under such pressure, manufacturers generally accept orders without sufficiently assessing their potential impact on capacity (Hans et al., 2007). Several factors increase the complexity of such assessment, including significant heterogeneity between customers' inquiries (e.g., in terms of specifications, tooling requirements, routing, and activity work content) and the dependency on common resource pools (Hicks et al., 2000).

After accepting orders, manufacturers perform rough-cut capacity planning, procurement planning, and macro-level process planning. Rough-cut capacity planning can be either proactive or reactive. Researchers such as Wullink et al. (2004) have observed considerable reductions in cost by proactively integrating scenario-based analysis into rough-cut capacity planning as a means to deal with system's complexity and schedule instability. Improvements other than cost minimization can derive from how robustly plans can accommodate disruptions, a challenging metric to quantify. Reactive rough-cut capacity planning is another common practice in ETO operations. For that reason, manufacturers apply replanning protocols upon disruptions or, more commonly, update existing plans more frequently (Hans et al., 2007).

According to Giebels (2000), rough-cut capacity planning has three primary objectives: verifying manufacturing capabilities, determining delivery dates for customers' inquiries, and analyzing expected margins at the multi-project level. Manufacturing capability can be verified by macro-level process planning, which helps to roughly assess how well a firm's resource combinations can deliver products per specifications (Cay & Chassapis, 1997).

Estimating delivery dates requires a detailed analysis of engineering and production workloads as well as lead times, because engineering determines product and production designs, material quantities and specifications, and technologies. For one, planning to source and purchase external contributions (e.g., consultants and subcontractors) is a procurement activity undertaken to complement, enhance, and support engineering and production considering all constraints on internal resources. For another, allocating or loading resources is undertaken to identify capacity-related problems early and activate process planning when necessary (Nobibon et al., 2015). However, for firms performing minimal engineering and production before receiving orders, routings and processing durations of engineering activities lack standard references (Cannas et al., 2019). Ventroux et al. (2018) have suggested reshuffling projects between and within organizations to mitigate increased pressure on concurrent engineering stemming from the lack of such references. Above all, reshuffling aims to maximize the number of interactions supporting critical decision-making and action-oriented processes.

Resource allocation primarily combats schedule instability and substantial uncertainty emanating from the limited commonality among low-volume, project-based production environments. Such uncertainty manifests in the incompleteness and inaccuracy of information related to processing and delivery lead times, problems that often require information technology support. Information technology not only helps to manage scattered, fragmented information in order to optimize resource loading but also enables predictions of lead times given relevant data from previous projects (Govil and Fu, 1999). However, predicting routing and the processing times of engineering activities is usually subject to substantial uncertainty given the lack of the abovementioned standard references.

Consequently, estimating the availability of engineering capacity also entails considerable uncertainty. Engineering activities are highly interdependent and require specialist engineers, which is often costly and scarce due to the need to accumulate expertise over extended periods. Therefore, specialists represent a bottleneck in ETO operations, and manufacturers thus aim to utilize them strategically (Giebels et al., 2000).

To finish rough-cut capacity planning, determining suitable delivery dates for customers' inquiries also requires estimating lead times of internal and external engineering and production activities. Determining production-related lead times requires more operational data regarding, for instance, order priority, the amount of work in process, routing, and batching (Giebels et al., 2000). Once those aspects are determined, estimating margins becomes possible. To avoid suboptimization, making trade-offs at the multi-project level between the cost of acquiring non-regular capacity (e.g., subcontracting) and performance benefits gained is necessary (Gademann & Schutten, 2005). Such trade-offs need, for example, the careful allocation of critical capacity for customers' orders in order to allow more competitive prices, earlier delivery dates, and higher quality (Cooper & Budd, 2007). Even so, pricing also depends on the level of competition. In short, the greater the competition, the narrower the margins.

Procurement is a fundamental tactical-level planning activity in ETO operations. Fulfilling each incoming order from customers requires the customized and timely purchasing of material, technology, transportation, and additional capacity (Olhager, 2010). At the same time, procurement may vary considerably between ETO environments. In complex planning environments, manufacturers cannot establish strategic partnerships with a relatively small number of suppliers (Sabolová & Tkáč, 2015). Strategic partnering affords benefits of scale and scope that translate into lower costs, higher quality, and more flexibility. Accordingly, sourcing and purchasing activities from large supply bases increase the requirements for coordination. Thus, decisions made throughout sourcing and purchasing processes can influence total costs, product specifications, and delivery dates (Gosling et al., 2015).

Last, Giebels et al. (2000) claim that the manufacturing processes required for order fulfillment should be planned at a tactical macro level due to the extended lead times of production engineering and industrialization requirements. *Macro-level process planning* refers to selecting manufacturing processes and conducting related manufacturability analysis. By contrast, *micro-level process planning* refers to selecting and sequencing operations and generating optimal plans for processes (Cay & Chassapis, 1997).

Specialists in macro-level process planning usually possess relevant in-depth engineering knowledge that enables effective rough-cut capacity planning (i.e., allocating technological and logistics capacity, determining process routing, and outsourcing process engineering tasks). Therefore, macro-level process planning has to concurrently support rough-cut capacity planning while dealing with the complexities driven by internal manufacturing (e.g., manufacturing schedule instability), demand (e.g., variability in customers and orders), and supply (e.g., variability in suppliers' lead times). In practice, such concurrency is essential because securing helpful information about the master production schedule, routings, and processing times at the tactical level is challenging unless macro-level process planning is integrated into tactical planning (Giebels et al., 2000).

### 2.2.3. Planning at the tactical level: Sales and operations planning

According to Gelders and Van Wassenhove (1982), tactical-level planning activities integrate a firm's activities hierarchically in two directions: (1) vertically to and from the strategic level to and from operational levels and (2) horizontally (i.e., laterally) across organizational functions. Vertically, tactical-level planning objectives have to be disaggregated from a firm's strategic goals in order to align with business priorities, marketing plans, and core competitive capabilities. At the same time, tactical-level objectives should translate the measured performance of day-to-day activities into corresponding high-level indicators. Such indicators often need longer time horizons to be achieved, including resource utilization and hit rates. High-level indicators help to control customers' demand and the capacity of supply in the pursuit of demand–supply balance.

As with hierarchical production planning, material planning and control are frequently addressed in recent literature as constituting a system that links manufacturing processes across strategic, tactical, and operational levels (e.g., Bower, 2018). Planning horizons, planning objects, and frequencies differ across various planning levels within material planning and control systems; the higher the material planning and control hierarchy, the longer the planning horizon, the lower level of detail, and the more approximate the information (Jonsson & Mattsson, 2009).

At the tactical level, S&OP is an example of a planning process that integrates sales, supply, and production plans into an overall aggregate plan (Noroozi & Wikner, 2017). S&OP has emerged in numerous conceptual forms since the 1950s, including integrated business planning, manufacturing resource planning, aggregated production planning, and demand–supply balancing (Feng et al., 2008; Thomé et al., 2012). However, the majority of scholars have regarded S&OP as a tactical planning process (e.g., Goh & Eldridge, 2019; Kreuter et al., 2021b; Ling & Goddard, 1988; Noroozi & Wikner, 2017; Pereira et al., 2020; Tuomikangas & Kaipia, 2014; Wallace & Stahl, 2008). The Association for Supply Chain Management defines *S&OP* as

> a process to develop tactical plans that provide management the ability to strategically direct its businesses to achieve competitive advantage on a continuous basis by integrating customer-focused marketing plans for new and existing products with the management of the supply chain. The process brings together all the plans for the business (sales, marketing, development, manufacturing, sourcing, and financial) into one integrated set of plans. (Blackstone, Jr., 2010, p. 133)

By syncing demand and supply and integrating hierarchical planning levels and relevant functions, S&OP enables reaching business targets (Tuomikangas & Kaipia, 2014), including profit maximization (Grimson & Pyke, 2007). The literature showcases four variations in S&OP practice: the S&OP setup, the S&OP process, S&OP organization, and S&OP interfaces with other processes.

First, the S&OP setup involves determining the focus of planning (i.e., on an object and in terms of time) and the frequency of planning. Although a highly suitable S&OP planning object is product families (Wallace & Stahl, 2008), some manufacturers may implement S&OP at a stock-keeping unit level or in combination with product families (Thomé et al., 2012). As for the focus on time, the recommended horizon for S&OP is 1–2 years (Blackstone, Jr., 2010). Nevertheless, some studies have shown examples of S&OP with longer and shorter horizons (Kristensen & Jonsson, 2018). As for the frequency of planning, many studies suggest that S&OP is a monthly rolling schedule of activities (Thomé et al., 2012). However, dynamic planning environments may instead require a looser timeline of conducting S&OP twice monthly (Wallace & Stahl, 2008).

Second, the S&OP process varies in terms of activities (Kjellsdotter Ivert et al., 2015), inputs, outcomes (Kristensen & Jonsson, 2018), methods, information systems, and performance measurements (Danese et al., 2017). Although Ling and Goddard (1988) were the first to detail generic S&OP process activities, many studies on S&OP (e.g., Grimson & Pyke, 2007; Noroozi & Wikner, 2017) have been based on the work of Wallace and Stahl (2008) instead. In line with those works, the generic process activities of S&OP involve medium-term demand and supply planning, the alignment of demand- and supply-related plans (i.e., S&OP plan reconciliations), and top management's review of updated plans (i.e., S&OP executive meetings). Figure 2.3 shows generic steps of the S&OP process numbered from 1 to 5; the converging arrows represent relevant flows of information. Unlike in the figure, however, reviewing planned product portfolios sometimes precedes demand planning (Kjellsdotter Ivert et al., 2015). After all, S&OP activities are both individual and collective efforts—through meetings and collaborations—that generate many outcomes in the form of decisions, assessments, and updated plans (Noroozi & Wikner, 2017).

An example of how S&OP inputs vary stems from the possible ways that demand can be planned. For instance, in customer-driven environments such as ETO operations, medium-term demand planning considers forecasted numbers less than assumptions from experts (Olhager, 2010). Beyond that, some S&OP outcomes (e.g., updated finished product inventories) do not apply to many ETO operations (Wallace & Stahl, 2008). A recent literature review has provided comprehensive configurations of generic S&OP activities, inputs, and decisions (Pereira et al., 2020).

The literature that describes S&OP in terms of effectiveness associates several variables of maturity that provide rich insights into variations in methods, information systems, and measurements of performance (e.g., Danese et al., 2017; Feng et al., 2008; Grimson & Pyke, 2007). However, such literature does not elaborate on variations that can derive from contextual variables and problems with implementation (Kreuter et al., 2021a; Kristensen & Jonsson, 2018). For one, *S&OP methods* are the principles and approaches specifying ways to process data and generate and update plans related to demand, supply, and capacity (Danese et al., 2017). For another, *information systems* refer to the means of collecting, processing, and disseminating data required to support S&OP activities in generating intended outcomes. Last, *performance measurement* refers to assessments adopted to evaluate S&OP's effect on performance (Grimson & Pyke, 2007), as this subsection details later.

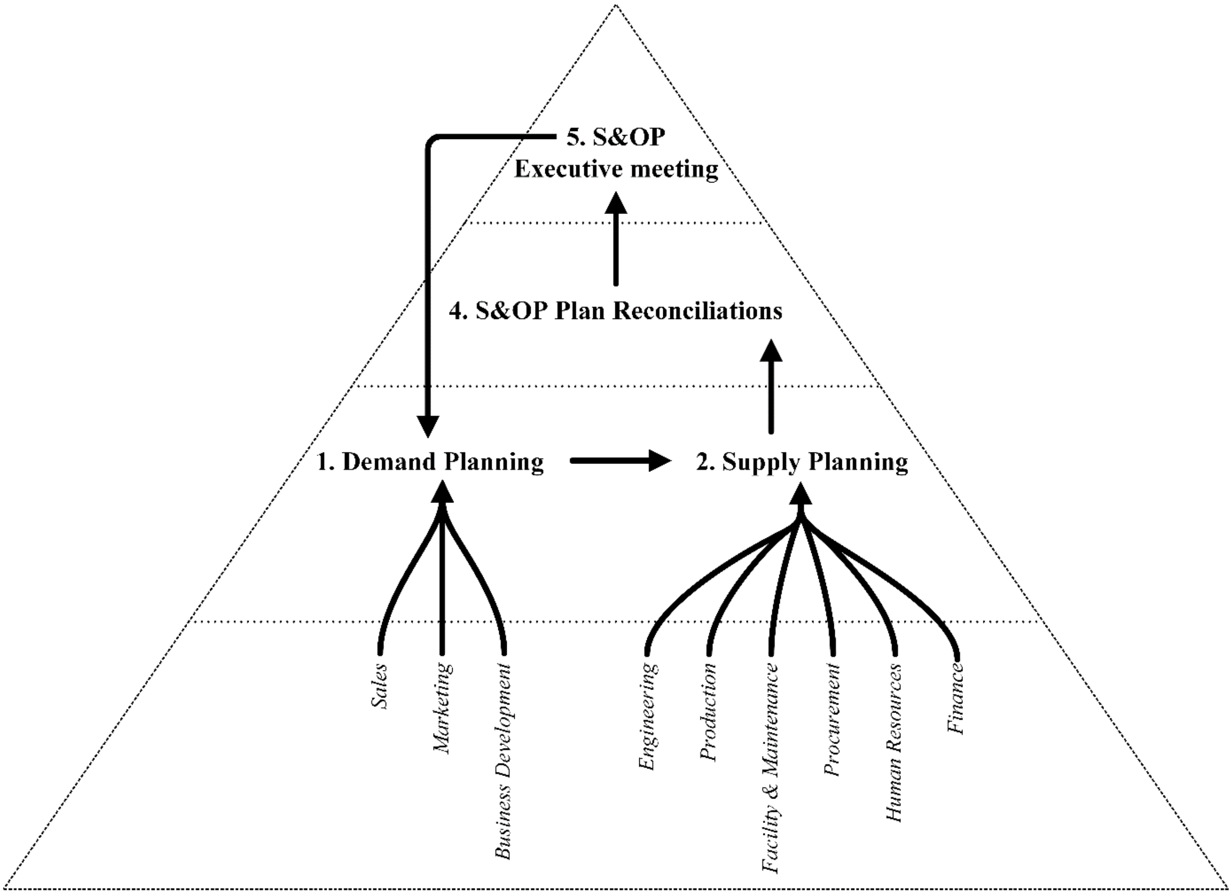



**Figure 2.3.** Generic sales and operations planning (S&OP) process within organizations

Third, as for S&OP organization, the key participants within demand planning activities are usually individuals from sales and marketing functions responsible for generating and reviewing demand forecasts. In supply planning activities, the procurement function is typically in charge of consolidating the forecasts and translating the numbers into projected material requirements for the supply chain. Another supply planning activity is production planning; the production function is responsible for preparing a preliminary production plan. Once the supply plans are ready, pre-S&OP activities commence. Accordingly, managers from the demand- and supply-related functions investigate how to adapt the preliminary plans and escalate unresolved problems to the next S&OP executive meeting. In such meetings, executive managers address escalated problems and make crucial decisions concerning, for instance, the demand intake and associated investments (Wallace & Stahl, 2008).

The involvement of specific competencies and supporting functions other than those mentioned earlier in each S&OP activity varies across planning environments (Kristensen & Jonsson, 2018). Such involvement depends on the need for specific knowledge that generates and validates information during decision-making and the ability to ensure an efficient teamwork environment (Hulthén et al., 2016a; Kjellsdotter Ivert et al., 2015; Oliva & Watson, 2011; Tuomikangas & Kaipia, 2014). The latter is evident in meetings, which may, according to Wallace and Stahl (2008), have various agendas, lengths, participants, review routines, inputs, and outcomes depending on the context. Apart from the hard side of the S&OP organization, other critical soft variables can be executive support, culture, and collaboration (Pereira et al., 2020).

Last, concerning S&OP interface, S&OP interacts with processes other than those associated with medium-term demand and supply planning—for instance, risk management, budgeting, business planning (Noroozi & Wikner, 2017), customer order fulfillment (Pereira et al., 2020), master production schedule, and sales and operations execution (Pukkila, 2016). Those processes vary in horizons, and the respective tactical-level rolling schedules may intersect with S&OP. The setting coordinating the interface between S&OP and other processes varies as well (Tuomikangas & Kaipia, 2014), particularly in their interactivity and intensity (i.e., level of integration). The intensity of coordination ranges from mere reciprocations of inputs and outcomes to dedicated activities within S&OP or the other processes.

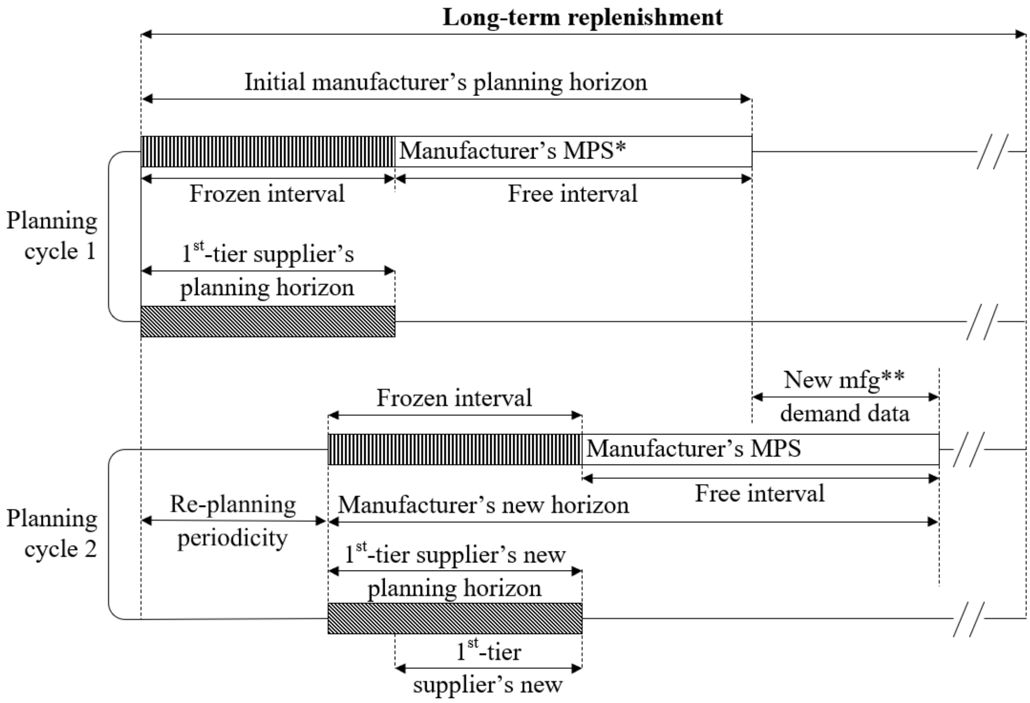
S&OP performance should consider the consequent effects on demand–supply balancing (Feng et al., 2008; Thomé et al., 2012). In that respect, the literature provides objective operational measures and subjective normative measures. There is limited evidence that S&OP results in quantifiable improvements in performance, including inventory turnover, capacity utilization, the reliability of delivery, the flexibility of volume, market share, growth rate, profitability, costs, lead times, and quality (Hulthén et al., 2016a). The challenge is validating increased performance as a direct effect of S&OP according to a chain of evidence. Improvements in performance are usually incrementally accumulated as a result of short-term efforts. By contrast, S&OP's effect typically manifests as increased visibility and support for decision-making processes through cross-functional platforms. Such a challenge has urged authors such as Oliva and Watson (2011) and Tuomikangas and Kaipia (2014) to focus on subjective normative measures, namely the cross-functional integration effect of S&OP.

Oliva and Watson (2011) have suggested four primary variables related to the integrative quality of S&OP: information quality, procedural quality, alignment quality, and quality of constructive engagement. *Information quality* concerns the S&OP's role in facilitating the establishment of bases of appropriate information in terms of content and format to support decision-making. According to Sivadasan et al. (2013, p. 255), information quality ensures "the relevant information on all flows" and that it is "accurate and comprehensive … accessible to the right place, at the right time" and "in the correct format." Next, *procedural quality* concerns the S&OP's role in ensuring sensible inference rules to validate information during decision-making. By contrast, *alignment quality* concerns the S&OP's role in facilitating vertical and horizontal alignments, supporting organizational and functional goals, and synchronizing the consequent actions. Last, the *quality of constructive engagement* concerns the S&OP's role as a facilitator in encouraging relevant participants to actively and effectively engage in collecting, validating, and processing information.

### 2.2.4. Planning at the tactical–operational interface: Material delivery scheduling

The material delivery scheduling process converts short- and medium-term material requirements into scheduled material deliveries from suppliers, all projected on a planning horizon covering more than a year (Li & Disney, 2017). Material requirements planning systems and bills of material usually help to generate and project material requirements over planning periods that divide the horizon evenly (Pujawan, 2008). The delivery schedules previously developed undergo revision whenever a planning period enters the execution phase, and the horizon rolls forward. Consequently, material requirements planning systems update the existing material requirements and, in turn, generate material requirements corresponding to a new planning period following the most distant period of the previous horizon (Carlson et al., 1979).

Figure 2.4 shows a simplified example of a manufacturer that has just revised the material delivery schedule corresponding to the initial planning cycle covering an initial planning horizon. First-tier suppliers receive updated quantities and dates of future deliveries beyond the frozen interval; intervals representing the most imminent customers' orders are already scheduled for production, often in sequence. The frozen interval of the manufacturer's master production schedule represents the minimum horizon of the replenishment schedule of first-tier suppliers. Usually, manufacturers will not alter material quantities or dates within the frozen period. However, such stability requires high-quality internal operations able to absorb disruptions such as equipment breakdowns, labor shortages, and problems with quality (Law & Gunasekaran, 2010).




* Master production schedule, ** Manufacturing

Figure 2.4. Rolling horizon of delivery schedules in supply chains (adapted from Sahin et al., 2013)

When rolling forward to the second planning cycle, the frozen interval moves forward along with the first-tier suppliers' replenishment schedule. *Re-planning periodicity* refers to the number of periods (e.g., days or weeks) between successive replanning events (Herrera et al., 2016). The policy specifying how freezing operates during replanning periodicity depends on the supplier–buyer agreement (Krajewski et al., 2005). Upon entering replanning in the second cycle, manufacturers generate new manufacturing data corresponding to the new horizon's new (i.e., distant) period. Moreover, they revise the material quantities and the delivery dates that first-tier suppliers need to fulfill within the remaining interval that is not yet frozen.

## 2.3. Theories related to complexity management

Complexities in a planning environment can be strategic, non-strategic, or dysfunctional. Because reducing strategic complexity is either impracticable or unfavorable for business growth (Turner et al., 2018), strategic complexity should be absorbed instead (Serdarasan, 2013). On the contrary, reducing non-strategic complexity is a best practice (Rauch et al., 2018). However, such an approach requires drawing a clear borderline to ensure that reduced complexities no strategic importance.

Of the several theoretical perspectives that inform complexity management, this thesis adopts certain established ones to analyze the interface between tactical planning (i.e., customer order fulfillment, S&OP, and material delivery scheduling) and complexity in a planning environment with the goal of demand–supply balance. Those theories are cross-functional integration theory, organizational information-processing theory, process theory, and structured insights into complexity interactions. Subsections 2.3.1–2.3.3 respectively define and describe the perspectives.

### 2.3.1. Cross-functional integration theory

Integration is highly fragmented in the literature regarding its conceptualization, definition, and operationalization (Turkulainen & Ketokivi, 2012). Whereas literature in operations management typically refers to *integration* as the set of practices used in integration efforts, other literature conceptualizes the idea as an organizational state (Sherman et al., 2005). Similar to several previous works (e.g., Turkulainen & Ketokivi, 2012), this thesis differentiates integration from achieved integration with reference to Lawrence and Lorsch's (1967) definition, which holds that *integration* is the state of interdepartmental relations. In this thesis, integration is conceptualized as achieved integration.

Lawrence and Lorsch (1967) have identified two primary aspects of achieved integration: the quality of collaboration among organizational units and the organizational devices used to achieve it. In that sense, increased achieved integration implies that "the organisation works as a unified whole and the capability of the organisation to transfer, process, interpret and exploit information across functional sub-units is frictionless" (Turkulainen & Ketokivi, 2012, p. 450). Such characterization emphasizes high-efficiency information transfer across functions and the thorough use of the information transferred.

At a more abstract level of integration, collaboration and interaction have been proposed by Kahn (1996a) as two key dimensions that bring departments together into a cohesive whole. From that perspective, the way in which cross-functional activities (e.g., communication exchange) are structured represents an interaction. By contrast, the state of cross-departmental relationships—that is, how functions "work together, have mutual understanding, have a common vision, share resources and achieve collective goals" (p. 139)—represents collaboration. Coordination and collaboration have the potential to absorb the negative impact of structural and dynamic complexity on operations (Fernández Campos et al., 2019).

Although this thesis accepts collaboration and interaction as integration-related constructs, the ways in which collaboration and interaction relate to integration are conceptualized somehow differently. *Interaction* does not necessarily refer to structured reciprocal actions. In business contexts, *interaction* is "an occasion when two or more people or things communicate with or react to each other" (Combley, 2011, p 446). That is, interactions are not necessarily structured. Therefore, in this thesis, *interactions* are defined as reciprocal actions that can signal a structured coordination setting or collaborative behavior. In short, cross-functional integration is assumed to be possible via coordination and/or collaboration.

Regarding cross-functional integration, this thesis's scope is limited to the dimension of coordination. One reason is that coordination frequently appears in literature on tactical planning (e.g., Fleischmann & Meyr, 2003; Goh & Eldridge, 2019; Mello Mario, 2015; Mello et al., 2015; Tang, 2010; Tuomikangas & Kaipia, 2014; van Donselaar et al., 2000; Ventroux et al., 2018). Another reason is that studying coordination alone requires extensive investigation due to several related mechanisms. Beyond that, the suitable approach to studying collaboration is somewhat different from how coordination is in fact studied. Studying coordination within a process implies looking into the structure of the underlying interactions. By contrast, studying collaboration implies looking into the affective aspects of integration such as trust (Kahn, 1996a), which needs intensive data collection at the individual level. The depth and intensity of such data are essential to capturing evidence such as emotions and attitudes. In sum, because coordination is a broad area with high relevance in tactical planning nevertheless, collaboration may need to be studied by following a different approach, which makes studying both coordination and collaboration within one study a challenge.

Coordination organizes interactions within and among businesses to achieve a common goal. *Coordination* is "the process of organising the different activities or people involved in something so that they work together effectively" (Combley, 2011, p 177). In line with that conceptualization, Chow et al. (1995) have defined *integration* in logistics as the degree of the coordination of logistics tasks and activities within a firm and across the supply chain.

*Coordination* and *integration* are thus slightly different terms (Oliva & Watson, 2011). Whereas *coordination* is the process of aligning decentralized decisions (e.g., resource allocations) with the system's objectives by securing appropriate information and incentives for various decision-makers across hierarchies (Narayanan & Raman, 2004), *cross-functional integration* more broadly encompasses the determination of the system's objectives themselves (Oliva & Watson, 2011).

In the literature on integration, findings about integrative mechanisms related to coordination are reported to be considerably fragmented. According to Turkulainen and Ketokivi (2012), most researchers studying operation management address integrative practices representing mechanisms, including centralization, standardization, and formalization; cross-functional teams, task design, and integrators; and information systems. In this thesis, those mechanisms, defined as ways "of doing something that is planned or part of a system" (Combley, 2011), help to operationalize the concept of cross-functional integration.

Regarding the mechanisms of centralization, standardization, and formalization, Chow et al. (1995) have defined *centralization* as the distribution of power (i.e., decision-making authority) or the extent to which decisions are made at relatively high hierarchical levels. By contrast, *formalization* refers to the extent to which formal rules and standard policies and procedures govern decisions and working relationships independently of the personal attributes of individuals occupying positions in the structure (Daugherty et al., 1992). Last, *standardization* refers to the similarity in the resources used within a firm or in the way that resources are exchanged across firms (Chow et al., 1995).

As for the mechanisms involving human resources, Holland et al. (2000) have suggested that cross-functional teams, integrators, and task design are fundamental when developing new products. The way in which teams are composed and how their members are aligned and located reflect the quality and degree of integration (Mathieu et al., 2014). Moreover, Nihtilä (1999) has observed that successful firms dedicate individual integrators and cross-functional teams when developing new products in order to communicate product-specific strategic objectives across departments and to facilitate interorganizational interactions with customers and suppliers. Hirunyawipada et al. (2010) have confirmed that the design of a task influences how integrative it can be. Designing integrative tasks requires substantial problem-solving and a high degree of information completeness but offers more possibilities for concurrency between tasks and task cohesion—that is, the division of tasks into specialist and generalist domains (Adler, 1995; Galbraith, 1974a).

Last, information systems represent the medium by which increasingly more organizational interactions occur. The level of support provided by information systems to information-processing tasks within cross-functional interactions also indicates the integrative degree of the systems (Daft & Lengel, 1986).

### 2.3.2. Organizational information-processing theory

Information-processing theory is another theoretical perspective that emphasizes integration within and across organizations. According to the theory, appropriate integration between demand and supply increases the cross-functional utilization of information and transfer efficiency, both of which positively impact decision-making (Daft & Macintosh, 1981). Information-processing theory also maintains that a greater level of task uncertainty implies greater dependence on information from external sources (Galbraith, 1977).

Information-processing theory emerged to address problems with design in large organizations, especially to guide the fulfillment of IPNs (Galbraith, 1970). Its focus is the uncertainty embedded in a firm's business environment. Because such uncertainty can impede integration (i.e., coordination and collaboration), firms need to have sufficient information-processing capacity that matches IPNs usually driven by contextual uncertainties. *Information-processing capacity* refers to an entity's capability to gather, interpret, and synthesize information (Tushman & Nadler, 1978). Failing to match the information-processing capacity with the IPNs generated by uncertainty in a planning environment establishes poor conditions for sound decision-making (March & Simon, 1993).

Matching IPNs and information-processing efficiencies for demand–supply balance is possible through two primary strategies: reducing the information required to coordinate planning activities and increasing the capacity to process more information (Galbraith, 1973). Usually, firms apply combinations of those two strategies (Gattiker, 2007). Departing from a contingency perspective (see Sousa and Voss (2008)), in this thesis the internal organizational processes are assumed to be dynamic and adaptable, whereas the external business environment is considered to be static. Consequently, the information-processing strategies highlighted earlier turn into mechanisms that heavily influence internal planning environments. Those mechanisms either boost information-processing capacity (e.g., information systems and lateral relations) or minimize the uncertainty of the IPNs (e.g., self-contained tasks and slack resources).

Information systems encompass both the information technology and people who use such technology in operations. Firms aim to increase those resources' capacity to acquire and utilize additional information. In lateral relations, firms apply various mechanisms of cross-functional integration to increase discretion at lower levels of the organization, thereby allowing decisions to be made at the point where the information originates (Galbraith, 1973).

There are various types of slack resources: the additional time that customers have to wait, underutilized person-hours and machine time, in-process inventory, and higher costs. Typically, slack resources are hidden amid increased resource availability due to unexplored ways of better achieving efficiency (Galbraith, 1977). As for creating self-contained tasks, the focus is minimizing the escalation of decisions upward in the organizational hierarchy. Using self-contained tasks, organizational shift from an input- to output-based task design—that is, from functional to autonomous product-based units located in different places (Galbraith, 1974b).

Each IPM is subject to contingency and has both benefits and costs. Usually, firms gravitate toward low-cost IPMs that produce the most benefits (Galbraith, 1970). However, various mechanisms can be used to effectively manage low-level uncertainty and serve as prerequisites for implementing the IPMs described earlier: suitable hierarchies of authority, rules and procedures, planning and goals, and spans of control (Galbraith, 1977).

### 2.3.3. Process theory and complexity interactions

Process theory suggests several principles, two of which concern variations and complexity in processes: that variations exist in all "inputs, tasks, and outputs" and occur in "quality, quantity, and timing" that "can be buffered by a combination of … time, inventory, and capacity" (Holweg et al., 2018, p. 89). In Shewhart's (1926) classic view on variations in a process, variations are attributable to common causes or assignable causes. Common-cause variations are random and unpredictable, whereas assignable-cause variations are non-random, manageable variations caused by identifiable factors with well-defined characteristics.

In any process, complexity is "a function of the number of static elements (structure) ..., their heterogeneity, and their dynamic interactions" (Holweg et al., 2018, p. 129). Therein, each complexity interaction represents a direct relationship between two variables (Serdarasan, 2013), each of which involves a driver of structural complexity and a driver of dynamic complexity (Bozarth et al., 2009). Of them, structural complexity has two categories: variety and numerousness.

Dittfeld et al. (2018) have suggested a comprehensive structure of three types of interaction that enhance the visibility of complexity's development: horizontal, vertical, and diagonal. Regarding vertical interactions, those authors delineate boundaries separating the levels of environments, supply chains as underlying self-organizing systems seeking equilibrium, and plants along the supply chains. This thesis slightly refines that vertical structure in line with its perspective on focal firms to suit demand–supply balancing. As such, it posits the plant level as a focal environment of internal operations influenced by external variables of complexity in demand–supply environments such as supply chains. By extension, it recognizes three levels of vertical interactions: demand, internal operations, and the supply chain. Accordingly, there are no direct interactions between demand and supply chain environments; such interactions have to descend from the demand environment to the supply chain environment, or vice versa (i.e., ascend through internal operations). Separating the environments as the source of complexity into demand-related and supply-related interactions also suits the dyadic perspective and helps to operationalize complexity. Prominent studies on managing supply chain complexity have adopted a similar structure (e.g., Bozarth et al., 2009).

By contrast, a horizontal interaction connects two variables within the same vertical level and across three horizontal levels: dynamic complexity, variety, and numerousness. Variety mediates the development of complexity toward the levels of dynamic complexity and numerousness. In other words, numerousness and dynamic complexity have no direct interactions connecting them.

Last, diagonal interactions represent a direct relationship between two variables from different hierarchical and vertical levels (Dittfeld et al., 2018).

## 2.4. Tactical planning to manage demand–supply balancing in complex manufacturing operations

This subsection situates the relevance of the three RQs within the conceptual framework of this thesis (see Figure 2.1) in light of relevant contributions from the literature. The RQs address the interfaces between the planning processes in the framework and the complexity emanating from complex manufacturing operations therein.

### 2.4.1. Customer order fulfillment and complexity in engineer-to-order operations

As presented earlier, ETO operations are complex planning environments for demand–supply balancing at the strategic–tactical interface, and the customer order fulfillment process encompasses activities and decisions relevant at that level. However, customer order fulfillment is generally not formalized as a tactical-level planning process, as in the case of S&OP, for instance. A chief benefit of such formality is setting demand–supply balancing as an explicit business objective (Grimson & Pyke, 2007). Such clarity encourages managers of various functional units to jointly balance demand and supply and fulfill overall business objectives over the medium and long term (e.g., Oliva & Watson, 2011).

Many environments of ETO operations do not implement a formal tactical-level planning process such as S&OP. The capital goods and construction industries are examples of such environments due to extended lead times and the rareness of parallel orders, among other reasons. In such industries, manufacturers mostly need to focus on longer-term demand–supply balancing because the complexity of handling order fulfillment within shorter time frames—that is, for planned and ongoing projects—is considerably less challenging (Rauch et al., 2018). Therein, customer order fulfillment stands out as a strong candidate for tactical-level planning.

As described in Subsection 2.2.2, studies on ETO have identified four tactical-level planning processes equivalent to the S&OP subprocesses: order acceptance, rough-cut capacity planning, procurement, and macro-level process planning (Hans et al., 2007). However, such studies have not comprehensively described those individual subprocesses as an integrated whole or explicitly highlight associated planning activities and decisions relevant to demand–supply balancing. Establishing integrated planning processes nevertheless requires clear descriptions of choices, purposes, restrictions, and acceptable uses of optimization algorithms (Fleischmann & Meyr, 2003; Kjellsdotter Ivert & Jonsson, 2014).

Another research trajectory has proposed reference frameworks for customer order fulfillment processes in relation to ETO operations (e.g., Adrodegari et al., 2015; Weber et al., 2000). However, the frameworks do not distinguish between the various decoupling settings of ETO operations. Even though they describe activities and decisions, from tender requests to final cost assessments upon order completion, the delineation within the process from the perspective of hierarchical production planning is not explicit and leaves much to speculation regarding whether the different processes' activities and decisions are strategic, tactical, or operational. Such boundaries help planners to predict the impact of their choices and focus on medium-term problems instead of getting stuck in near-term firefighting (Gansterer, 2015).

As mentioned, RQ1 implicitly addresses how ETO characteristics influence the demand–supply balancing role of the customer order fulfillment process. In Figure 2.5, the arrow between customer order fulfillment and complexity is thus double-headed; one direction indicates how the complexity of ETO operations affects the customer order fulfillment process, whereas the other indicates the impact of tactical-level decisions and mechanisms of cross-functional integration generated by tactical-level activities on structural and dynamic complexity. Applying the perspective of cross-functional integration helps to highlight the customer order fulfillment configurations that allow processing the growing complexity in a planning environment (Tuomikangas & Kaipia, 2014).

### 2.4.2. Sales and operations planning and complexity in engineer-to-order operations

As described in Subsection 2.2.3, S&OP has been widely regarded as a tactical-level planning process dedicated to medium-term demand–supply balancing (e.g., Jonsson & Holmström, 2016; Noroozi & Wikner, 2017; Pereira et al., 2020; Tuomikangas & Kaipia, 2014). S&OP has indeed received considerable attention in the past decade (e.g., Ben Ali et al., 2019; Hulthén et al., 2016a; Kreuter et al., 2021a; Kristensen & Jonsson, 2018; Noroozi & Wikner, 2017; Pereira et al., 2020; Tuomikangas & Kaipia, 2014), and a few studies have generated configurational insights into how S&OP can address uncertainties in ETO operations (e.g., Bhalla et al., 2021; Christogiannis, 2014; Kymäläinen, 2020; Romão et al., 2021; Sharma, 2017). However, the contributions of those studies are highly practice-oriented and provide case-specific recommendations. Other studies have associated S&OP with ETO characteristics and attributed a few contextual variations to the increased importance of estimating capacity availability compared with estimating inventory (Ling & Goddard, 1988; Olhager, 2010; Wallace & Stahl, 2008). Although those works help to clarify various basics and principles for S&OP prerequisites in ETO operations, research on S&OP addressing context-dependent process configurations in other operational environments also reveals substantial limitations (Kreuter et al., 2021a; Kristensen & Jonsson, 2018). Therefore, in general, such literature presents highly fragmented knowledge that lacks theoretical support and guidance concerning how to configure S&OP in various ETO environments.

Earlier subsections have underscored the need for S&OP to identify and respond to the medium-term significance of engineering capacity in terms of type and quantity. Such actions are necessary because engineering capacity's significance varies depending on how ETO markets evolve in the short term. In addition, obtaining and training personnel with engineering competencies are often time-consuming processes (Shurrab et al., 2020a). Therefore, overlooking the variability in the need for critical engineering capacity in a tactical-level planning process such as S&OP limits its demand–supply balancing capability and thus entails substantial costs (Olhager, 2010). Furthermore, planning environments vary substantially even within the ETO environment. For example, Gosling et al. (2017) have presented cases of ETO operations that entail design activities of varying intensity after orders are received. Such intensity refers to the amount of engineering and production activities required for to fulfill demand; as the intensity increases or decreases, managerial approaches other than those adopted may become more suitable (Cannas et al., 2019).

That contingency also applies to how well S&OP configurations suit the context depending on the level of underlying uncertainty (Kreuter et al., 2021a; Kristensen & Jonsson, 2018). Because customization entails varying levels of uncertainty in different areas across various ETO operations (Johnsen & Hvam, 2018), rules for configuring S&OP should consider the specificities of various ETO environments. Therefore, RQ2 of this thesis addresses the interface between uncertainties in ETO operations and S&OP configurations, and the double-headed arrow in Figure 2.5 indicates that the focus of RQ2 is twofold. One direction addresses variations in uncertainties emanating from ETO operations relevant to S&OP, whereas the other addresses the impact of various S&OP configurations on those uncertainties. Both directions are investigated in this thesis using information-processing theory as a theoretical lens.

Resource dependency theory and information-processing theory explicitly associate cross-functional integration with improved performance. Whereas resource dependency theory revolves around departmentalization and how it prevents resources from completing tasks autonomously (Clark & Fujimoto, 1991; Cooper, 1983; Salancik & Pfeffer, 1978), the latter, more comprehensive information-processing theory captures resource interdependency from an informational perspective, namely by focusing on increased task uncertainty that leads to an increased dependence on information from other functions and external sources (Galbraith, 1977).

Context-fitted S&OP represents an information-processing problem, and information-processing theory has promising theoretical and practical implications concerning the configuration of processes. Consequently, taking the perspective of information processing may reveal rich insights, especially into the information-processing prerequisites of demand–supply balancing in ETO operations. Information-processing theory additionally suggests that uncertainties in a firm's context form the IPNs that the firm has to manage (Tushman & Nadler, 1978). Translating those uncertainties in ETO operations into IPNs is thus part of the scope of RQ2. The other part concerns capturing the IPMs generated by the S&OP process in terms of activities and decisions.

Although no work in the literature investigates uncertainty in ETO operations using information-processing theory, several contributions to the broader area of operations planning and control have adopted the information-processing perspective. Using Simon's (1957) theory of cognitive limits, Galbraith (1974b) analyzed the role of planning from an information-processing perspective and postulated that planning is the foundation for organizational interventions such as group problem-solving and information systems. Later, Rogers et al. (1999) observed that the selection of a strategy shapes the types and amounts of information necessary for planning and moderates its effect on results. Since then, Gattiker (2007) found that planning information systems and their possibilities for enhancing coordination are evident amid high interdependence between marketing and manufacturing. Such a characteristic is typical of ETO operations (Birkie & Trucco, 2016). Grabot et al. (2011) also observed that the configurations of planning processes are inadequate if they fail to consider sociotechnical specificities such as trust, the distribution of power, and mutual understanding. Added to that, Srinivasan and Swink (2015) concluded that the firm's planning capabilities have to be comprehensive in order to achieve outstanding performance through investments in technology and integration. More recently, Srinivasan and Swink (2018) found that the visibility of demand and supply represents a prerequisite for improving performance via analytics capabilities. The benefits of such visibility are increasingly attainable when maintaining capacity to efficiently and quickly apply the consequent analytics-generated results. Most recently, Schlegel et al. (2020) identified options for managing uncertainties and resultant IPNs that big data analytics enable for S&OP.

Although all of those contributions depart from an information-processing perspective, their insights into the causality of uncertainties in a complex environment such as ETO operations and corresponding IPNs relevant to demand–supply balancing are limited. Moreover, despite the relevance of that dynamic, no work in the literature generally analyzes the role of cross-functional integration and of corresponding IPMs in S&OP from an information-processing perspective.

### 2.4.3. Material delivery scheduling and complexity in configure-to-order operations

As described in Subsection 2.1.2, the complexity in medium-mix, high-volume CTO operations is challenging for material demand–supply balancing at the tactical–operational interface. The challenge stems from the need for tight synchronization in sectors in which supply chains compete (Li et al., 2015; Stock et al., 1998). The supply chains in such sectors—for example, automotive supply chains (Gansterer, 2015; Lalami et al., 2017; Simchi-Levi et al., 2015)—have large bases because the final products are complex and have expansive production configurations (Rezapour et al., 2017). Therefore, medium-term demand–supply balancing in medium-mix, high-volume CTO operations has to ensure minimal short-term variations across the supply chain (i.e., minimal bullwhip effects). In that respect, material delivery scheduling is considered to be a relevant process in many studies (e.g., Atadeniz & Sridharan, 2019; Blackburn et al., 1985; Carlson et al., 1979; Filho & Fernandes, 2009; Heisig, 2002; Ho, 1989, 2002, 2008; Ho & Carter, 1996; Ho & Ireland, 1998; Ho, 1993; Ho et al., 1992; Kabak & Ornek, 2009; Kadipasaoglu & Sridharan, 1997; Kadipasaoglu & Sridharan, 1995; Law & Gunasekaran, 2010; Lee & Adam, 1986; Li & Disney, 2017; Pujawan, 2004; Sridharan & Lawrence LaForge, 1990; Steele, 1975; Tang & Grubbström, 2002; van Donselaar et al., 2000; van Donselaar & Gubbels, 2002; Zhao et al., 2001; Zhao & Lam, 1997; Zhao & Lee, 1993). All of those studies focus on the phenomenon of material delivery schedule instability as an indicator of demand–supply balancing failure. Accordingly, that phenomenon is the focus of RQ3 in this thesis.

Figure 2.5 shows RQ3 as a one-headed arrow moving from the planning environment of CTO operations to the material delivery scheduling process. The question focuses on the impact of complexity in CTO operations and of the process design of material scheduling on the development of variation or instability in material delivery schedules. Sivadasan et al. (2013), who argue that identifying the factors of schedule instability is necessary for experimental research, have expanded the essential input of optimization models to test strategies and policies in order to minimize instability. Past studies have also identified many factors that cause or moderate schedule instability upstream in the supply chain. However, insights into selected factors such as lot sizing and schedule freezing are available only as fragmented and experimental inferences based on dummy data in most publications, as reviewed in Subsection 2.1.2.

By contrast, a few studies have produced more comprehensive frameworks elicited from empirical data, a necessity for advancing knowledge about the dynamics of material delivery scheduling (Sahin et al., 2013). The earliest was Inman and Gonsalvez's (1997) work, which offers several plausible explanations of material delivery schedule instability. Nevertheless, some of the identified reasons are outdated in current operations planning systems. Pujawan and Smart (2012) and Law and Gunasekaran (2010) have additionally examined the relationship between schedule instability and factors emanating from internal processes and external relationships. In a more recent study, Pujawan et al. (2014) enriched the discussion of variations leading to schedule instability by first pinpointing relevant factors, predictable consequences, and mitigation strategies from the literature. Then, they conducted a multiple-case study that led to propositions highlighting the impact of supply chain characteristics and cross-functional integration on schedule instability.

Even so, the cited contributions do not explicitly identify the impact on instability in terms of causality (i.e., mediation) or amplification (i.e., moderation). However, such clarity is essential to constructing models with acceptable internal validity (Hayes, 2017) that can be used to test strategies for mitigating instability. Beyond that, those studies have provided highly practical context-specific insights that nevertheless lack a theoretical basis to enhance generalizability. Therefore, RQ3 adopts two theoretical perspectives: complexity and process.

As shown in Figure 2.4, a framework for analyzing complexity interactions was adapted for this thesis from a perspective proposed by Dittfeld et al. (2018). The framework incorporates relationships between variables representing dynamic complexity interactions highlighted in past research. The focus on the dynamic dimension of complexity is due to the ambiguity of how schedule instability develops as a phenomenon. Above all, that ambiguity represents the area examined in this thesis that lacks understanding (Sahin et al., 2013). Even then, the interface of structural and dynamic complexity is part of RQ3's scope; however, that scope considers only the subdimension of variety concerning the impact of underlying variables on dynamic complexity.

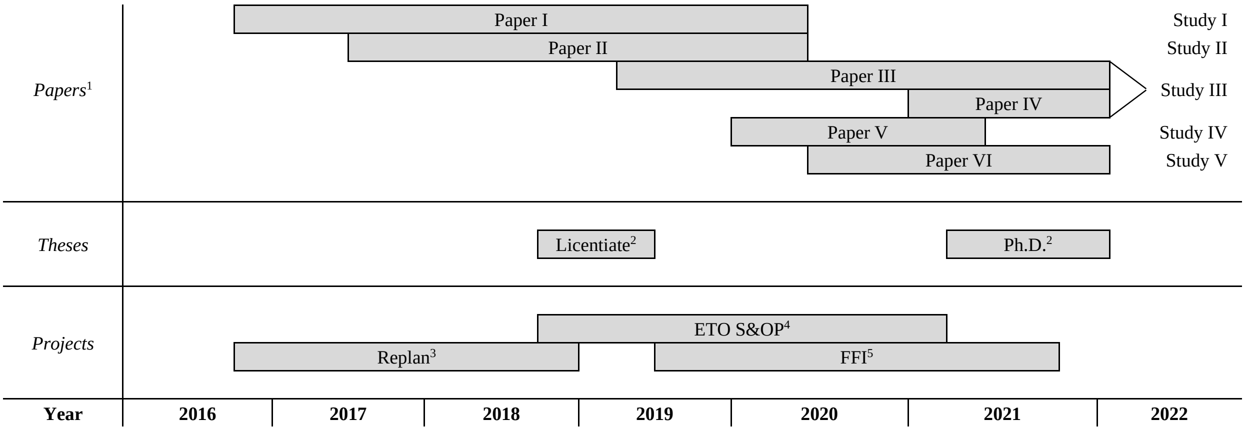
In this thesis, Holweg et al.'s (2018) process theory is applied to visualize the complexity interactions identified in terms of variations that originate from the planning process's design and context. Such a perspective theoretically strengthens the results and helps to operationalize the knowledge generated, thereby closing the gap between theory and practice.

# 3. Methodology

This chapter describes the research methods used in the five studies that form the basis of this thesis and that resulted in six research papers. The following four subsections organize the details of the methods. Section 3.1 describes the research process; Section 3.2 describes the research design that guided the research process throughout the thesis; Section 3.3 describes the research methods, the reasons for selecting them to address the research problems, and how they were applied; and Section 3.4 serves as an assessment of the validity and reliability of the adopted methods.

## 3.1. Research process

This thesis represents the result of 5 years of research. This subsection summarizes the research activities done during that period, as shown in Figure 3.1.




[1] The period extends to the date of the manuscript's acceptance by the journal, if applicable. If the paper has not yet been accepted, then the period end refers to the date when the latest revised version was submitted for review. The work included in the papers' periods comprises planning, data collection, and writing. All papers were revised multiple times.
[2] The writing period of the cover paper
[3] Resource-efficient planning for competitive production networks (i.e., Phase B)
[4] Engineer-to-order sales and operations planning
[5] Future of sharing schedule information in automotive industry supply chains using advanced data analytics

**Figure 3.1.** Timeline of the research process

My doctoral study commenced at the beginning of September 2016 and ended in October 2021. During that 5-year period, I was a member of three research projects respectively funded by Vinnova (i.e., Sweden's innovation agency), Chalmers University of Technology, and Fordonsstrategisk forskning och Innovation ('Vehicle Strategic, Research and Innovation,' FFI), a partnership program between Vinnova and the Swedish automotive industry. The project that started first, Replan, was funded by Vinnova, while the project that ended last was part of FFI's program. Between them, and partly overlapping both, I organized and propelled a relatively minor project financed by Chalmers dedicated exclusively to Study III (i.e., on S&OP in ETO environments). All three projects represented collaborations between academia and industry.

The first project that this thesis draws on was Replan, which was officially titled "Resource-Efficient Planning for Competitive Production Networks: Phase B" and occurred between 2015 and 2018. Replan aimed to explore the benefits that tactical planning offers the loosely coupled systems used by many manufacturers in the construction and recycling industries. The project was a collaboration between academic partners (i.e., Chalmers University of Technology and Linköping University) and industrial partners (i.e., NCC, Arcona, Ragn-Sells, Optimity, Stiftelsen Chalmers Industriteknik, and

Vico Software). I joined the project in the middle of its second phase (i.e., Phase B).

The second project was ETO S&OP, which occurred between 2018 and 2021. The project started as a collaboration with the aerospace industry and later expanded to four more ETO-oriented industries facing similar tactical planning challenges. To a great extent, I used the findings of the research conducted within Replan and some findings associated with ETO S&OP as the basis for my licentiate thesis, which focused on tactical planning in ETO environments. It was published on May 20, 2019, and presented on June 10, 2019.

The third project was FFI, or officially titled "Future of Sharing Schedule Information in Automotive Industry Supply Chains Using Advanced Data Analytics." The project occurred between 2018 and 2021 and targeted delivery schedule (in)accuracies. The project represented a collaboration between Chalmers University of Technology as the academic partner and several industrial partners (i.e., Volvo Group, Volvo Cars, Scania, Veoneer, Automotive Components Floby, Bulten, Heléns Rör, Meridion, Odette, and Plasman). I joined the project in the post-licentiate period starting in September 2019.

Tactical-level planning processes to manage complexity were not the only elements of the Replan and FFI projects. The research conducted within each project is illustrated in Figure 3.1 as studies. Study I, part of Replan's scope, began as an in-depth single-case study that led to Paper I. Study II expanded the sample used by Study I to cover multiple cases represented by firms beyond the members of the project constellation in order to enhance the findings' external validity. Study III embraced ETO-S&OP's scope, and Studies IV and V were part of FFI's scope. Study III generated Papers III and IV, and Studies IV and V resulted in Papers V and VI.

Paper II introduces the need to venture beyond planning activities to investigate the mechanisms of cross-functional integration that contribute to complexity management. Therefore, Paper II was written several months after Paper I was initiated. Those two papers and the whole Replan project focused on loosely coupled systems that have not implemented a formalized process for tactical planning such as S&OP. At the same time, because literature describing S&OP in ETO environments was nearly nonexistent, the authors of Papers III and IV, me included, began looking for examples of that topic, which eventually led to an initiative with a company in the aerospace sector. The project took a form of a single-case study that later developed into a multiple-case study. The study's findings led to Papers III and IV, which respectively focus on information-processing needs and information-processing mechanisms.

Studies IV and V were conducted to expand the knowledge of the development of instability in material delivery schedules. Therefore, the work on Paper V began with an inductive investigation concerning the potential variables and relationships involved in the phenomenon. Identified relationships were then modeled and tested a few months later. The findings of such testing are documented in Paper VI.

## 3.2. Research design

The research design of this thesis included the three RQs mentioned earlier, five primary studies, and several methods of data collection and analysis and strategies for ensuring a certain level of validity and reliability in the results (Bell et al., 2018). Following the guidance of the research design, the research primarily adopted a qualitative approach based on case studies. By contrast, a quantitative approach was adopted in Study V (Hayes, 2017). According to Flick (2009), qualitative research design entails determining the RQs, objectives, theoretical frameworks, and empirical data collection given available resources.

RQs represent fundamental components of a research design enclosed and shaped by a conceptual framework, goals, and methods (Maxwell, 2012). This thesis's RQs and each paper's scope and purpose were influenced by the current state of practice and the literature. The research project partners allowed for continuous practical assessment, and the issues raised by the industrial partners have been matched with available literature to verify the need for additional investigation. Therefore, the RQs were under constant development in line with changes in the selected methods, purpose, and theoretical frame of reference. Table 3.2 illustrates the relationships between the RQs, the studies, and the papers.

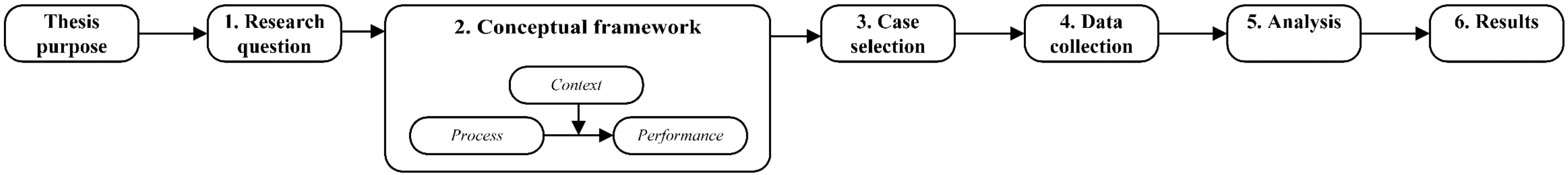
Both theory and practice allowed developing the theoretical framework presented in Figure 2.1. An obvious example is the specifically selected contexts of high-mix, low-volume ETO operations and medium-mix, high-volume CTO operations described in Section 2.1. Another example is the series of specifically selected processes described in Section 2.2. As shown in Chapter 2, planning in production systems and supply chains impacts demand–supply balancing at various hierarchical levels. Although this thesis focuses on relationships between planning processes and demand–supply balancing, the literature confirms that such relationships cannot be perfectly understood without considering the planning environment. Therefore, the context has been accounted for from the outset of the research process, wherever relationships between planning and demand–supply balancing cannot be adequately understood. In that way, the research projects and the literature have influenced the thesis's account of the tactical planning context.

The methods applied were selected in line with the research problems. I collected empirical data through an in-depth single-case study, three in-depth multiple-case studies, and a modeling study to answer the RQs. The case study method was the chosen approach because knowledge concerning tactical planning in ETO and CTO operations has been scarce and because case research is thought to help to clarify poorly understood phenomena (Yin, 2009). A literature review, conducted and continuously updated throughout the research process for each study, served as a foundation for empirical data collection.

## 3.3. Research studies and methods

Five primary studies yielded six research papers—that is, one paper per study except for Study III, which generated Papers III and IV. In all five studies, some sort of case-study design was adopted, for several reasons. First, case studies provide empirical evidence that facilitates the refinement of theory (Eisenhardt, 1989) and generate rich insights into the contemporary dynamics of a phenomenon (Yin, 2009). Second, case studies uphold the tradition of triangulation supported by the possibility of clarifying questions that together make data collection from several sources a common research practice (Flick, 2009). According to Meredith (1998), triangulation increases the validity of research, and Eisenhardt (1989) has posited that triangulation also enables verifying constructs and propositions. Third, case studies can produce rich managerial knowledge due to engaging several experienced managers (Gibbert et al., 2008). Fourth, case studies are recommended by several notable researchers in operations management for developing or extending theories in operations management (e.g., McCutcheon & Meredith, 1993; Sousa & Voss, 2008; Stuart et al., 2002; Voss et al., 2002).

Studies I–IV adhered to similar research processes to fulfill the thesis's purpose through exploratory investigations, whereas Study V adopted an explanatory quantitative approach; see the overview presented in Figure 3.2.




| **Research process** | | **Study I** | **Study II** | **Study III** | **Study IV** | **Study V** |
|---|---|---|---|---|---|---|
| **1. Research question** | Research question (RQ): | RQ1 (Decisions and activities) | RQ1 (Cross-functional integration) | RQ2 (Information-processing needs and mechanisms) | RQ3 (Development of schedule instability) | RQ3 (Development of schedule instability) |
| | *Unit of analysis*: | Customer order fulfillment process (acceptance phase) | Customer order fulfillment process (acceptance phase) | Sales and operations planning process | Material delivery scheduling | Material delivery scheduling |
| | *Approach* | Exploratory | Exploratory | Exploratory | Exploratory | Explanatory |
| **2. Conceptual framework** | *Process*: | Medium-term decisions | Integration mechanisms | Information-processing mechanisms | Complexity drivers and process design | Operating variables |
| | *Context*: | Structural and dynamic complexity | Structural and dynamic complexity | Information-processing needs | Structural and dynamic complexity, process context | Operating conditions |
| | *Performance*: | Overcapacity, undercapacity, demand–supply balance | Overcapacity, undercapacity, demand–supply balance | Planning quality | Delivery schedule instability | Schedule inaccuracy |
| **3. Case selection** | *Data inquiry*: | Single, embedded, in-depth | Multiple (4), in-depth | Multiple (4), in-depth | Multiple (4), in-depth | Single, quantitative |
| | *Homogeneity*: | Engineer-to-order, tender-orientation | Engineer-to-order, tender-orientation | Engineer-to-order, sales and operations planning, large firm, high performing | Configure-to-order, automotive OEM, supply chain complexity | - |
| | *Heterogeneity*: | Decoupling | Decoupling, supply chain complexity, integration | Decoupling, uncertainty, process maturity, competition | Planning parameters | - |
| **4. Primary data** | *Interview*: | 1,320 minutes | 2,430 minutes | 2,910 minutes | 3,030 minutes | - |
| | *Quantitative:* | - | - | - | - | 16.5 million transactions |
| | *Respondents*: | 10 managers | 19 managers | 28 managers | 9 managers | - |
| **5. Data analysis** | *Approach*: | a. *Embedded case analyses*: Process per case<br>b. *Cross-category analysis*: Process vs. complexity | a. *Within-case analyses*: Process mechanisms per case<br>b. *Cross-case analysis*: Integration mechanisms vs. complexity | a. *Within-case analyses*: Processing needs and mechanisms per case<br>b. *Cross-case analysis*: Needs vs. mechanisms, planning quality | a. *Within-case analyses*: Complexity interactions per case<br>b. *Cross-case analysis*: Instability causes and moderators | a. Qualitative (root-cause) analysis<br>b. Correlation analyses<br>c. Logistic regression analysis |
| **6. Results** | *Preliminary*: | EurOMA 2017 | NOFOMA 2018 | EurOMA 2019, IWSPE 2020 | NOFOMA 2020 | EurOMA 2021 |

*Note.* EurOMA = European Operations Management Association, NOFOMA = Nordic Logistics Research Network, IWSPE = International Workshop Seminar on Production Economics, OEM = original equipment manufacturer

**Figure 3.2.** Research design overview of Studies I–V

### 3.3.1. Research approach, research questions, and conceptual frameworks

The thesis's RQs are exploratory in nature. As shown in Chapter 2, the literature on tactical planning in ETO operations relating explicitly to demand–supply balancing is scarce. Therefore, a substantial in-depth analysis was needed to understand the interplay between planning and complexity (Eisenhardt, 1989), as fulfilled in Studies I–III by following case-study designs. Similarly, Study IV was based on a case-study design in light of the fragmentation of literature concerning factors of instability, material delivery scheduling, and the need for qualitative empirical research in the specific area, as Sahin et al. (2013) have recommended. Last, Study V followed a single-case design due to the massive amount of data that needed to be collected, including historical transactions of material deliveries during a 2-year period and qualitative data about case-specific causal factors of instability.

Studies II–IV were based on multiple cases. Multiple-case studies are suitable for exploring mechanisms that describe the development of phenomena (Yin, 2009). As for Study I, an embedded single-case approach was adopted to gain a comprehensive, detailed understanding of a planning process beyond merely the mechanisms and interactions therein (Eisenhardt, 1989). Empirically rich, context-specific, and holistic, single cases allow for in-depth analyses and valuable contributions to the construction of theory (Stake, 2000). In particular, single-case studies expand analytic generalizations to theoretical propositions without extrapolating probabilities and statistical inferences to populations (Yin, 2009).

Studies I and II followed exploratory theory-building approaches to illuminate the interplay between the customer order fulfillment process, represented by medium-term planning decisions and mechanisms of cross-functional integration, and the complexity influencing demand–supply balancing. The two studies answered RQ1.

Next, Study III addressed S&OP in ETO operations following an inductive, exploratory approach to answer RQ2. As presented in Chapter 2, context-fitted S&OP as a phenomenon lacks empirical and conceptual contributions in the literature, especially regarding ETO operations and from a perspective such as information processing (Kreuter et al., 2021b; Kristensen & Jonsson, 2018). The case-study method came into play to explore contextual needs and process mechanisms as well as to elaborate theory because managing ETO uncertainty requires substantial theoretical contributions (Shurrab et al., 2020a). Such insights are a prerequisite for applying information-processing theory in effective S&OP designs (Rogers et al., 1999).

After that, to answer RQ3, Study IV comprehensively investigated the causes of instability within the process of material delivery scheduling. A considerable depth of data inquiry was necessary to connect identified factors of instability as chained cause-and-effect events related to dynamic complexity interactions. Drawing on the results, the study also involved expanding generalizations from analysis into theoretical propositions (Yin, 2009).

Last, contributing to RQ3, Study V built on Study IV to explain how causal factors generate inaccuracies in forecasted material delivery schedules.

Each case study departed from a theoretically grounded framework (Eisenhardt, 1989) that supplied the building blocks of the thesis's framework presented in Figure 2.1 and described in Chapter 2. The framework comprises process-, context-, and performance-related constructs. The relationships between the constructs followed the structure displayed in Figure 3.2, wherein context moderates the process's impact on performance.

### 3.3.2. Case selection

Generating knowledge from case research is possible by studying heterogeneous and homogeneous case characteristics to ensure theoretical representation, increase the generalizability of findings, and deepen the analysis (Voss et al., 2002). More specifically, incorporating additional cases has value if it highlights or reduces the differences between the research units (Yin, 2009). Therefore, the selected cases in Studies II–IV and embedded cases in Study I needed to fulfill criteria relevant to variables of interest in the research.

For Study I, a general contractor from the construction industry that managed customers' orders with varying complexity was selected to ensure cross-case heterogeneity and increase the generalizability of the findings. According to Cannas et al. (2019), to be adequate, managerial approaches such as planning practices have to meet the requirements of specific ETO decoupling settings (Cannas et al., 2019). In that respect, many actors in the construction industry, especially general contractors, need operations that encompass a broad set of engineering decoupling configurations, including research-to-order, develop-to-order, design-to-order, modify-to-order, and combine-to-order configurations (Gosling et al., 2017). The construction solutions offer deep structures with extensive scopes of customization that entail substantial exceptionality across orders and between project-based manufacturing processes (Gosling et al., 2015). General contractors serve as OEMs in supply chains because they choose tender requests and providers, determine manufacturing methods, and direct deliveries within the customer order fulfillment process (Hicks et al., 2001).

To some extent, the selected general contractor served as a revelatory, common, and longitudinal case. Those characteristics supported the choice of a single case-study design (Yin, 2009). The general contractor had started an initiative to improve planning and customer order fulfillment with the aim of maximizing critical capacity utilization, which represents a problem in tactical planning according to Carvalho et al. (2015). The initiative represented an opportunity to observe and analyze demand–supply balancing, one that afforded the possibility of thoroughly studying the current state of a common customer order fulfillment process over an extended period (i.e., September 2016 to September 2018).

For Study II, to ensure cross-case homogeneity, manufacturers were selected that dedicate their ETO operations to customizing products according to a universal definition (Gosling & Naim, 2009). Furthermore, the manufacturers featured similar structures in their processes of customer order fulfillment that increased cross-case comparability. As for cross-case heterogeneity, the manufacturers varied in complexity and cross-functional integration settings, which enabled inferring each setting's impact on demand- and supply-driven detail and uncertainty. Cross-functional integration settings and their mechanisms in specific configurations of complexity highlighted their growing necessity as well as their contingent effects. Such heterogeneity also enabled rationalizing the number of cases, which was necessary because investigating the applied mechanisms of cross-functional integration within customer order fulfillment requires in-depth inquiries (Eisenhardt, 1989).

For Study III, large (i.e., according to EU recommendation 2003/361) ETO-oriented manufacturers were selected that have adopted S&OP and operate in several regions. Because S&OP is not widely implemented in ETO sectors (Kristensen & Jonsson, 2018), the selection criteria substantially reduced the population available for study. At the same time, the criteria increased homogeneity and allowed greater control of variations in the population (Eisenhardt, 1989). Four industries that typically deal with ETO challenges were targeted to ensure generalizability from such a reduced population. One representative manufacturer was selected per industry. My co-researcher and I verified that the chosen manufacturers manage massive pressure in realizing demand–supply balancing. The cases have global operations that need to handle various types of frequent engineering changes, which constitute the chief source of ETO-specific uncertainty (Shurrab et al., 2020a).

Given the breadth of the S&OP domain and the need for in-depth data inquiry, extensive data collection was expected to be needed in each case company. Therefore, the selected sample needed to be small yet ensure substantial heterogeneity in the dimensions of interest (Eisenhardt, 1989). Specifically, manufacturers that differed in their engineering and production decoupling strategies, as suggested by Cannas et al. (2019), and S&OP maturity levels (Danese et al., 2017) were selected. Such contrasts ensured increased heterogeneity and theoretical replication, and literal replication was partly applied, as recommended by Miles and Huberman (1994). The product families provided by each selected manufacturer represented different decoupling strategies. In other words, there were products with similar decoupling configurations across the cases, although the planning object of S&OP was, as usual, at the product-family level (Wallace & Stahl, 2008).

Last, information-processing capability is an indicator of a firm's performance (Prajogo et al., 2018). Therefore, high-performing manufacturers with extensive information-processing capability were selected. Arguably, being a manager in firms with efficient information-processing flows enables individuals to systematically delineate uncertainties and their sources. Following earlier procedures, four cases were selected, and my co-researcher and I regarded the sample size of four cases as sufficient given Study III's aim to expand generalizations from analysis to theoretical propositions (Yin, 2009).

Study IV contributed to a research project consisting of several actors in the automotive sector. The project members included specialists in material planning and control managers representing three OEMs. My co-researcher and I were able to informally meet and collaborate with those specialists on several occasions throughout the project and jointly tackle instability within the material delivery scheduling process at each OEM. Such access allowed us to verify if the OEMs fulfilled the case selection criteria. The cases—a car manufacturer and two heavy vehicle manufacturers—ensured heterogeneity among the drivers that generate dynamic complexity as the dimensions of interest (see Paper V for details). Study V capitalized on Study IV, as described earlier, by addressing the same car manufacturer investigated in Study IV.

### 3.3.3. Data collection

The primary source of data for Studies I–IV was semistructured interviews, supported by follow-up communication when a discrepancy or missing piece of information appeared. Secondary data collection, site visits, and opportunistic observations were undertaken to clarify and validate the results of the interviews, as recommended by Voss et al. (2002). Secondary data were fundamental in Studies III and IV.

Some characteristics of construction and their terminology are unique, and equivalent activities in other sectors are thus labeled differently (e.g., Dubois & Gadde, 2002). For that reason, Study I involved three construction management researchers in refining the interview protocol to ensure its inclusivity and relevance. The interviews helped to develop a detailed, comprehensive map of the customer order fulfillment process. The informants provided details about each activity's work content, rationale, and related systems and tools, as well as answered questions concerning the impact of complexity on the processes at their firms, and vice versa (see Paper I for details).

The interview questions in Study II also focused on customer order fulfillment, specifically mechanisms underlying coordination, guided by the corresponding topics in the conceptual framework. The questions were assessed and modified by some practitioners, as recommended by Yin

(2009). The selected informants represented the participating functions, and during their interviews, they shared documents describing the process in question, which helped to produce a detailed map in each case. The initial informants also guided the subsequent selection of informants. Later interviews focused on mechanisms of coordination and their impact on complexity.

In Study III, the interviews focused on S&OP IPNs and IPMs at each case company. The data consisted of detailed descriptions, perceptions, and experiences that delineated the flows of information within S&OP and thus departed from a generic conceptual framework of S&OP (Pereira et al., 2020). The informants were individuals with more than 10 years of experience working in demand and supply planning functions. The earlier interviews were conducted with the help of an initial guide consisting of constructs used in previous studies (e.g., Cannas et al., 2020; Oliva & Watson, 2011; Tuomikangas & Kaipia, 2014). Whenever the informants touched on additional aspects of general interest not incorporated in the guide, an updated, more comprehensive version of the guide was developed for later interviews. After some interviews, considering repetitiveness to represent a form of saturation, as termed by Yin (2009), my co-researcher and I stopped changing the interview guide when no new topics arose during the discussions (see Papers III and IV for details).

In Study IV, because the interviewees were material planning specialists from the OEMs participating in the research project, my co-researcher and I were familiar with the backgrounds of several informants. Those informants suggested other representatives in their organizations when additional information was needed. Overall, the selected informants represented functions responsible for demand, production, and material planning and control. The initial interviews resulted in a detailed map of material delivery scheduling in each case that departed from the conceptual framework. Later, the interviews shifted focus to the causes of instability guided by factors suggested in the literature and the complexity interactions that explain the underlying dynamics.

The secondary data in Studies I–IV encompassed publicly available and internal data and were crucial for Studies III–IV. As for Study III, S&OP is a wide-ranging process using company-wide data that need to be in a specific format to appropriately support decision-making in S&OP (Schlegel et al., 2020), via aggregation from operational levels, disaggregation from strategic levels, and reciprocation between several functions using many documents, systems, and individuals. As for Study IV, evidence was required from the informants concerning their answers when necessary; examples of such evidence were the results of relevant internal studies and analyses supporting the informant's claims concerning a factor of instability or associated relationships. Such data were essential to describing and visualizing the production and material ordering process, subprocesses, and systems.

Examples of the publicly available data used across the studies were documents describing the company's background, solutions, and services as well as press releases (e.g., annual reports, initiative reports, reports on flagship projects, and reports on modern technology). In Study I, additional publicly available data came from documents from Swedish construction associations describing standard organizational structures, roles and responsibilities therein, and the routines of various competencies in the construction sector.

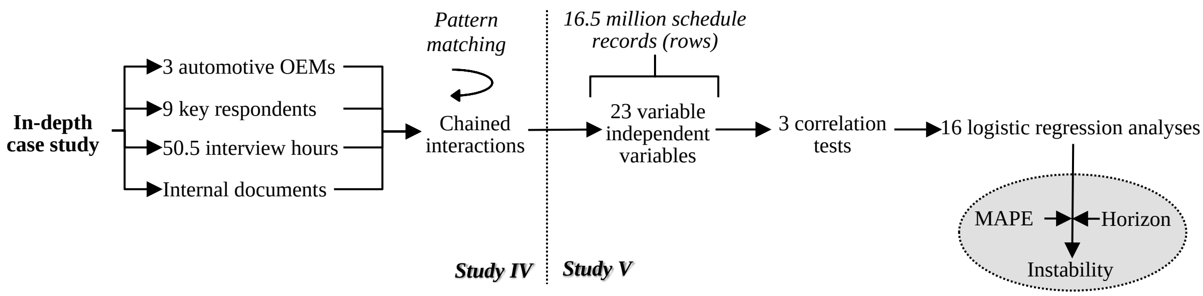
By contrast, examples of internal data across the studies were historical communications among participants in the studied processes, graphical illustrations of the process (e.g., agendas, inputs, and outcomes), templates, checklists, instructions, guidelines, policies, procedures, presentation slides, and worksheets. Some internal documents used in Study I also described information systems and software support in project portfolio management, resource planning, the optimization of capacity utilization, customer relationship management, and virtual design and construction. Studies I–III included documents describing the ETO product families and detailed production and engineering activities. As for Study IV, internal data also included documents from previous and ongoing internal initiatives geared toward managing scheduling instability. Examples of such records were a basic radial diagram of factors of instability, assessments of instability and its effects on relevant factors, and an Ishikawa diagram highlighting the factors of instability.

Last, Studies I and IV involved influential opportunistic direct observations. Opportunistic observations in Studies II and III were limited to a few demonstration sessions and an arranged workshop. In general, observing practitioners in their daily routines enriches the descriptions of the related social situations, while monitoring a connected system increases the understanding of a phenomenon's structures (Flick, 2009). The interview protocols and answers from the interviews already conducted guided observations during firms' internal meetings, and those observations resolved pending ambiguities, gaps, and contradictory information.

In Study I, observations were performed during weekly, monthly, and quarterly meetings held during a 2-year period. My co-researchers and I paid careful attention to the discussions and conversations during meetings concerning an internal initiative that tackled tactical planning activities and decisions as well as about the support-related requirements of information systems. During those meetings, many graphical illustrations of incoming and ongoing projects were also shown. In addition, observations were performed during four semiannual workshops involving representatives from critical functions and external software providers. Whereas the earlier workshops sought consensus regarding activities, decisions, and information system requirements via brainstorming, the later workshops were demonstration and assessment sessions focused on proposed process configurations and upgrades of software systems. Beyond merely documenting reflections, participating in the meetings and workshops concerning the initiative allowed observing how key decision-makers discussed alternatives and selected choices.

In Study III, I participated in two workshops and took notes on discussions between the OEMs' representatives and their suppliers. Observations also took place during interviews, particularly when some informants showed how they usually work with production planning and material ordering systems and dashboards in their daily routines.

Study V benefited from Study IV, as shown in Figure 3.3. It began with a qualitative exploratory study to identify causes and specified variables with potential causal effects on the accuracy of delivery schedules. A massive amount of data was collected in a database representing the delivery scheduling process, factors of inaccuracies, and material transactions during a 2-year period at the car manufacturer. Delving into the case data was required to identify and verify variables specifically relevant to the selected case and to interpret the findings in detail. Complementary variables from the literature and Study IV were considered as well.




*Note.* OEM = original equipment manufacturer, MAPE = mean absolute percentage error

**Figure 3.3.** Research design overview of Studies IV and V

### 3.3.4. Data analysis

Apart from Studies I and V, which were based on a single-case design, Studies II–IV followed similar approaches concerning data analysis, starting with within-case analyses that enabled cross-case analysis. The collected data were coded using a content analysis approach in all of the studies. Therein, I qualitatively inferred and systematically coded and categorized the content of textual data into patterns or themes (Hsieh & Shannon, 2005).

In Study I, the customer order fulfillment process represented a single case, while the engineering decoupling configurations of the previous customers' orders served as embedded single cases. Key informants assisted in matching the firm's product families with each type of decoupling using information from previous projects. My co-researchers and I compared process variations within and across the types of decoupling as an initial validation of order matching. Additional details about the characteristics of the matched orders (e.g., typical customer profiles, customers' input, and final products) supported us in comparing and verifying their commonality and homogeneity (Gosling et al., 2017). Other features such as tender types, contractual terms, related risks, typical margins, and lead times further supported the matching process.

Associating projects with one of the five decoupling categories extended the generalizability of the results within ETO operations and increased the visibility of the firm's response to various customers' orders and underlying structural and dynamic complexity. The data describing those varying responses were used to develop a comprehensive map of the process, one including tasks, decisions, and other related details, that departed from the corresponding framework. My co-researchers and I compared and identified differences between the activities and decisions regarding the different orders. Those variations served as evidence for how the general contractor manages complexity. The identified activities and decisions were deemed tactically relevant if they directly impact the firm's medium-term objectives, often called *strategic alignment* (e.g., Kristensen & Jonsson, 2018).

The next part of analysis elicited the impact on complexity from the empirical data, which departed from the synthesized theoretical insights concerning drivers of complexity that guided the coding process. Inferring a decision's impact on dynamic complexity was based on the consequent changes in uncertainties, even though dynamic complexity and uncertainty are different concepts—namely, dynamic complexity is largely generated by uncertainties in time and randomness (Serdarasan, 2013). Likewise, inferring a decision's impact on structural complexity was based on the consequent changes in details but not necessarily associated with a definite type of detail due to possible overlap. A decision's impact on uncertainties and details was determined based on evidence from the collected data according to Galbraith's (1977) perspective on information processing.

In Studies II–IV, the corresponding process, context, and performance frameworks were initially sorted within the empirical data of the cases (Eisenhardt, 1989). Such coding helped to identify mechanisms of cross-functional integration within customer order fulfillment in Study II, IPNs and IPMs within S&OP in Study III, and complexity interactions that generate instability within material delivery scheduling in Study IV. The results represented a within-case analysis per case (Corbin & Strauss, 1990). The coding process benefited from the depth of the collected data and allowed detailed clarifications of each manufacturer's unique pattern (Eisenhardt, 1989). As suggested by Ellram (1996), tabular displays were used to compare the process, context, and performance across the cases and thus allowed a cross-case analysis (Pratt, 2008). Drawing on cross-case similarities and variations, several interpretations concerning the applied mechanisms of cross-functional integration, IPNs, IPMs, and complexity interactions were inferred. Rival explanations were explored, and follow-up interviews were conducted when uncertainties emerged.

In Study III, new codes were inductively identified as critical themes of ETO uncertainty and S&OP's first- and second-order IPMs across the cases. The process benefited from associating data with relationships and concepts of information-processing theory via pattern matching (i.e., matching empirical data with corresponding literature). The coding process was iterated, and the generated second-order codes were condensed. Each IPN and IPM was associated with dimensions of planning quality suggested by Oliva and Watson (2011) as measures of performance. Such analyses highlighted the effectiveness of S&OP configurations, and the detected themes and patterns allowed elaborating information-processing theory and discussing the findings in general.

In Study IV, the informants recommended focusing on factors of schedule instability inside the fixed master production schedule. Accordingly, my co-researcher and I identified several causal and moderating factors through pattern matching. The conceptual framework of complexity interactions allowed identifying new factors that did not appear in the literature on instability, as recommended by Eisenhardt (1989) and Yin (2009). The informants scored the identified factors on a 5-point scale ranging from 1 (*lowest*) to 5 (*highest*) regarding the effect's severity and frequency of occurrence. The scores allowed us to rank factors that required delving into the data for further validation. Next, cross-case analysis following a causal network approach (Miles & Huberman, 1994) helped to elicit the impact of factors of instability on each other as chained events by interpreting cross-case variations in patterns. Variations in the settings of material delivery scheduling and environment were searched for and tested as explanatory arguments for any detected variation concerning the effect of each identified factor across the three OEMs.

In Study V, data analysis involved three stages. First, my co-researchers and I identified operating (i.e., independent) variables with expected explanatory effects on schedule inaccuracy while drawing on the literature and several workshops and dialogues with company representatives. The dependent variable was schedule inaccuracy, measured using the mean absolute percentage error (MAPE), which equals the mean of the absolute percentage difference between the scheduled volume and the reference volume (i.e., the actual order volume) for each schedule. When actual order volumes were zero, the percentage error was undefined; therefore, those errors were set to 100% if the scheduled volume was greater than zero. MAPE was measured as symmetric MAPE to overcome the asymmetry inherent in MAPE by favoring under-forecasting (Kim & Duffie, 2004).

Second, correlation tests were conducted to identify highly correlated independent variables for removal. Third, the explanatory impact of the qualified variables was analyzed using logistic regression models. The data were analyzed jointly by four researchers and two practitioners; two researchers handled the data analytics, while the other two led the conceptualization, overall analysis, and documentation process. As for the practitioners, one member was a specialist in material planning and delivery schedules at the case company, while the other was an external specialist in delivery scheduling and information sharing in the automotive industry. The findings of analysis were presented to and discussed with the case company representative and other practitioners within a related research project, and their feedback guided the refinement of the finding.

The preliminary findings of Studies I–V were first presented to case representatives, then at academic conferences, and lastly finalized and submitted to scientific journals (see Figure 3.2).

## 3.4. Validity and reliability

According to Yin (2009), four primary dimensions represent validity and reliability in research: construct validity, internal validity, external validity, and reliability. The research behind this thesis approached validity and reliability by considering alignment with those dimensions as described in the following subsections; each subsection explains the meaning of one dimension and discusses how it was considered in the thesis's five studies.

### 3.4.1. Construct validity

Voss et al. (2002) have defined *construct validity* as the degree of correctness for the operational measures used to study concepts. From a different angle, Yin (2009) has emphasized the importance of using multiple sources of evidence as an indicator of acceptable construct validity. Sources of evidence should serve as a chain of evidence by ensuring the traceability of the collected data over time. Ensuring such traceability is possible by recording the sequence of activities of data collection and gaining approval from the key informants concerning the drafts of the case-study report. In that respect, Voss et al. (2002) have recommended direct observations as an essential source of evidence to ensure construct validity by predicting relationships between variables. The following paragraphs describe how the studies in this thesis involved related methods to support construct validity.

Studies I–IV were based on case studies. To establish a chain of evidence and ensure construct validity, the development of those studies followed similar procedures. Data triangulation was applied because it helps to illuminate phenomena (Barratt et al., 2011). The starting point of triangulation in each study was a literature review that entailed a framework. The frameworks guided predictions for relationships between the variables of interest and thus served as a standard approach to achieving construct validity.

Triangulation was also applied using archival data and direct observations before developing case descriptions as various sources of information to ensure the accuracy of descriptions from interviews about customer order fulfillment (i.e., for Studies I and II), S&OP (i.e., for Study III), and material delivery scheduling (i.e., for Study VI) and to validate them. In that way, detailed documents describing those processes at the respective case companies were studied before and after the interviews. Publicly available and internal documents describing the processes (e.g., policies, reports, instructions, guidelines, checklists, and presentation slides) were collected to assess the alignment of the informants' perceptions and opinions. Whenever potential discrepancies or missing data surfaced, follow-up conversations were conducted with the informants via email or in person, as suggested by Voss et al. (2002).

Most of the interviews were recorded, and all such interviews were transcribed within a maximum of 1 week from the dates when they were conducted. The archival data were sent digitally via email or extracted from the recordings of the virtual interviews in which informants shared views and illustrations of internal documents. In some cases, the archival data were delivered in paper form by hand during face-to-face interviews. Notes were taken when voice recordings were not allowed, and interview summaries were compiled directly after the interviews.

The interviews were conducted in a specific order that ensured logical data collection such that questions about particular areas were posed to suitable informants. A database was established to manage all of the collected data. My co-researchers and I also requested reviews from key informants about the case-study reports and collected comments via email and in person to refine the results. Beyond that, the conclusions from Studies I–IV were discussed with relevant practitioners and industrial partners in several events that were part of the related research project, including representatives from the case companies in question.

In Study V, my co-researchers and I conducted a regression analysis using quantitative data. The study departed from the variables identified in Study IV and proceeded with a qualitative study to specify the variables relevant to the selected case. Those two steps guided the selection of variables that potentially explain inaccuracies in material delivery schedules. Four researchers and two practitioners jointly conducted the study, and the diversity of the team members' skills and exposure allowed ensuring higher construct validity.

To further support the construct validity of the selected variables, my coauthors and I conducted a set of correlation tests, which reduced the number of variables from 23 to 13. In addition, throughout the phases of the study, a continuous dialogue with the industrial parties concerning whether and how each variable relates to schedule instability was maintained as part of the related research project. The representatives of the case companies also reviewed and approved each variable during several workshops.

### 3.4.2. Internal validity

Voss et al. (2002) have defined *internal validity* as the ability to visibly draw a causal relationship by showing how certain conditions lead to other conditions. Yin (2009) has proposed four approaches to ensuring internal validity: matching patterns, developing explanations, addressing rival explanations, and using logic models.

To ensure internal validity, inferences made regarding an event that cannot be directly observed from case studies have to be correct (Yin, 2009). For this thesis, the studies primarily relied on such inferences. In Study I, direct observations of the impact of customer order fulfillment on demand–supply balancing were impossible; therefore, the interviews focused on the root causes of demand–supply balancing from the perspective of complexity, represented by detail and uncertainty as primary measures. That is, inferring that particular activity or decision influenced demand–supply balancing occurred indirectly with reference to its evident influence on detail and uncertainty.

Drawing causal links between demand–supply balancing and both detail and uncertainty was based on a theoretical framework. Determining whether a specific activity or decision influenced a particular type of detail and uncertainty negatively or positively was also based on a theoretical framework as well as the different data sources collected (i.e., interviews, observations, and archival data). The data described how the customer order fulfillment process managed various projects that served as embedded cases. During interviews, the informants clarified variations in handling those different project groups and the underlying reasons, and their answers were tested against each other and the authors' initial explanations. Iterations of follow-up conversations resolved any discrepancies and added the missing information.

As in Study I, my co-researchers and I inferred the relationship between demand–supply balancing and mechanisms of cross-functional integration in Study II. Again, the perspective of complexity came into play through detail and uncertainty. However, Study II also involved using collected data about customer order fulfillment from four cases to extend and further specify the drivers of complexity and the integrative mechanisms. The collected data allowed mapping the cross-functional interactions throughout the customer order fulfillment process in each case (see Paper II for details). My co-researcher and I used the maps to assess the influence of the identified integrative mechanisms on the identified drivers of complexity in each case. The assessment combined evidence from the archival data and interviews. Along with pattern matching with the literature, the archival data and interviews enabled cross-case comparisons that strengthened the research's internal validity.

In Study III, the effect of uncertainty within S&OP in ETO operations on IPNs was first inferred using four dimensions of planning quality: information quality, procedural quality, alignment quality, and constructive engagement. My coauthor and I associated each identified area of uncertainty with a dimension of planning quality. Second, we inferred the effect of planning quality from various S&OP

configurations, and pattern matching with the literature was used to map the S&OP process and guide the identification of areas of uncertainty within S&OP, their impact on planning quality, and IPMs represented by various S&OP configurations.

Because the literature on S&OP, information-processing theory, and ETO operations is firmly established, pattern matching entailed detailed case descriptions of the S&OP processes and contexts of four ETO-oriented manufacturers. The data about S&OP came from comprehensive archival documents describing the latest updates of the sequenced S&OP activities: the inputs, objectives, decisions, and outcomes of each activity; the methods, subprocesses, and systems used to perform and support the activities; the representatives from each function; and the actors involved in each activity. Such details helped to map the S&OP process at each company and to gather relevant data through interviews more effectively.

Having detailed insights into configurations of the S&OP process and contexts helped to reveal unique patterns of uncertainty and IPMs primarily attributed to several characteristics of ETO. Inferring ETO-specific uncertainty was based on whether or not it influenced the medium-term needs of engineering resources. Inferring ETO-specific IPMs was based on the potential impact of specific S&OP configurations on ETO-specific uncertainty expressed in terms of planning quality.

Study IV was also based on a case-study design. The study involved identifying factors that cause and moderate instability in material delivery schedules elicited from three automotive OEMs. The situations that required changing a material delivery schedule within the fixed horizon represented causal factors, whereas situations that perpetuated a change or increased its magnitude represented moderating factors. Those situations were compared against descriptions and explanations of corresponding factors or concepts in what served as pattern matching. The factors resulting from the case study were plenty; some were supported by historical data showing significant correlations, and some were backed indirectly by relevant data. Furthermore, two theoretical perspectives were applied: complexity theory and process theory. The alignment of the results from both perspectives reinforced the internal validity of the study's conclusions.

In Studies II–IV, my co-researchers and I explored the descriptions of the within-case analyses and compared them against the (raw) data. When discrepancies, contradictions, and ambiguities were identified, we searched for rival explanations and conducted if–then analyses, triangulation, and follow-up conversations with relevant informants to resolve those inconsistencies. By doing so, we ensured that we arrived at findings based on sound inferences.

In Studies I–IV, my notes, as primary investigator, were used to summarize the primary narrative of the detailed case studies, while the reflections and perceptions of the co-researchers were used to corroborate the narrative. When discrepancies appeared, we referred to relevant informants in all ways possible. As for our biases as researchers, one author analyzed the case data using relevant theories, and all authors jointly assessed and refined the findings later.

Last, ensuring internal validity in Study V was straightforward. The study highlighted the potential factors of schedule instability using a massive amount of empirical data from an automotive OEM through regression analysis, the steps of which were documented in detail and made accessible to my co-researchers, the other industrial partners, and me. The data underwent cleaning to remove outlier and incomplete schedules. Moreover, we excluded data that reflected patterns impacting the results, including delivery schedules of phased-in and phased-out items. The results of data cleaning and the analysis were continually discussed with larger groups of industrial partners representing the data source—that is, the OEM—and some members of the OEM's supply chain.

### 3.4.3. External validity

*External validity*, or *generalizability*, describes the possibility of using a study's findings beyond the scope of the study. Generalizing results through case research has been criticized for insufficient evidence, because each case has a unique context. In response, Yin (2009) has proposed logical replication in multiple cases to improve the external validity of case research.

Following multiple-case study designs, such replication logic was applied in Studies II–IV. Study I was an exploratory investigation on the relevance of the customer order fulfillment process as a tactical-level planning process, namely by capturing its effect on demand–supply balancing. Study II, to some extent, used findings from Study I and replicated its approach using the same perspective on complexity but focused on cross-functional integration. Therefore, Studies I and II complement each other, and the external validity of the conclusions of those studies was improved by applying replication logic and pattern matching with the theoretical framework used in the within-case analyses.

Study III was based on a multiple-case study design. Thorough reviews of the literature concerning ETO operations, S&OP, and information-processing theory preceded the case study and ensured its alignment with previous research. Rich data about the S&OP process and the planning environment at each case were available, and representatives from each case regularly reviewed the overall results about the others' processes and uncertainty as they emerged, which further strengthened the case study's external validity.

The embedded (sub)cases of the single-case design adopted in Study I and those selected in Studies II and III represented various production and engineering decoupling configurations. Such purposeful selection allowed extending the generalizability of the results within ETO operations.

Study IV was based on a multiple-case study design, and Study V included data from one case. However, those two studies complemented each other nonetheless. Study IV explored factors of delivery schedule instability at three automotive OEMs, whereas Study V explained some of those factors quantitatively at one of the OEMs. Before data collection, a thorough literature review on material requirements planning as well as production schedule instability and nervousness was conducted to ensure alignment with previous research regardless of the context in question.

For Studies IV and V, my co-researchers and I had access to rich data beyond the data used in the analysis. A massive amount of historical data from several automotive suppliers and results from similar analyses were available. Beyond that, although data from one OEM was used in Study V, the other researchers and I had access to corresponding data from the other two OEMs that were part of the selected cases in Study IV. We considered one case to gain the possibility of obtaining data about additional factors such as take rate, order life, and product models. On top of that, the results were regularly presented to and discussed with representatives of many actors in the automotive industry (e.g., suppliers, management consulting firms, and information technology providers) to further enhance external validity.

### 3.4.4. Reliability

In research, *reliability* describes the degree to which the conditions of a study allow other researchers to reach the same findings if the study is replicated. In case research, reliability implies the replicability of analysis using the same case, which can be ensured using a case research protocol and a database (Yin, 2009).

As discussed earlier in this chapter, protocols and databases were established and maintained in Studies I–IV. The procedures applied in each case study were thoroughly documented to manage the effects of a priori beliefs when collecting and analyzing data. Such documentation involved direct observations and time and activity logs of the research work, including the collected data (i.e., the recordings and transcriptions or summaries of the interviews and the note summaries of each workshop and site visit).

The protocols increased transparency concerning data sources and served as the plan and template for data collection. They were developed drawing on the literature reviews that preceded each case study and by delineating the primary criteria during data collection. The final version of the protocol used in each case study was tested by different researchers who interviewed informants representing the same function separately. Thus, all researchers arrived at the same findings independently.

As for Study V, data collection, cleaning, and analysis were documented in detail, and such documentation ensured the replicability of the research. Studies such as Study V have high replicability, because the same input data will lead to the same results—that is, the same factors—which were selected based on correlation’s significance. Regression analysis will always return the same results regardless of the researcher as long as the researcher uses the same mathematical formulas, parameters, and data.

# 4. Summary of appended papers

This chapter summarizes the six appended papers and their contributions to the literature and managerial practices.

## 4.1. Paper I: A tactical demand–supply planning framework to manage complexity in engineer-to-order environments: Insights from an in-depth case study

### 4.1.1. Aim and results

Balancing demand and supply in ETO operations is challenging due to substantial complexity in the planning environment. Paper I aims to expand the understanding of managing the complexity constraining demand–supply balancing by identifying the tactical planning process within customer order fulfillment and the impact of the underlying decisions on complexity.

As a result of an in-depth single-case study on a construction company, the paper presents a tactical-level planning process framework that incorporates nine momentous decisions: (1) selecting and prioritizing fit inquiries, (2) assigning capacity to analyze the prioritized inquiries, (3) determining external capacity to support the analysis, (4) selecting critical design concepts, geometrics, and material, (5) selecting manufacturing processes and equipment, (6) performing the preliminary allocation of internal capacity, (7) selecting external contributors for project execution, (8) determining changes in final designs and execution methods and plans, and (9) accepting or rejecting inquiries before contracting. Three crucial tactical-level planning activities address those decisions and have potential complexity-reducing and complexity-absorbing impact: selecting and prioritizing customers' orders, selecting external contributors, and multi-project optimization.

In the research supporting Paper I, the complexity constraining demand–supply balancing was observed to be reduced by following two major strategies. First was selecting orders from fewer but relatively reliable customers that generate significant sales and frequently request both common and unique designs. Second was optimizing the supply base by minimizing the number of external contributors and maximizing the representation of local, efficient external contributors who are the most reliable. The complexity embedded in orders requiring substantial engineering (i.e., uniqueness) was observed to be absorbed by prioritizing the selected orders in settings that maximize the utilization of critical capacity.

Multi-project optimization entails minor simultaneous modifications on several plans that balance the overall complexity across customers' orders and ongoing projects. For instance, applying alternative material, geometrics, methods, and allocations of capacity on some plans can increase the utilization of critical resources (i.e., absorb complexity) and reduce the overall risks (i.e., reduce complexity).

### 4.1.2. Contributions

Paper I's primary contribution to theory is twofold. First, it proposes a detailed framework for tactical planning in ETO operations that departs from a conceptual framework synthesized from models that lack clear demarcations of constructs of tactical planning. Second, drawing on complexity theory, it reveals insights into complexity-reducing and complexity-absorbing strategies and provides empirically rich evidence from a complex context to explain propositions from previous studies concerning variety-reducing and variety-decoupling strategies.

Paper I's primary contribution to managerial practices is also twofold. First, the proposed tactical planning framework serves as a guide for formalizing a tactical planning process that balances demand

and supply and addresses ETO-specific complexity in a structured, transparent process. Second, maintaining order selection, order prioritization, and multi-project optimization as crucial activities implies that decision-makers need appropriate information technology support. For instance, they need to seamlessly accumulate input from previous projects as well as from internal and external sources to conduct robust, comprehensive scenario-based analyses. Decision-makers also need the firm's capacity to be sufficiently visible in order to identify its current and future significance. Such visibility is a prerequisite for predicting the medium-term consequences of decisions on capacity.

## 4.2. Paper II: Managing complexity through integrative tactical planning in engineer-to-order environments: Insights from four case studies

### 4.2.1. Aim and results

Tactical planning balances demand and supply within a medium term through cross-functional integration represented by mechanisms of coordination and collaboration. Paper II aims to identify cross-functional integration (i.e., coordination) mechanisms applied within customer order fulfillment to mitigate the negative impact of complexity on demand–supply balancing in four ETO-oriented settings.

The paper presents seven mechanisms that positively impact complexity in ETO operations and 15 mechanisms with a positive impact depending on some contextual factors. Two of the seven mechanisms apply to the whole customer order fulfillment process: (1) formalized activity sequences that consider cross-functional interdependencies for the rules of inference adopted to ensure information validity and (2) established information systems capable of processing massive demand- and supply-related data to address uncertainty. The other mechanisms apply only to customization and workload analysis: (3) small, heterogeneous cross-functional teams, (4) clear problem-oriented objectives, (5) optimized task concurrency between demand- and supply-facing functions, (6) enhanced task cohesion, and (7) information systems that support the modeling and optimizing of designs and processes.

Other mechanisms have a positive but contingent impact on complexity. For instance, standardizing activities, formalizing customer order fulfillment using stage gates, and ensuring the co-location of cross-functional team members all affect complexity positively in firms with large engineering organizations.

### 4.2.2. Contributions

Paper II's primary contribution to theory is threefold. For one, it provides a simplified normative approach to analyzing the complexity of a particular planning environment. For another, it combines a complexity-focused perspective with areas of cross-functional integration rooted in information-processing theory to generate a set of testable propositions. Those propositions provide granular detail to explain, enrich, and complement descriptions of generic coordination practices in literature on managing complexity, practicing S&OP, and managing ETO operations. Last, the paper proposes a refined perspective of integration, from which coordination and collaboration can be viewed as serving two dimensions of integration, while interactions can be viewed as representing mere reciprocal actions that signal the state of coordination or collaboration.

Paper II's primary contribution to managerial practices is twofold. First, several contextual factors drive the suitability of applying numerous mechanisms of cross-functional integration. Those factors and the paper's propositions serve as a practical guide to predict the consequences of organizational changes and new management approaches. Second, managers may benefit from the paper's insights in establishing integration strategies dedicated to managing complexity. For instance, managers have to allow greater detail in demand and related uncertainty if the desired strategy requires higher responsiveness or flexibility in relation to demand. To balance such an increase in complexity, managers need to apply mechanisms of cross-functional integration with equivalent complexity-absorbing impact on the corresponding detail of supply and related uncertainty.

## 4.3. Paper III: Managing information processing needs in engineer-to-order organizations: A prerequisite for demand–supply balancing

### 4.3.1. Aim and results

The S&OP process needs to address uncertainties that, if not deftly handled in the medium term (i.e., 6–24 months), cause delays in order fulfillment. However, the areas of uncertainty that S&OP needs to address in ETO environments and how those areas translate to IPNs in terms of requirements for planning quality had never been studied before. In response, Paper III focuses on how engineering changes in ETO environments create uncertainty and information-processing needs in the S&OP process.

Thirty-one areas of uncertainty were identified within the S&OP domain, 21 of which were not in the literature on S&OP, at four ETO-oriented manufacturers. Nineteen areas of uncertainty are attributable to ETO contextual characteristics; the level of nine of the ETO areas vary from low to high levels stemming from demand, production, and the supply chain. Demand affects uncertainty by volume per order, whereas production causes uncertainty through overall product customizability, customizable systems per product, production capacity, process quality, labor skill development pace, and labor type. Two areas of uncertainty originate from the supply chain: external labor and subcontractors, on the one hand, and subcontracting costs on the other.

Ten ETO areas are shown to have caused substantial uncertainty across all of the cases. Three stem from demand—sales process revenue, budget per order, and technical specifications—whereas seven originate from production: setup cost, minimum inbound inventory, production layout, machine productivity, internal labor availability, labor productivity, and inter-resource equivalences.

The uncertainty resulting from applying engineering changes after receiving customers' orders and affecting medium-term demand–supply balancing generates unpredictability and limits the visibility of variabilities in demand, the configurability of capacity, variations in solutions, and variations in relationships. The greater the unpredictability and more limited the visibility resulting from applying those engineering changes, the higher the IPN for ensuring medium-term demand–supply balancing.

The information-processing capacity matching the IPNs caused by applying engineering changes requires a sufficient degree of planning quality represented by four dimensions: informational quality, procedural quality, alignment quality, and constructive engagement. First, S&OP's *informational quality* refers to the visualization needed to enable seamless collection (i.e., from secure databases) and intuitive analytical experience with up-to-date, detailed, aggregate, and easy-to-view data related to demand, products, capacity (i.e., machinery and labor), processes, material, and the supply chain. Second, S&OP's *procedural quality* refers to its problem-solving capability, which is essential to improving the predictive capability of customers' demand and variabilities in product design (e.g., hit rates and learning curves), the ability to develop solutions (e.g., layout, customization, and scalability), and the ability to match or validate (e.g., skill vs. task). Third, S&OP's *alignment quality* refers to the level of coordination required to activate intra- and interdepartmental interactions relevant to the flexibility of production capacity, the quality of processes, and learning curves through aligned goals, incentives, and budgets. Fourth and last, *constructive engagement* refers to the collaboration needed to encourage actors with tacit knowledge relevant to engineering tasks and required skills to collaborate toward continuously and comprehensively standardizing engineering tasks.

### 4.3.2. Contributions

Paper III's primary contribution to theory is threefold. First, it contributes to research on information-processing theory by showing how uncertainty translates to IPNs in granular detail using in-depth empirical data. Second, in relation to the literature on managing ETO operations, the paper expands the understanding of uncertainty in ETO operations by identifying numerous new areas and providing details about other areas discussed in past studies. Third, the findings contribute to research on S&OP concerning the context-fitted configuration of processes. The identified areas of uncertainty and consequent IPNs represent a comprehensive set of potential conditions that shape the prerequisites that configurations of S&OP processes need to fulfill in order to be responsive.

Meanwhile, Paper III's primary contribution to managerial practices is fourfold. First, the dimensions of planning quality serve as indicators of the qualitative performance of S&OP. By matching those dimensions with the areas and levels of uncertainty, the paper can guide manufacturers in exploring what their S&OP processes need to fulfill in order to absorb additional contextual uncertainty. Second, the paper offers advice to firms that seek to improve their planning processes, namely to feature visibility and predictability as measures that can be improved by enhancing the visualization of the performance of processes, problem-solving, coordination, and collaboration. It also provides firms with conceptual insights into matching each type of those capabilities with the dynamics of specific uncertainty and examples for how to improve them. Third, given findings showing that case-specific contextual characteristics considerably shape demand-related uncertainty, ETO-oriented firms have to carefully benchmark demand planning practices because the demand context varies across ETO businesses significantly. They can also continue to benefit from benchmarking several engineering and production planning practices. Fourth and finally, the findings show that S&OP requires tighter alignment with other internal planning processes in ETO operations (e.g., tendering, budgeting, and organizational development). Because those processes are necessary to enhance informational and procedural quality, ETO manufacturers need to find solutions for how internal processes can support S&OP without duplicating activities such as reporting and meetings.

## 4.4. Paper IV: Information-processing mechanisms of tactical planning to address demand–supply balancing uncertainty in engineer-to-order organizations

### 4.4.1. Aim and results

Balancing medium-term demand and supply through S&OP requires a context-fitted process design that effectively responds to the IPNs in a planning environment using suitable IPMs. Previous research on context-fitted S&OP has not applied information-processing theory despite its promising explanatory potential for managing uncertainty in a complex planning environment such as ETO operations. Therefore, Paper IV aims to elucidate the impact of effective planning on demand–supply balancing in ETO operations by identifying S&OP's IPMs and the quality of planning generated.

Various configurations of S&OP generate IPMs that mitigate uncertainty by reducing the consequent IPNs or increasing the information-processing capacity that absorbs uncertainty. S&OP reduces IPNs in ETO operations through mechanisms that create slack resources (e.g., customer order selection and centralization) and self-contained tasks (e.g., organizational structures). The selection of customers' orders reduces IPNs resulting from, for example, the uncertainty about product customizability. Organizational structures also reduce IPNs associated with ETO uncertainty, including market structure (e.g., uncertainty about technical specifications), geographical structure (e.g., uncertainty about the flexibility of production capacity), product structure (e.g., uncertainty about customizable systems per product), network structure (e.g., uncertainty about subcontracting costs), and functional structure (e.g., uncertainty of production capacity). In the research conducted for the paper, the impact of IPN-reducing IPMs was found to be contingent upon the product's complexity, the size and dispersion of the firm, and the balance between bottom-up and cross-functional alignments.

S&OP increases the sort of information-processing capacity able to absorb ETO uncertainty through other mechanisms. Those mechanisms enhance information system support (e.g., data currency, data localization, data globalization, the formalization of information flows, and human–machine information processing) and create lateral relations (e.g., direct contact between managers, liaisons, permanent cross-functional teams, and integrated roles). Mechanisms of information system support are relevant to some areas of ETO uncertainty, namely data currency (e.g., uncertainty about internal labor availability), data localization (e.g., uncertainty about inter-resource equivalences), data globalization (e.g., uncertainty about the flexibility of production capacity), the formalization of information flows (e.g., uncertainty about sales process revenue), and human–machine information processing (e.g., uncertainty about budget per order). Similarly, mechanisms of lateral relations are relevant to some areas of ETO uncertainty, particularly direct contact between managers (e.g., uncertainty about external labor and subcontractors), liaisons (e.g., uncertainty about process quality), permanent cross-functional teams (e.g., uncertainty about overall product customizability), and integrated roles (e.g., uncertainty about the flexibility of production capacity).

Six primary interfaces between the quality of S&OP and IPMs are identified in Paper IV. First, S&OP's IPMs creating slack resources enable and are enabled by dimensions of procedural quality: the predictability of decisions' consequences, the capability to develop solutions, and the capability of the bottom-up validation of information. Second, S&OP's IPMs creating self-contained tasks enable various dimensions of the alignment quality: outside-in, inside-out, top-down, cross-functional, and bottom-up alignment. Third, the product structure enables a dimension of constructive engagement—that is, the active involvement of relevant managers and subordinates. Fourth, S&OP's IPMs enhancing information system support enable two dimensions of informational quality: data format and validity. Fifth, human-machine information-processing activates three dimensions of procedural quality: the predictability of demand and variabilities in product designs, the ability to develop solutions, and the ability to validate information. Sixth and last, S&OP's IPMs creating lateral relations enable dimensions of the alignment quality, namely top-down alignment, cross-functional alignment, bottom-up alignment.

### 4.4.2. Contributions

Paper VI's primary contribution to theory is threefold. First, it contributes to research on context-fitted S&OP by providing detail and a theoretical framework about configurations and mechanisms that manage areas of uncertainty in ETO operations. That context has received limited attention in the literature on S&OP. Second, the paper is based on a study that applied information-processing theory, a theoretical lens rarely adopted in studies on S&OP despite being highly relevant. It thus provides an example of how to approach S&OP problems purposefully by using relevant theories. Such an example is pivotal because most studies on S&OP are based on applied or practical problems and poorly address them from a theoretical standpoint. Third, by operationalizing how IPMs activate planning quality, the paper extends the usability of information-processing theory as a theoretical lens.

Paper IV's primary contribution to managerial practices is twofold. On the one hand, it can help ETO-oriented manufacturers to predict the effects of adapting configurations of S&OP to improve the quality of planning. On the other, it encourages investments in information systems to support S&OP in complex operations. Specifically, information systems need to enable the aggregation and disaggregation of qualitative and quantitative data beyond data regarding sales volumes only.

Predicting the consequences of decisions in complex environments such as ETO operations requires data that clarifies the significance of internal and external capacity, especially for engineering.

## 4.5. Paper V: Untangling the complexity generating material delivery "schedule instability": Insights from automotive OEMs

### 4.5.1. Aim and results

Changes frequently applied to material delivery schedules accumulate upstream in the supply chain and thus cause a bullwhip effect. Paper V aims to elucidate the develop of instability within automotive OEMs by identifying the causal and moderating factors and related common scenarios and showing how they trigger each other.

The paper confirms that the primary causes and moderators of delivery schedule instability originate from a firm's internal (i.e., horizontal) dynamic complexity interactions. Those causes and moderators represent variations in quantity, timing, and quality that are not adequately buffered by time, inventory, and capacity. The ability to absorb higher variations within internal operations implies the possibility to produce less overall instability. However, developing such capability through slack resources requires maximizing the gains from reduced instability. Slack resources unlock two highly instability-mitigating (i.e., moderating) factors: low enforcement for order fulfillment and higher capacity scalability. The paper's findings also confirm that discrepancies in inventory stock and low actual demand can cause instability as well.

Apart from dynamic complexity, the paper shows that detail (i.e., structural) complexity can trigger interactions that eventually cause instability due to increased varieties of products and algorithms of planning models. No evidence indicates that supply chains can directly develop instability, however.

### 4.5.2. Contributions

Paper V's primary contribution to theory is threefold. First, it presents a comprehensive, synthesized reference framework that conceptualizes complexity as generic interactions, which departs from complexity-oriented perspectives and insights from studies on material delivery scheduling. Second, the interactions revealed in the case study provide a granular view of the dynamic complexity that generates instability by introducing new variables and networks of relationships. Third, those interactions are operationalized and discussed using principles from process theory to shed light on the phenomenon of instability.

Paper V's primary contribution to managerial practices is twofold. First, the crucial role of capacity scalability, suppliers' flexibility, and flexibility in supply chain order fulfillment in mitigating schedule instability encourages supply chain managers to consider establishing strategies and initiatives to improve those capabilities. Second, because the paper confirms that (slow-moving) items with low consumption rates—for instance, ones entering the phased-in or phased-out zones—have the most unstable schedules, detecting them is essential. To that end, item profiling and leveraging relevant data analytics are recommended actions, and once slow-moving items are spotted, material schedulers need to monitor them more closely. It may also help that some of the process parameters of material delivery scheduling (e.g., periodicity) change to fit the phased-in and phased-out dynamics.

## 4.6. Paper VI: Explaining root-causes to delivery schedule inaccuracies in supply chains

### 4.6.1. Aim and results

Factors of material delivery schedule instability may significantly impact minor or more considerable variations in schedules. However, the literature does not address causal factors of such instability in terms of its effects on short- and long-term horizons. Understanding whether and how factors affect inaccuracies along those dimensions are preconditions to generating accurate predictive models. Therefore, Paper VI empirically tests variables with the potential to explain instability in material delivery schedules in terms of the time horizon as well as the level of inaccuracy.

The findings of logistic regression analysis confirm that the impact of factors explaining schedule instability differs depending on the planning horizon. In addition, the item's take rate, order life cycle, unit load, and pickup frequency are verified as significant causal variables. The findings also verify that the causal effect of the planning horizon on the accuracy of schedules can be positive or negative.

### 4.6.2. Contributions

Paper VI's primary contribution to theory is threefold. First, it explains the phenomenon of instability using a massive dataset from a European automotive OEM, whereas the phenomenon has largely been investigated using dummy data in past research. Second, it stresses that the causal factors generating instability in schedules have contingency effects moderated by the schedule's horizon as well as the schedule's accuracy. Those two contextual factors were not emphasized in previous studies. Third, four essential variables that potentially explain inaccuracy in delivery schedules are introduced.

Meanwhile, the paper's primary contribution to managerial practices is twofold. On the one hand, material planning functions have to establish routines suitable for managing material deliveries under various horizons and levels of accuracy beyond freezing orders. On the other, regarding the take rate, life cycle, unit load, and pickup frequency of items that potentially explain instability in schedules, the possibility for collecting, recalling, and comparing related data against instability indicators has to be established, automated, and preferably made easy to visualize.

# 5. Results

This chapter answers the three RQs presented in Section 1.4 in light of the findings in the six appended papers and discusses the findings in relation to relevant literature.

## 5.1. Research Question 1: Complexity and order fulfillment in ETO operations

RQ1 addresses how complexity in ETO operations influences demand–supply balancing within the customer order fulfillment process. Complexity ETO operations were found to require specific planning configurations represented by activities and mechanisms of cross-functional integration. As detailed in Paper I, the activities included order screening, customization, workload analysis, review, and contracting, as shown in Figure 5.1 within a rectangle directly connected by an arrow departing from complexity. The complexity can be dynamic or structural.

*Screening customers' orders* refers to selecting inquiries from customers that align with the business's objectives and can be delivered using available capacity. *Reviewing customers' orders* refers to evaluating all customers' orders in the pipeline at an aggregate level to determine compromises to some offers in order to optimize the overall return on investments in customization. *Complexity in ETO operations* was found to increase the need for two primary mechanisms of cross-functional integration within order screening, review, and contracting activities: formalized screening procedures and adequate data management. That complexity-generated need is shown in Figure 5.1 as arrows departing from the mechanisms (i.e., in grayscale italics) toward the activities (i.e., in bold).

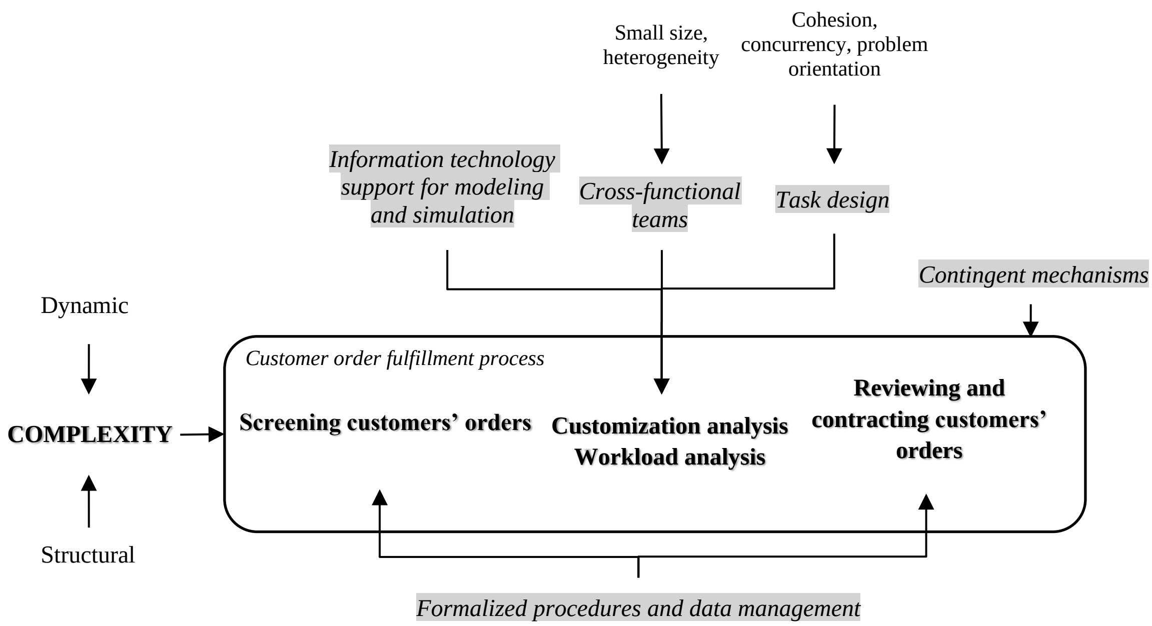



**Figure 5.1.** Complexity's influence on demand–supply balancing within the customer order fulfillment process in engineer-to-order operations

*Order customization analysis* and *workload analysis* include activities such as procurement and product and process engineering. Order workload analysis entails resource loading, procurement, and estimating costs and durations of customization solutions. Those activities were found to shape complexity in later stages of order fulfillment and to require four mechanisms of cross-functional integration: (1) assigning small customization teams with various levels of experience, age, and tenure,

(2) ensuring clear, problem-oriented objectives for tasks, (3) maximizing concurrency between product and process development functions, and (4) ensuring information system support for product and production design modeling and optimization. Other mechanisms of cross-functional integration can be critical to one or more planning activities under specific contextual complexity settings. Those are referred to as *contingent mechanisms* in Figure 5.1 (see Paper II for details).

Complexity in ETO operations is primarily driven by customizations that vary in the amount of engineering required (i.e., decoupling configurations) after customers' orders are received (Cannas et al., 2019). The minimal engineering work after orders are received has to at least entail minor modifications to the product design and associated production processes in order to qualify as ETO demand (Gosling & Naim, 2009). The following subsections discuss the findings shown in Figure 5.1.

### 5.1.1. Screening customers' orders

Complexity in ETO operations was also found to require order-screening activities (i.e., preliminary assessment and resource loading) that apply two primary mechanisms of cross-functional integration regardless of the decoupling configuration of customers' orders: formalizing order-screening procedures by recognizing cross-functional interdependencies and practicing adequate data management. Because ETO operations embed substantial cross-functional interdependences (Gosling & Naim, 2009; Mello et al., 2015), recognizing the sequential dependencies between functions as rules of inference is critical for order fulfillment in ETO operations due to the critical role of information validity. Second, large engineering organizations represent a fundamental part of ETO operations (Hicks et al., 2000). In that respect, effective cross-functional interactions involving engineers require seamless companywide and real-time data management infrastructure. Those engineers have to efficiently review design artifacts, assess interdepartmental requirements, and retrieve relevant data from previous projects (Kahn, 1996a; Sherman et al., 2005). Other mechanisms of cross-functional integration such as standardization become critical when screening more complex customizations, namely more complex decoupling configurations such as design-to-order and research-to-order settings.

Selecting, prioritizing, and winning research-to-order or develop-to-order inquiries were actions found to necessitate tying scarce competencies capable of fulfilling complex customers' orders effectively, which corroborates Cooper and Budd's (2007) results. Managing the fulfillment of those customizations was found to require exceptional coordination skills in order to absorb aspects of substantial structural and dynamic complexity: large organizations and numerous involved functions, underdeveloped specifications and problem statements, considerable freedom given to sales to develop and propose solutions to customers, recurrent modification requests, underdeveloped technology, and the substantial depth of customizable product structures that challenges modularization. Those aspects determine suitable strategies for engineering and production decoupling (Cannas et al., 2020). Order screening requires assigning suitable specialists to perform order customization and workload analyses.

### 5.1.2. Customization and workload analyses

Complexity in ETO operations was additionally found to require order customization and workload analyses. Those activities vary in intensity depending on the decoupling configuration in question (Gosling et al., 2017). Applying changes in design to fulfill each incoming order makes order customization critical. Order customization implies evaluating the aggregate requirements for customization and includes determining solutions for procurement, product engineering, and process engineering. Predicting the consequences of those decisions on capacity and performance can be done through workload analysis. Order workload analysis entails resource loading, procurement, and estimating costs and durations of the developed or selected solutions. It also validates the availability of internal and external capacity and their constraints at an aggregate, multiple-order level.

The greater the complexity underlying the engineering decoupling configuration of a customer's inquiry, the greater the uncertainty of order customization and workload analysis. Orders corresponding to research-to-order and develop-to-order configurations require extended order customization and workload analyses compared with orders requiring little customization (e.g., combine-to-order inquiries). Beyond that, the internal capacity of specialists for assessing customers' inquiries is critical to research-to-order and develop-to-order customizations. By contrast, performing pre-contract activities through external interventions is generally acceptable for modify-to-order and combine-to-order customizations. The same applies to the number and criticality of suppliers and subcontractors; in highly complex projects, suppliers and subcontractors deliver up to 80% of the final product's value (Potts & Ankrah, 2014).

In short, order customization and workload analyses represent the core of the engineering element in ETO operations, one that shapes complexity in later stages of order fulfillment. Using solutions that minimize needs for critical capacity was found to serve as a complexity-absorbing practice. Usually, critical capacity demanding solutions primarily depend on global suppliers' contributions or require highly reliable and compatible suppliers and internal resources.

The research's findings show that the more the external contributors, the greater the risk of disturbing internal manufacturing schedules, the longer and more unreliable the lead times, and the more globalized the supply bases embedding significant cross-border uncertainties. Similar results have been identified by Bozarth et al. (2009). In turn, the larger the supply bases, the more coordination required to manage suppliers' contributions and respective relationships. Beyond that, the more coordination necessary for demand–supply balancing—either due to increased dynamic or structural complexities—the higher the pressure on supply capacity (Oliva & Watson, 2011). Specific types of external contributors require substantial coordination (e.g., foreign external contributors that need to follow different regulations and pose cross-cultural and language barriers and external contributors that have incompatible planning and control systems), which frequently causes unexpected absenteeism in internal labor and equipment stoppages and have inputs (e.g., material quality) causing instability in internal manufacturing that cannot be directly captured by classic lead time management. Such coordination is even more pivotal for inquiries involving final products that cannot be stored because the timeliness of their respective fulfillment activities is similarly pivotal (Olhager, 2010).

As mentioned, complexity in ETO operations was found to require four mechanisms of cross-functional integration within order customization and workload analysis, regardless of the decoupling configuration in question: (1) assigning small customization teams with various levels of experience, age, and tenure, (2) ensuring clear problem-oriented objectives for tasks, (3) maximizing concurrency between product and process development functions, and (4) ensuring information system support for product and production design modeling and optimization.

First, balanced cross-functional team composition is a driver of success in new product development (Holland et al., 2000; Mathieu et al., 2014), one embedded as integrated engineering activities within the order fulfillment process (Mello et al., 2015). Second, the design of tasks—another critical cross-functional integration mechanism (Hirunyawipada et al., 2010; Holland et al., 2000)—can reduce uncertainty in tasks by presenting clear, problem-oriented objectives (Daugherty et al., 1992) and compress engineering lead times through concurrency (Gosling et al., 2015). Task concurrency is necessary for timely customization and workload analysis (Cooper & Budd, 2007), even in less complex environments (Turkulainen & Ketokivi, 2012). In addition, task cohesion is a crucial mechanism of cross-functional integration for new product development (Hirunyawipada et al., 2010). New specialized product domains evolve and grow relatively quickly in ETO operations regardless of the type of ETO-oriented firm in question (Hicks et al., 2001). For that reason, promoting specialists generalists who possess interdisciplinary knowledge and leadership skills is necessary for efficiently setting standards and managing those evolving areas.

Last, the findings show that without appropriate support that enables efficient modeling and optimizing design solutions within customization and workload analysis, meeting deadlines requires substantial engineering capacity. In general, as the findings imply, information transparency is a fundamental principle of design and operations (Gosling et al., 2015).

### 5.1.3. Reviewing and contracting customers' orders

Complexity in ETO operations was found to require an aggregate review of all customers' orders in the pipeline, which represents the core of medium-term demand–supply balancing within the order fulfillment process. Because highly customized product markets are dynamic and subject to substantial uncertainty (Birkie & Trucco, 2016) and because the delivery lead times are relatively long (Bertrand & Muntslag, 1993), customers' orders with all possible statuses (i.e., prospective, pre-contract, or post-contract) need regular assessment at an aggregate level by top management. Reviewing customers' orders requires aggregating the outcomes of order customization and workload analysis to a suitable level of detail that allows visualizing constraints and interdependencies corresponding to individual orders. Such visibility needs to maximize synergies among resources and minimize compromises across the parallel ongoing and upcoming orders by, for example, applying modifications to the planned offers. However, the increased complexity of customization makes minimizing overall risks and conflicts and maximizing overall performance more challenging due to the complexity of data that need aggregation.

The findings show that the best solution offered to a customer is often not necessarily the one that features the most fulfilling designs and ensures the highest profit margin. At an aggregate level, compromises to some offers can be crucial to optimizing the overall return on investments in customization. Increasing the demand intake to resolve undercapacity is possible by unlocking the critical capacity resulting from adequately matching risk levels with corresponding competencies. As in order screening, the complexity in ETO operations requires formalizing policies and procedures and adequate data management within the process of reviewing and contracting orders. Other mechanisms of cross-functional integration were found to be critical in specific settings involving contextual complexity. For instance, recruiting individuals with exposure to target customers and interdisciplinary skills is critical when the customizable product architectures have substantial depth.

## 5.2. Research Question 2: Complexity and S&OP in ETO operations

RQ2 addresses how complexity in ETO operations influences S&OP. Uncertainty represents dynamic complexity from the perspective of information processing (Galbraith, 1977). ETO uncertainty was found to make demand increasingly multifaceted, and S&OP thus needs to capture numerous dynamic, difficult-to-measure variables at the level of customers' orders. ETO uncertainty was also found to limit the predictability and visibility of numerous demand- and supply-related variations, as depicted by uncertainty connected by an arrow departing from complexity in Figure 5.2. Those types of uncertainty were found to require numerous dimensions of the quality of planning, presented in the figure as planning quality requirements connected by an arrow from uncertainty and another pointing downward to the IPNs. The latter arrow indicates that the requirements for the quality of planning increase the IPNs that S&OP has to handle in ETO operations to balance demand and supply. Details are available in Paper III.

The IPNs stemming from ETO uncertainty were found to be reduced within S&OP by IPMs creating slack resources and self-contained tasks, whereas S&OP's information-processing capacity was found to be increased by IPMs creating information system support and lateral relations. Those mechanisms are shown in Figure 5.2 in grayscale rectangles on the right side under the S&OP's information-processing mechanisms. On the left side of each grayscale rectangle, dimensions of the quality of planning represent corresponding outcomes resulting from the IPMs; those outcomes translate to reduced IPNs and increased information-processing capacity and lead to demand–supply balancing, as detailed in Paper IV.

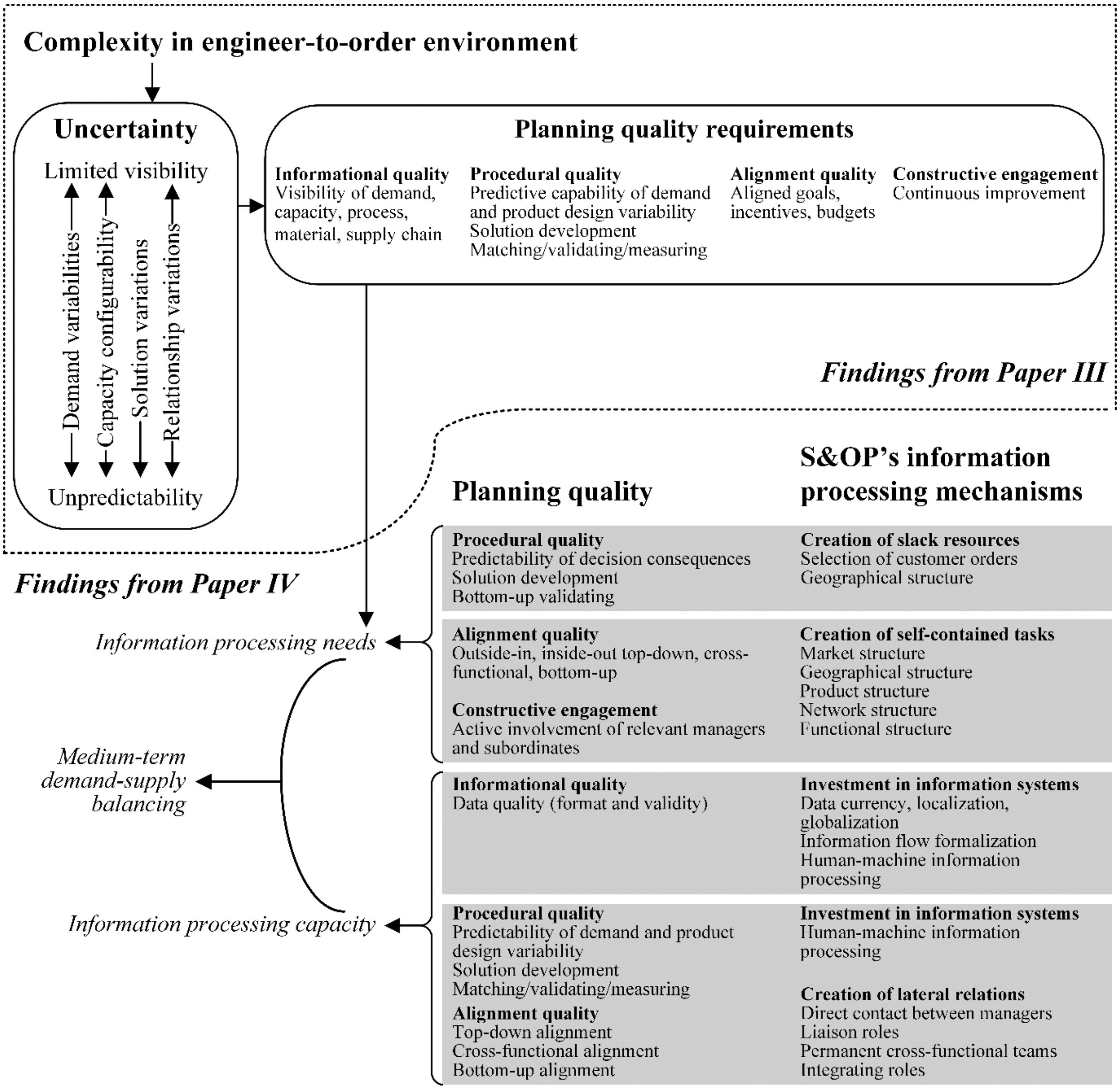



**Figure 5.2.** Engineer-to-order uncertainty and mechanisms of sales and operations planning (S&OP)

### 5.2.1. Information-processing needs

Complexity in ETO operations, represented by various areas of uncertainty, limits the predictability and visibility of variability in demand, the configurability of capacity, variations in solutions, and variations in relationships.

Demand volatility can be captured using several methods. However, when the data describing such volatility is found to be increasingly qualitative due to, for instance, underlying variables that are multifaceted, forecasting demand in ETO operations with acceptable accuracy is challenging (Jonsson & Mattsson, 2009). ETO demand comes in large bites that cause lumpiness, and lumpy demands are typically the trickiest to forecast (Gutierrez et al., 2008).

The configurability of capacity was found to result from the uniqueness of ETO demand that requires customization in products, production, and capacity, unlike changes in product designs delivered through mass customization (Gosling & Naim, 2009). As the customizability of products increases, the space of feasible solutions increases substantially. Manufacturers respond to pressure for increased customizability by establishing various types of relationships to increase flexibility regarding capacity, production, and supply chain configurations. Consequently, the manufacturing equipment becomes more general in purpose, the organization involves more specialists in various overlapping engineering domains, and material and services become delivered by various suppliers on various contractual terms. Such a considerable increase in variations was found to cause ambiguity for decision-makers when selecting from among alternatives and validating the consequences.

The findings show that the increased unpredictability of variability in demand manifests in hit rates, budget requirements, technical specifications, the number of products, item demand, and lower visibility of, for example, the characteristics of items in demand. The increased unpredictability of the configurability of capacity emerges as an expanded space for solutions concerning, among other things, production layout, inter-resource equivalences, the flexibility of production capacity, the quality of processes, and the pace of the development of labor skills. The lower visibility of the configurability of capacity applies to, for instance, setup costs, the availability of internal labor, labor productivity, and labor type.

The increased unpredictability of variations in feasible solutions concerns the overall customizability of products and the customizable systems per product. Increased variations in relationships with suppliers and subcontractors increase the unpredictability of subcontracting costs, among other things, and reduce the visibility of external labor and subcontractors, among other factors.

### 5.2.2. Information-processing mechanisms

ETO uncertainty was found to be managed within S&OP by IPMs representing the four primary IPMs that Galbraith (1977) has suggested: slack resources, self-contained tasks, information system support, and lateral relations. Figure 5.3 presents a breakdown of the IPMs divided into primary (i.e., in bold grayscale) and secondary mechanisms within S&OP. The gray arrows start from variables that increase the requirements on the corresponding mechanisms.

Creating slack resources was found to take two underlying forms within S&OP: strictly capacity-oriented order selection and centralized planning, engineering, product, and procurement. Moving from the strategic–tactical interface to the tactical level, the consequences of selecting customers' orders become more challenging to redress as increasingly more capacity becomes committed to order fulfillment. Selecting orders may ensure the minimal commitment of capacity and customization and the maximum budget per order fulfillment. ETO demand represents large orders that require attention beyond volume, and each order drains substantial capacity (Hicks et al., 2000). Therefore, the pressure on S&OP to unlock slack resources requires tackling demand at the level of customers' orders. The variables that may unlock slack resources include additional allowances for delivery lead times, an internal budget for capacity, and capacity requirements for order fulfillment and customization.

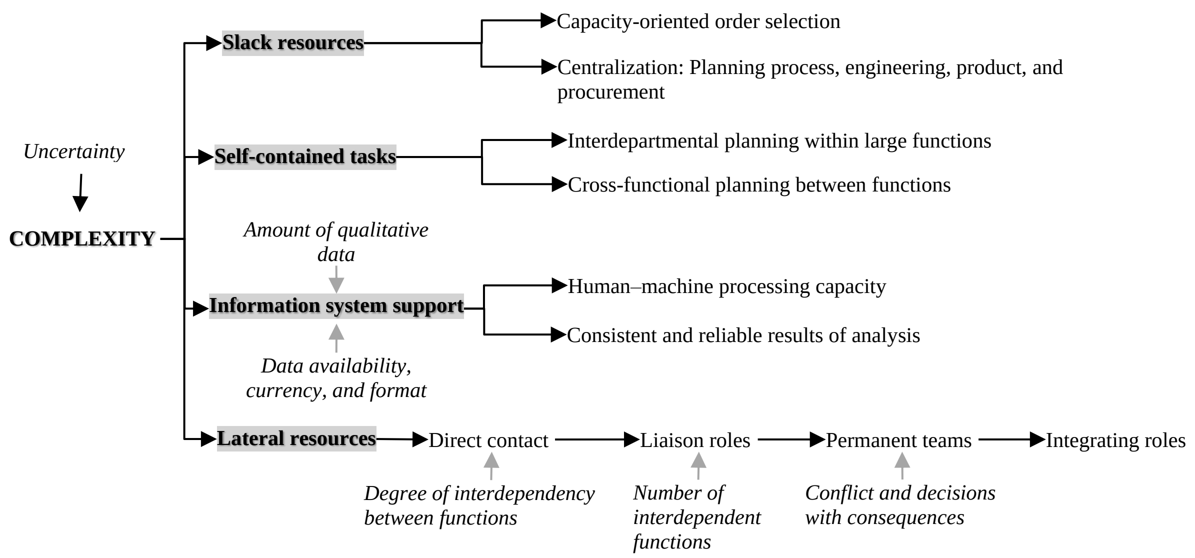



**Figure 5.3.** Primary and secondary information-processing mechanisms in sales and operations planning

Apart from order selection, intensive engineering in ETO operations was found to increase the need for centralizing the engineering capacity to the same level of S&OP. Such centralization minimizes constraints on capacity by reducing suboptimization at local levels. Similarly, due to the considerable manufacturing and supply chain complexity in ETO operations (Alfnes et al., 2021), centralizing products and procurement through a network structure is crucial. Centralizing S&OP and commodities through a functional structure may also be necessary.

As ETO uncertainty increases, the pressure to create self-contained tasks within S&OP increases as well. For instance, as customers become increasingly represented and influential in a market, continually learning about and influencing those customers' operations in all regions becomes increasingly significant. In addition, planning customized order fulfillment requires input from numerous divisions within functions that have large organizations, including product development, production, and the supply chain network (Bhalla et al., 2021). Therefore, S&OP needs to facilitate self-contained planning and the reciprocation of information about the plans dedicated to the business's overall objectives from each division's perspective.

ETO uncertainty was also found to require the processing of significant qualitative data, as Mello et al. (2015) have similarly shown. Therefore, making informed decisions using information system support requires effectively combining human and machine information processing. That combination has to ensure data availability, data currency, and the consistency of data formatting to various decision-makers across the functions and hierarchies. In addition, it needs to ensure consistent, reliable results of analysis even when conducted by different analysts.

Qualitative data are difficult to manipulate (e.g., aggregate, consolidate, and/or condense) using automated data processes (Evers, 2018; Tenhiälä, 2011). Therefore, handling such data within S&OP is often a manual activity (Bhalla et al., 2021). Machines alone cannot enable information system support for fact-based decision-making (Kjellsdotter Ivert & Jonsson, 2014), for they make limited contributions to specific complementary analyses in a few activities, and integration is therefore necessary (Schlegel et al., 2020). Individuals have to manually ensure that the data available to various decision-makers across the functions and hierarchies are up-to-date and available in a suitable format. Findings in Paper III show that those requirements specifically apply to data that visualize demand (e.g., tender requests and due dates), products (e.g., customizability and incompatibilities), machine capacity (e.g., performance and constraints), labor capacity (e.g., skills, availabilities, and learning curves), processes (e.g., setup cost dependencies and task requirements), materials (e.g., items' life cycles), and the supply chain (e.g., outsourceable requirements for customization).

In addition, qualitative data represent a challenge for the consistency of analyses. The greater the degree of human involvement in information processing, the greater the tendency of performing inconsistent analyses (Ackerman, 1987). In other words, the need for manual analysis reduces the reliability of the results of analysis. After all, S&OP needs to ensure consistent results from critical information flows and human–machine interactions.

Last, reducing ETO uncertainty was found to be possible by leveraging various lateral relations within S&OP. Figure 5.3 shows that complexity in the cross-functional interaction of S&OP represents cross-functional interdependency. The lower the interdependencies between functions and underlying divisions, the more likely that cross-functional problems are resolvable through direct contact between corresponding managers (Galbraith, 1977). As such interdependency increases, coordinating lateral relations between functions needs to shift from a direct contract between managers to liaisons. A plan suggested by one function may need revision or be subject to rejection due to constraints evidenced at the other function. A typical example in ETO operations is involving engineering and production managers in meetings to review demand in order to gain immediate feedback and validate the feasibility of the proposed plan for demand.

If interactions require systematic handshaking between more than two functions or divisions, forming permanent teams representing those functions is necessary. That dynamic explains why S&OP processes, even in contexts other than ETO environments, often have permanent teams dedicated to coordination (Noroozi & Wikner, 2017; Tuomikangas & Kaipia, 2014). Within functions, representatives from divisions need to be assigned as permanent participants in functional meetings within S&OP—for example, sales specialists as permanent participants of meetings to review demand and engineering managers as permanent participants in meetings to review engineering capacity.

When conflicts and decisions with consequences increase, integrating roles is necessary due to increased task uncertainty, as Galbraith (1977) has similarly found, because decisions and decisions of consequence in joint-decision processes result from increased differentiation between departments. An example of such interaction concerns facility and maintenance planning. Whereas planning those areas in standardized-product settings is relatively stable, it is dynamic in ETO operations. Resolving conflicts and making decisions to align plans for facilities and maintenance require individual integrators (e.g., industrial managers or specialists) to ensure regular communication across product family departments involving, for example, controllers, operations managers, facility managers, maintenance managers, and machine purchasers. That order of lateral relations represents moving from the simplest, least costly form to the most advanced, most expensive form (see Figure 5.3).

## 5.3. Research Question 3: Complexity and material delivery schedule instability in CTO operations

RQ3 addresses how complexity in CTO operations influences instability within material delivery schedules. Complexity in CTO operations was found to generate instabilities through contextual variations and aspects of process design, as shown in Figure 5.4. Variations can appear in quality (i.e., conditions causing disruptions in production), quantity (i.e., low actual demand and discrepancies in inventory stock), and timing (i.e., uncertain item life cycles, late increases in demand, late changes in end-item specifications, misaligned supply chain operation times, short frozen production schedules, switching suppliers, and the visibility of underdeveloped master production schedules). Aspects of process design include the insufficient buffering of time (i.e., changed transport lead times and uncertainty about suppliers' inventory), the insufficient buffering of inventory (i.e., suppliers' limited flexibility and an inadequate safety stock policy), and the insufficient buffering of capacity (i.e., high enforcement levels for order fulfillment). Other dimensions of process design include bottlenecks in the system (i.e., requirements for full-truckload optimization), scale (i.e., low pickup frequency, suppliers' lot sizing, inadequate replanning periodicity, and large packaging), and scope (i.e., item variety and limited scalability in capacity).

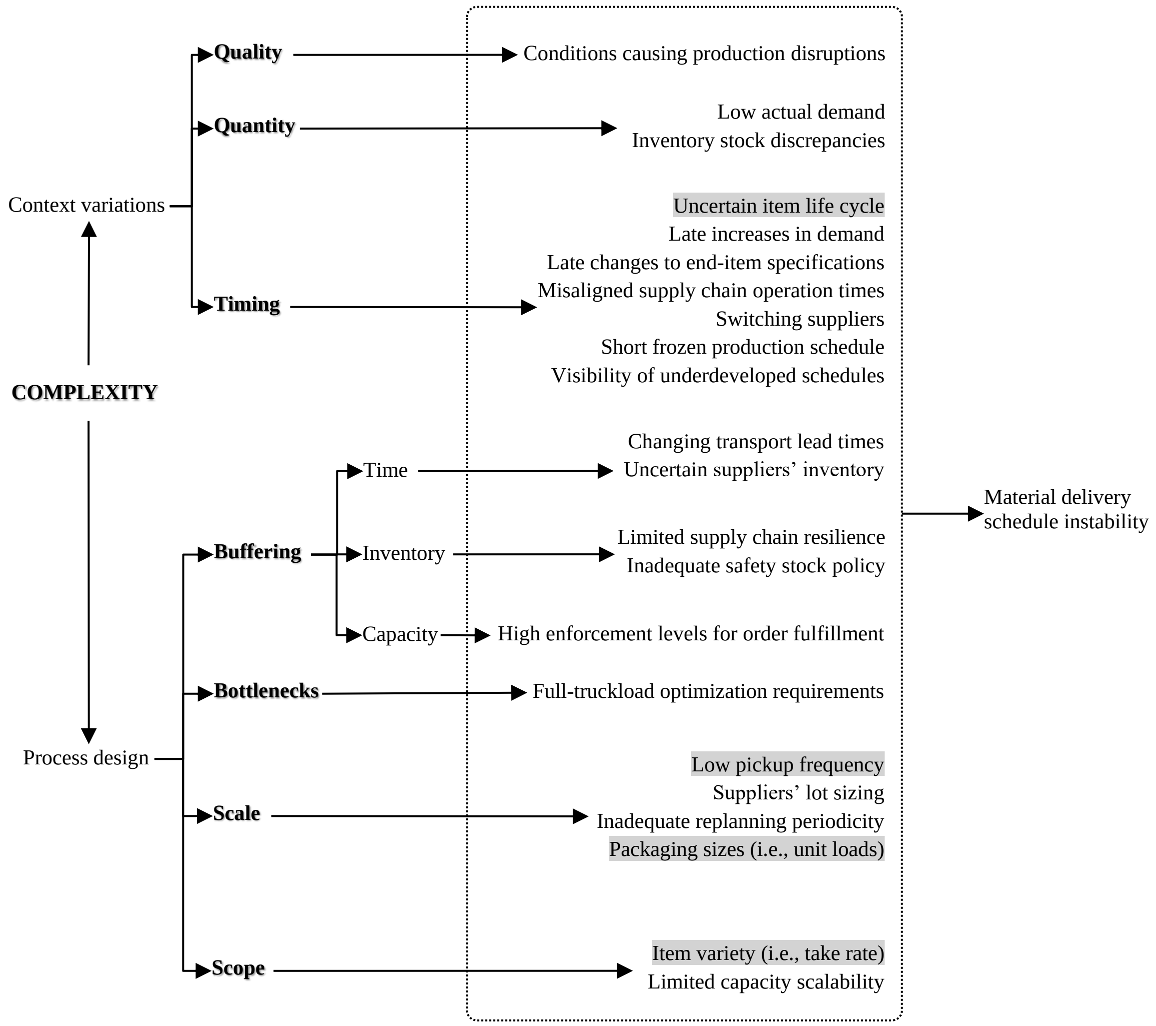



**Figure 5.4.** Complexity factors of instability within material delivery schedules

From the perspective of complexity theory, instabilities within material delivery schedules emerge primarily through drivers of dynamic complexity representing horizontal interactions within internal operations. Only two drivers of structural complexity were found to be relevant: the variety of products and planning models' algorithms. The supply chain was not found to directly induce instabilities, however.

Instabilities within the fixed period of production schedules represent the only driver of complexity found to directly affect the instability of delivery schedules. Several factors moderate the impact of production instability, and numerous factors causing production instability are identified: forecasting difficulty, changes to end-items shared on identical product lines, a lack of control over processes, changes in network design and flows, actual demand, late changes to end-item specifications, late demand, uncertainty in product life cycles, and the uncertainty and reliability of suppliers' lead times and quality (see Paper V for details).

The schedule horizon was found to statistically explain the effect of four variables on instability, which are shaded in gray in Figure 5.4: item's order life, take rate, unit load, pickup frequency, and modularized product configurations (see Paper VI for details). The following subsections discuss factors of complexity from a process-oriented perspective and the underlying complexity interactions that corroborate the findings shown in Figure 5.4.

### 5.3.1. Complexity factors causing schedule instability: A process-oriented perspective

Context-driven instability surfaces as variations in quality, quantity, and timing (Holweg et al., 2018). Variations in quality were found to manifest as disruptions in production due to the limited reliability of production. Disruptions destabilize production schedules and are seemingly the only direct causal factor of material instability within the fixed period, as detailed in the next subsection. Past studies have also confirmed such a relationship (e.g., Blackburn et al., 1985; Carlson et al., 1979; Steele, 1975).

Variations in quantity were found to stem from low actual demand and discrepancies in inventory stock, the latter of which has been proposed in several previous studies (e.g., Inman & Gonsalvez, 1997; Pujawan & Smart, 2012). Dampening the causal effect of those variations in quantity is challenging, and time fences (i.e., frozen portions of production schedules) are effective only until actual demand no longer covers the fixed periods that become partly based on forecasts (Narayanan & Robinson, 2010).

Variations in timing were found to originate from uncertainty in item life cycles (Nepal et al., 2012; Wänström & Jonsson, 2006), late increases in demand (e.g., Atadeniz & Sridharan, 2019), late changes to end-item specifications (e.g., Pujawan et al., 2014), unaligned supply chain operation times (e.g., Inman & Gonsalvez, 1997), short frozen production schedules (e.g., Atadeniz & Sridharan, 2019), switching suppliers, and the visibility of underdeveloped schedules. Such variations represent dynamic complexity that significantly influences instability, as also detailed in the next subsection.

The findings show that process-driven instability occurs due to insufficient buffering, bottlenecks, and expanding scales and scopes of processes, which aligns with Holweg et al.'s (2018) process theory. The first type includes the insufficient buffering of time, encompassing changed transport lead times (e.g., Inman & Gonsalvez, 1997) and uncertainty about suppliers' inventory (e.g., Pujawan & Smart, 2012); the insufficient buffering of inventory, encompassing inadequate safety stock policies (e.g., Atadeniz & Sridharan, 2019) and suppliers' limited flexibility; and the insufficient buffering of capacity, encompassing high enforcement levels for order fulfillment. *Suppliers' flexibility* refers to "the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions and recover from them" (Ponomarov & Holcomb, 2009, p. 131). It is presented in the literature as a concept related to managing disruptions in the supply chain (e.g., Kamalahmadi & Parast, 2016; Ponomarov & Holcomb, 2009).

The enforcement levels in the supply chain confine the flexibility of suppliers to deliver material within ranges instead of exact volumes (Forslund et al., 2021). If not, then enforcement policies impose penalties. The findings show that the more stringent those policies, the greater the instability. Suppliers capable of efficiently changing schedules repeatedly should be selected (e.g., Krajewski et al., 2005), because such flexibility enhance suppliers' flexibility. However, if the bases of the supply chain are extensive, then maintaining responsiveness in CTO operations is challenging, particularly because an enormous amount of data has to be revisited systematically. The findings recommend an opposite approach to minimizing instability: augmenting abilities to absorb internal disruptions, thereby affording suppliers' higher delivery quantities and more tolerant time frames.

Process-driven factors of instability were found to include bottlenecks (i.e., requirements for full-truckload optimization requirements), scale (i.e., low pickup frequency and suppliers' lot sizing; e.g., Inman & Gonsalvez, 1997), inadequate replanning periodicity (e.g., Pujawan & Smart, 2012), large packaging (e.g., Inman & Gonsalvez, 1997)), and scope (i.e., item variety and the limited scalability of capacity).

Planning systems for material requirements optimize material availability (Ptak & Smith, 2019). Nevertheless, environmental regulations increasingly push toward minimizing deliveries and maximizing truckloads (Wong et al., 2018). Low pickup frequencies can also result from supplier–buyer agreements (Krajewski et al., 2005) or constraints on a supplier's system. Such conditions were found to moderate any causal effect on instability as flexibility in delivery declines.

Constraints on the scalability of capacity determine the requirements for scaling capacity up or down, including heavy investments in the production infrastructure (Deif & ElMaraghy, 2006). The mechanism of slack capacity (e.g., higher strategic stock and more scalable capacity; see Galbraith, 1977) moderates the impact of causal factors on instability. Slack capacities allow optimizing performance in situations wherein decision-makers are risk-averse or when the probability of disruption is high (Nejad & Kuzgunkaya, 2014). Volatile demand environments require operations that enable adapting the underlying capacity repeatedly under as little ramp-up delay time as possible (Kim & Duffie, 2004). That capability has to be developed to the extent that it matches production stability with required market responsiveness without ending in production overshooting or unnecessary investments (Deif & ElMaraghy, 2006).

### 5.3.2. Complexity interactions leading to schedule instability

Several complexity interactions leading to instability in material delivery schedules were identified in the research. Complexity interactions can be vertical, horizontal, or diagonal (Dittfeld et al., 2018), and structural complexity was found to generate schedule instability through one diagonal interaction and one horizontal interaction.

Diagonally, when an OEM in CTO operations increases product variety, typically for competitiveness, the demand becomes more segmented and makes demand more variable, as past studies have highlighted (e.g., Aitken et al., 2016; Bozarth et al., 2009). Increases in demand variability lead to instability through three primary causal interactions (see Figure 5.5).

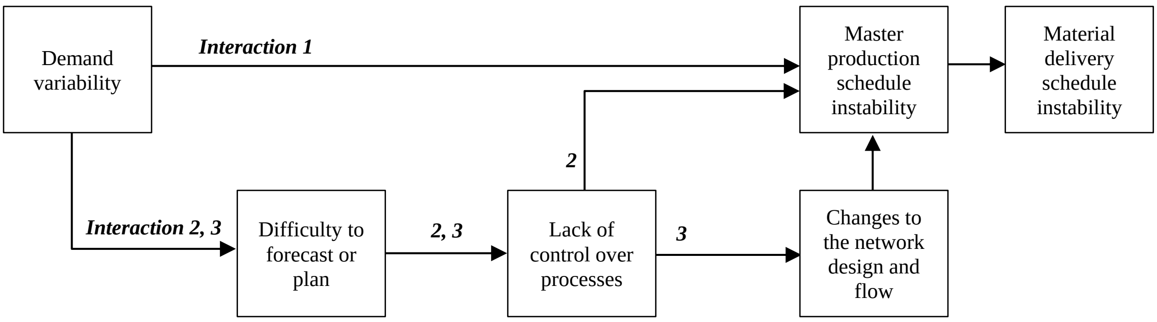



**Figure 5.5.** Diagonal complexity interactions generating schedule instability

Horizontally, in line with Serdarasan (2013), when the variety of algorithms used within an OEM's planning models in CTO operations grows, the ambiguity of planning logic and consequences increases. Such ambiguity causes instability through three primary causal interactions (see Figure 5.6).

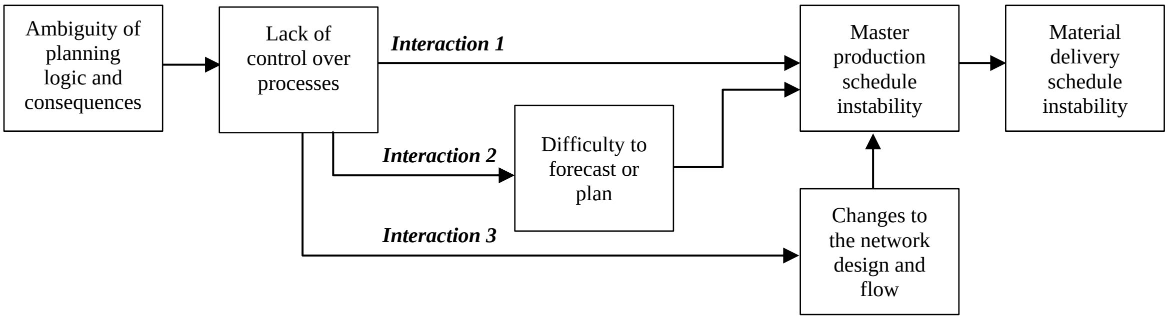



**Figure 5.6.** Horizontal interactions triggered by structural complexity leading to schedule instability

In line with previous research (e.g., Bozarth et al., 2009; Fernández Campos et al., 2019; Serdarasan, 2013), the findings additionally show that schedule instability is primarily caused and moderated by internal horizontal interactions. All causal interactions lead to instability by causing production instability, as suggested in many published works (e.g., Meixell, 2005; Narayanan & Robinson, 2010; Nepal et al., 2012; Sivadasan et al., 2013). Five factors moderate the impact of production instability on instability: market pressure and changes in customers' requirements (i.e., vertical demand-driven moderator), uncertainty in supply chain synchronization and compatibility (i.e., vertical supply chain-driven moderator), high enforcement levels on supply chain order fulfillment (i.e., horizontal moderator), constraints on the scalability of capacity (i.e., horizontal moderator), and suppliers' flexibility (i.e., vertical supply chain-driven moderator). Some studies have considered the first two factors to be drivers of complexity (e.g., Bozarth et al., 2009; Fernández Campos et al., 2019).

Numerous direct horizontal and vertical interactions were found to result in production instability. Three horizontal interactions apply such that when the forecasting difficulty increases, the following increases: changes in end-items shared on identical product lines, lack of control over processes, and changes to network design and flow. Three vertical demand-driven interactions also apply such that when the actual demand decreases, late changes in end-item specifications increase, late increases in demand increase, and the uncertainty of the product life cycle increases. Last, one vertical supply chain-driven interaction applies, starting with when the uncertainty and unreliability of suppliers' lead times and quality increase.

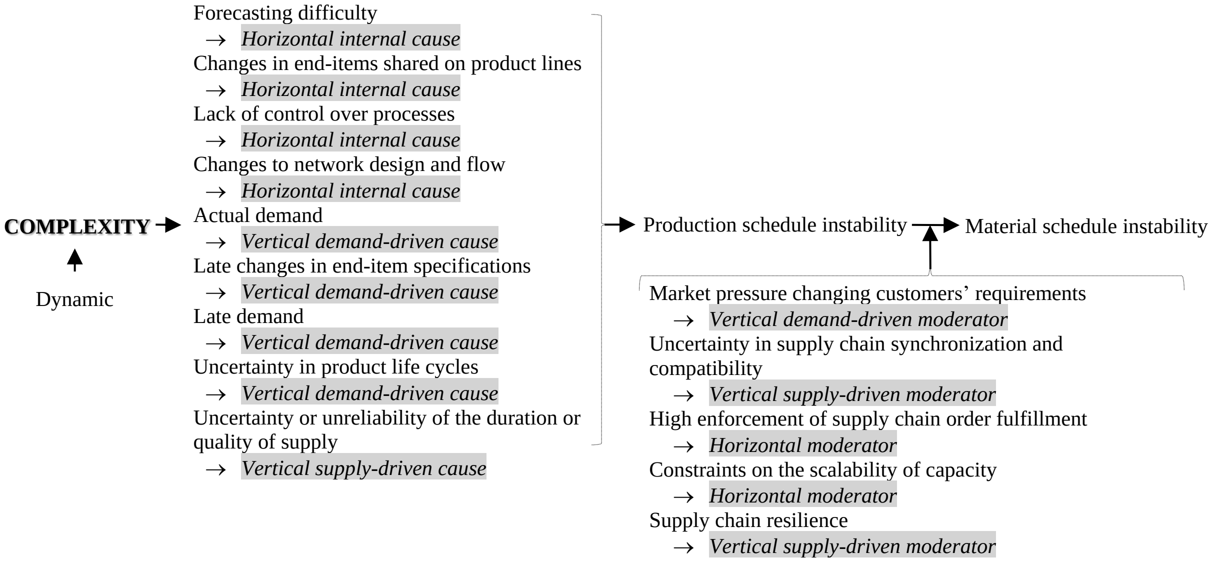



**Figure 5.7.** Factors of dynamic complexity interactions leading to schedule instability

The supply chain was not found to directly influence instability, especially when firms insource inbound logistics operations. By contrast, many studies have confirmed the role of the supply chain, either explicitly (e.g., Law & Gunasekaran, 2010; Pujawan & Smart, 2012) or indirectly (e.g., Dittfeld et al., 2018; Fernández Campos et al., 2019; Serdarasan, 2013). Figure 5.7 presents factors of dynamic complexity interactions leading to schedule instability.

### 5.3.3. Factors explaining schedule instability

Findings from Paper VI verify that the impact of factors explaining schedule instability differs depending on the planning horizon. The factors that potentially explain delivery schedule inaccuracies include items' take rate, items' life cycle, package size, and pickup frequency, as shaded in gray in Figure 5.4.

The inaccuracies of delivery schedules in MAPE were measured at the item level and within weekly bundles, starting from 20 weeks to 1 week before the delivery is due. The average MAPE values were as follows: 23% (i.e., 2-week horizon), 28% (i.e., 4-week horizon), 45% (i.e., 8-week horizon), and 53% (i.e., 12-week horizon).

The forecasted volume, production deviation, and transportation lead times were not significant in any regression model. The forecasted volume was not significant either, due to uncertainty concerning the number of units used per assembled car. Production deviation causes uncertainty only within fixed periods (Atadeniz & Sridharan, 2019; Pujawan & Smart, 2012), especially in the case of items with low take rate. One reason for the non-significant effect of production deviation in the regression models is the correlation with the order life. Another possible reason for the invisibility of the impact of daily deviation in production in the weekly bundles is that most losses in production capacity are resolved by overtime on the weekends during the same weeks. Unexpectedly, longer transport lead times did not significantly affect the regressions, perhaps due to the transportation lead times of most items that were shorter than a week at the OEM.

The item's order life and take rate have the most significance, as shown in some of the 5% and 10% models and all of the 50% and 100% models in Paper VI. The item's order life significantly impacts longer horizons due to the short sales history in the item's early life cycle, which limits the accuracy of demand forecasts (Wänström & Jonsson, 2006). It has a similar short-term effect specifically for the phased-out stage of items. In other words, the later an item is in the life cycle, the larger the probability of inaccuracy on shorter horizons. Increased inaccuracy was also identified for items close to phase out due to, for example, changed safety stocks and late phased-out rescheduling. Consequently, the order life cycle can explain schedule inaccuracies, with varying impacts on short and long horizons. The measure of order life cycle used indicates how late in a life cycle an item is, whereas alternative life cycle measures may cover other patterns such as phased-in and steady-state periods (Nepal et al., 2012).

Items' unit load per weekly demand was significant in all models, with a reverse effect for the 5% and 10% models compared with the 50% and 100% models. Larger unit loads stabilize minor variations but increase high inaccuracies under significant variations because they make the demand lumpier (Wänström & Jonsson, 2006). Items' pickup frequencies represented another variable with a significant effect in all regression models. In short, the greater the frequency, the greater the inaccuracy. Similar to unit loads, the frequencies are spread between daily and weekly schedules, and variations from daily pickups do not affect the schedule's accuracy if the weekly requirement is aggregated in weekly pickups.

Items' take rates—an operationalization of item commonalities—were significant in all models as well. Items with low take rates have lumpier and more intermittent demand due to, for example, batch sizing and unit loads. An increase in the total number of such items indicates the decreasing commonality between the items, which negatively influences instability (Meixell, 2005). The take rate's effect on the 2-week horizon similarly applies to other longer horizons and thus causes short-term inaccuracies.

Some car variants show significance in all horizons or levels of inaccuracy. The significant values on some horizons and levels of inaccuracy also differ in direction. Therefore, product modularization represents a potential causal factor that explains schedule instability. Nevertheless, interpreting how and why different car variants explain MAPE is too complex. A more detailed analysis of those models' operating variables and conditions is required to unlock a more granular understanding.

# 6. Discussion

This chapter discusses the thesis's results, suggesting a conceptual framework for managing the complexity affecting demand–supply balancing and highlighting the contributions to theory (Section 6.1). The chapter ends with a summary of managerial implications (see Section 6.2).

## 6.1. Conceptual framework and theoretical contributions

This thesis aims to elucidate how complexity in manufacturing operations influences demand–supply balancing and planning at the tactical level. Figure 6.1 shows a proposed framework that synthesizes the results of the thesis and extends its conceptual framework presented in Figure 2.1.

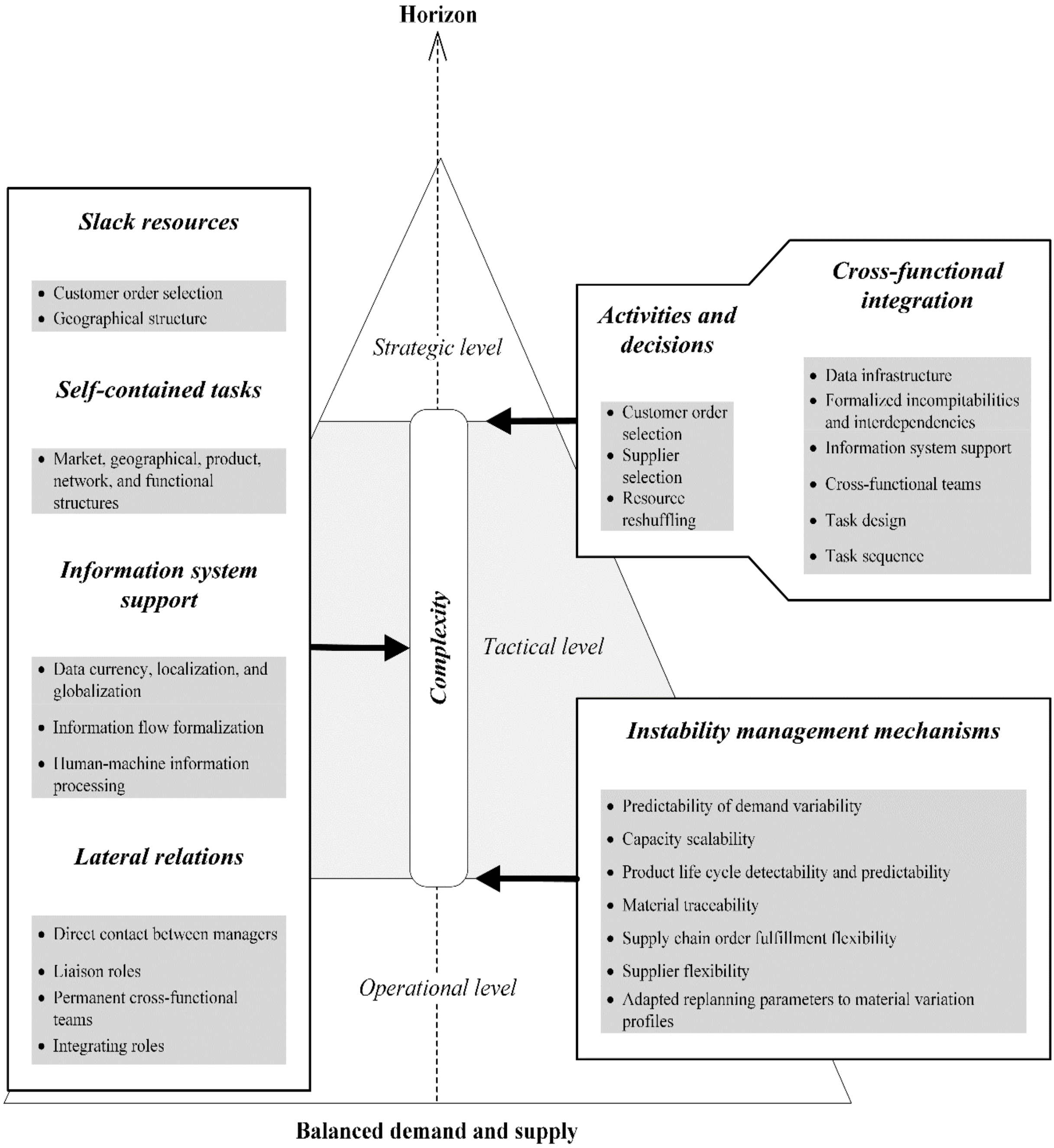



**Figure 6.1.** Summary of the implications of the findings in a conceptual framework

At the pyramid's strategic level, an arrow from the right points toward a high level on the x-axis (i.e., long-term horizon), thereby indicating that a set of mechanisms of cross-functional integration and planning activities and decisions within the customer order fulfillment process enable demand–supply balancing by managing the complexity at the strategic–tactical interface. Subsections 6.1.1–6.1.2 discuss the proposed constructs in greater detail.

At the pyramid's tactical level, an arrow from the left points toward a middle level on the x-axis (i.e., medium-term horizon), thereby indicating that a group of IPMs within S&OP enables demand–supply balancing by managing the complexity at the tactical level. Subsection 6.1.3 discusses the proposed constructs in greater detail.

Last, at the pyramid's operational level, an arrow from the right points toward a low level on the x-axis (i.e., short-term horizon), thereby indicating that mechanisms of instability management within material delivery scheduling enable demand–supply balancing at the tactical–operational interface. Subsection 6.1.4 discusses the proposed constructs in greater detail.

Subsections 6.1.1–6.1.4 also delineate how the thesis's results bridge theoretical gaps and respond to calls from previous research. The theoretical implications are summarized and presented in Subsection 6.1.5.

### 6.1.1. Medium-term demand–supply balancing within the customer order fulfillment process

Following a multidisciplinary approach, the underlying research connected literature from various areas—ETO operations management, complexity management, organization design, and tactical planning—to address the influence of complexity on demand–supply balancing at the strategic–tactical interface, with an emphasis on the customer order fulfillment process. Because this thesis assumes that the complexity affecting demand–supply balancing at the strategic–tactical interface is at relatively high in ETO operations, it draw on Gosling and Naim's (2009) generic insights concerning the concept of ETO, its conditions, and what it entails. Since that study, Gosling et al. (2017) and Cannas et al. (2019) have enriched the discussion of the concept by providing details about ETO typology based on a postponement strategy. This thesis extends the implications of various ETO-related concepts on the complexity affecting demand–supply balancing, with an emphasis on the customer order fulfillment process.

Adrodegari et al. (2015), Carvalho et al. (2015), Cooper and Budd (2007), Giebels et al. (2000), Hans et al. (2007), Potts and Ankrah (2014), and Weber et al. (2000) have provided rich insights into various activities and decisions within the customer order fulfillment process. This thesis adds detail to some of those activities and decisions as interconnected building blocks relevant to the complexity affecting medium-term demand–supply balancing. It thus offers a generic reference framework for tactical planning in ETO environments.

The proposed framework features interdependencies and sequences not addressed in previous studies. For instance, Hans et al. (2007) described rough-cut capacity planning and the selection of customers' inquiries as a unified subprocess without explicitly distinguishing inquiry selection from acceptance. Findings presented in Paper I show that rejecting orders can occur in the late stages of the order fulfillment process, even after contracts have been won. Therefore, accepting and rejecting orders are possible actions after the selection of inquiries. However, in several ETO businesses, customers impose penalties as conditions for bidders to prevent the late rejection of orders.

Another finding concerns rough-cut capacity planning, which according to the results is a subprocess with two primary resource-loading activities: resource loading for pre-contract activities, such as inquiry analysis, and resource loading for post-contract engineering and production. Giebels (2000) and Carvalho et al. (2015) have characterized resource loading as being limited to post-contract activities. At the same time, resource loading for pre-contract activities is critical because evaluating the customization requirements of incoming inquiries serves as the available-to-promise capability of ETO operations (Olhager, 2010). Such capability is generally constrained by the scarcity of personal who assess customers' inquiries such as estimation engineers and delivery specialists (Cooper & Budd, 2007). The procurement associated with the two resource-loading activities is also not explicitly visible in the literature as different activities with different objectives.

Fernández Campos et al. (2019) have proposed generic managerial practices as mechanisms for reducing and absorbing complexity in operations. This thesis highlights mechanisms of demand–supply balancing in the order fulfillment process by drawing on the potential consequences of underlying tactical-level activities and decisions. Figure 6.1 suggests optimizing the selection of customers' orders, optimizing the selection of suppliers, and performing aggregate capacity reshuffling to manage the complexity affecting demand–supply balancing at the strategic–tactical interface.

First, order screening potentially influences critical capacity and variations in customers. Selecting, prioritizing, and winning research-to-order or develop-to-order inquiries necessitate tying scarce competencies capable of fulfilling complex customers' orders effectively (Cooper & Budd, 2007). Selecting, prioritizing, and winning inquiries from strategic customers minimize the structural and dynamic complexity that ETO operations have to manage and increase operational capabilities in focal areas. Strategic customers represent a limited but reliable market segment that generates significant sales and requests similar product requirements more frequently than unique ones (Bozarth et al., 2009). Such selection serves as a strategy for reducing complexity and thereby reducing variety in demand to mitigate the negative impact of the product portfolio (Fernández Campos et al., 2019).

Focusing on strategic customers also allows identifying core market segments that ETO-oriented firms should target. Such clarity guides the development of capabilities toward core customers' needs within narrowed domains. Aligning the selection of orders with the firm's critical capability improves the overall win rate due to increased excellence in customization and reduced orders through the customer order fulfillment process (Cooper & Budd, 2007). Thereby, selecting and prioritizing orders can make demand–supply balancing easier. That proposition especially applies to situations when the targeted markets are booming and planners need to select options that help to avoid over- or undercapacity (see Paper I).

Second, the selection of suppliers potentially influences critical capacity and the supply chain's reliability. The pressure for coordination resulting from the proliferation of suppliers can be handled by utilizing available capacity more efficiently, acquiring additional capacity, or combining those two mechanisms (Hans et al., 2007). Using available capacity more efficiently is possible by optimizing the allocation of critical capacity. One example of such allocation is assigning critical specialists to orders that require substantial coordination through the purposeful reshuffling of projects' organizations (Ventroux et al., 2018). As for the supply chain's reliability, reducing external contributors entails reduced constraints and dependencies and thus represents a decoupling practice that mitigates the negative impact of external complexities on operations performance (Fernández Campos et al., 2019). Reducing specific external contributors (e.g., foreign external contributors, suppliers with incompatible planning and control systems, and suppliers with volatile production environments) lowers the pressure for coordination considerably.

Third, aggregate multiple-order review represents the heart of demand–supply balancing at the strategic–tactical interface. It potentially influences the supply capacity and demand intake as a result of modifications applied at the level of customer orders that, in turn, allow maximizing synergies among resources and minimizing compromises across parallel ongoing and upcoming orders. The primary objective of such optimization is to match customers' orders with the suitable critical capacity. Accordingly, the required modifications to reach an optimal resource allocation serve as a reference for reshuffling the projects' organizations (Ventroux et al., 2018). In that way, aggregate multiple-order review delivers complexity-absorbing and complexity-reducing impacts. When a specific state of complexity representing stable demand and supply capacity applies, an aggregate multiple-order review can unlock additional capacity using available resources by adequately distributing risks. For instance, critical competencies manage riskier projects involving new and global suppliers with long and less reliable lead times and compatibility.

### 6.1.2. Medium-term demand–supply balancing through cross-functional integration

Many studies have emphasized cross-functional integration within tactical planning and how the underlying mechanisms facilitate demand–supply balancing (e.g., Goh & Eldridge, 2019; Oliva & Watson, 2011; Tuomikangas & Kaipia, 2014). The focus, however, has been limited to the S&OP domain. The neglected focus on the customer order fulfillment process may be due to its rare associations with tactical planning, a relationship that this thesis explores.

A traditional perspective conceptualizes cross-functional integration as a combination of interaction and collaboration (Kahn, 1996a). This thesis refined that concept by instead viewing coordination and collaboration as dimensions. Therein, interaction is merely the medium of integration that reflects a degree of coordination and collaboration. In that way, the thesis outlines cross-functional integration as a broad area that can be studied by focusing on coordination and/or collaboration because the adequate research method to deepen the understanding of the two concepts is arguably different.

By way of primary mechanisms, cross-functional integration increases the performance of organizations and processes in general (Turkulainen & Ketokivi, 2012). This thesis provides numerous examples of how mechanisms of cross-functional integration that manifest in the customer order fulfillment process are critical in ETO operations. As implied, those mechanisms reduce and absorb the complexity affecting demand–supply balancing at the strategic–tactical interface. Figure 6.1 shows six relevant mechanisms, which are discussed in greater detail in what follows.

First, formalizing policies and procedures increases a process's procedural quality. Such an increase implies the enhanced validity of information and reduced uncertainty (Oliva & Watson, 2011). Second, adequate data management infrastructures doubtlessly mean greater information-processing capacity (Galbraith, 1977). Such infrastructure usually exists at high-performing firms (Galbraith, 1977; Troy et al., 2008), which implies that it increases complexity-absorbing capacity (Fernández Campos et al., 2019).

Third, minimizing the number of cross-functional team members and maximizing the representation of various levels of experience, age, and tenure boost the order fulfillment team's overall information-processing capacity. Balancing experience, age, and tenure among the team members represents an act of distributing critical competencies adequately, which typically leads to a higher overall win rate (Cooper & Budd, 2007).

Fourth, the design of tasks is a generic mechanism of cross-functional integration with potential complexity-absorbing capacity (Hirunyawipada et al., 2010; Holland et al., 2000). Designing tasks ensuring a problem-solving orientation and cohesion increases the complexity-absorbing capacity within order customization and workload analysis as well. Having clear, problem-oriented objectives for tasks reduces the uncertainty concerning which functions should execute certain tasks (Daugherty et al., 1992). Such task cohesion is an effective mechanism of cross-functional integration for design activities (Hirunyawipada et al., 2010). Within customization and workload analysis, it potentially unlocks capacity availability because tasks become practicable by more individuals.

Fifth, task concurrency also absorbs complexity (Fernández Campos et al., 2019), especially within order customization and workload analysis. It manifests as the maximized parallelization of tasks with interdependent product development and manufacturing functions. That parallelization enhances the capability of information validation within engineering interactions due to familiarity with the tasks gained earlier (Oliva & Watson, 2011) and thus leads to simplified, cost-effective designs (Sherman et al., 2005).

Sixth, having advanced information system support for products and production design modeling and optimization generates considerable complexity-absorbing potential in customization and workload analysis. Capable information systems support decision-making, and the generation of knowledge mitigates the negative impact of supply-related dynamic complexity on operations (Fernández Campos et al., 2019). The enhanced capability to optimize product functionalities implies efficiently testing solutions within problem-solving activities (e.g., Sherman et al., 2005; Troy et al., 2008).

### 6.1.3. Medium-term demand–supply balancing through information processing

Following a multidisciplinary approach, the underlying research connected literature from various areas—ETO operations management, organization design, and S&OP—to describe the influence of complexity on demand–supply balancing at the tactical level with an emphasis on the S&OP process. Alfnes et al. (2021), Cannas et al. (2020), and Gosling et al. (2017) have provided rich insights into ETO uncertainty in various decoupling settings. This thesis presents a more comprehensive overview of such uncertainty. As shown in the literature on S&OP, previous works have been highly practice-oriented and provided case-specific recommendations (e.g., Bhalla et al., 2021; Christogiannis, 2014; Kymäläinen, 2020; Romão et al., 2021; Sharma, 2017). Therefore, the research presented here was designed to sort out generic and case-specific areas of uncertainty and highlight the influence of each type of uncertainty on demand–supply balancing and the requirements for ensuring the quality of planning to address it adequately.

The literature on S&OP addressing context-dependent configurations of processes in operational environments other than ETO settings also reveals substantial fragmentation and a lack of theoretical support for configuring S&OP in line with its context (Kreuter et al., 2021a; Kristensen & Jonsson, 2018). This thesis contributes to research on context-fitted S&OP in two areas. First, it provides empirical evidence of the requirements for S&OP quality as shaped by the IPNs in a complex manufacturing environment such as ETO operations. Second, it translates the S&OP process into IPMs, thereby reducing uncertainty by absorbing it and reducing IPNs directed toward demand–supply balancing. The information-processing perspective has been adopted in one S&OP-related study (Schlegel et al., 2020), and the thesis contributes to that effort by showcasing the suitability of applying information-processing theory to elucidating context-relevant S&OP process design.

The complexity affecting demand–supply balancing at the tactical level is substantial in ETO operations and increases the pressure for quality S&OP (Bhalla et al., 2021). Such pressure emerges from engineering changes to a product's design after customers' orders are received (Cannas et al., 2019) and translates into uncertainty during decision-making (Serdarasan, 2013). Therefore, establishing an S&OP process able to effect demand–supply balancing requires an information-processing capacity that accommodates the IPNs resulting from uncertainty (Schlegel et al., 2020).

The IPNs resulting from ETO uncertainty translate to requirements for quality in S&OP. According to

Oliva and Watson (2011), the quality of S&OP can be divided into informational quality, procedural quality, alignment quality, and constructive engagement. Along those lines, as shown in Figure 5.2, managing complexity at the tactical level requires abilities to visualize, predict, and resolve uncertainty, as well as cross-functional coordination and collaboration to support the interactions involved.

First, ETO environments require S&OP to have informational quality in order to provide data of suitable format and validity regarding each ETO-specific uncertainty. In general, informational quality concerns visualizing data sources representing an area of uncertainty. The ability to combine numerous data sources from inside and outside a firm indicates S&OP's high efficiency and effectiveness (Schlegel et al., 2020). Improved informational quality thus implies enabling seamless collection, ideally from secure databases, and intuitive experience with analyzing up-to-date, detailed, and easy-to-view data related to the uncertainty in question (Oliva & Watson, 2011).

Second, the ETO environment requires S&OP to enhance primary capabilities contributing to its procedural quality: the ability to predict variations in ETO demand and product designs, the ability to develop solutions for customization, and the ability to validate information. As those examples show, procedural quality primarily represents the problem-solving level of S&OP. The higher a firm's ability to combine data that enhances various predictive analyses, the higher the efficiency and effectiveness of its S&OP (Schlegel et al., 2020). Improving S&OP's procedural quality thus means improving the accuracy or validity of approaches or methods used to identify or measure the uncertainty in question (Oliva & Watson, 2011).

Third, as for alignment quality, ETO operations require specific intra- and interdepartmental interactions (Mello et al., 2015). More broadly, alignment quality requires cross-functional coordination represented by inside-out, outside-in, top-down, cross-functional, and bottom-up alignments. In ETO operations, meeting those requirements involves aligning goals, incentives, and budgets between specific functions that handle particular demand–supply balancing questions (e.g., flexibility of production capacity, the quality of processes, and labor learning curves). The adaption of capacity in ETO operations has extended lead times, which explains why most manufacturers follow a lead strategy (Olhager et al., 2001). Likewise, maintaining robust quality in the manufacturing process in ETO operations is challenging due to dynamic requirements from customers that led to continuously changing allowances from order to order (Yang, 2013). Last, learning curves in ETO operations are generally asynchronous and individualized (Lu et al., 2009).

Fourth, the ETO environment requires S&OP's constructive engagement to involve as many engineers as possible in standardizing engineering tasks (e.g., through a continuous improvement process). Constructive engagement thus primarily represents cross-functional collaboration (Kahn, 1996b). Improved constructive engagement means encouraging actors with tacit knowledge relevant to the uncertainty in question to communicate their input before decision-making becomes necessary (Oliva and Watson, 2011). Their motives for contributing likely rest in soft aspects such as mutual trust and shared goals (Kahn, 1996a).

Figure 6.1 also shows two primary IPMs that reduce IPNs (i.e., slack resources and self-contained tasks) and two others that increase information-processing capacity (i.e., lateral relations and information system support). Accordingly, those mechanisms, discussed below in greater detail, can be used to manage the complexity affecting demand–supply balancing at the tactical level.

First, S&OP creates slack resources in ETO operations by guiding the selection of customers' orders, centralizing S&OP and engineering capacity at a regional level, and centralizing production and procurement in the global supply network. Those mechanisms enable and are enabled by dimensions of procedural quality, namely the predictability of decisions' consequences and the development of relevant solutions following formal review meetings and the bottom-up validation of feasibility and compatibility. Klaczynski et al. (2001) have attributed the predictability of decisions' consequences to individuals' cognitive abilities, while Mayer et al. (1995) have claimed it can be enhanced by increasing trust in relationships. The predictability of decisions' consequences depends on the information available to make valid inferences according to certain rules. If those rules are improvised or the logic or criteria are arbitrary, then predicting the consequences of decisions is difficult. The same dynamic applies to performance in problem-solving.

Second, S&OP creates self-contained tasks through organizational structures based on the market, customers' location, product design, production networks, supply chain networks, and functional business hierarchies. Those mechanisms enable and are enabled by S&OP's dimensions of alignment quality—that is, outside-in alignments, inside-out alignment, top-down alignment, cross-functional alignment, and bottom-up alignment. Outside-in and inside-out alignments are common concepts in innovation management with an emphasis on balancing adaptation to the market and the supply chain by introducing outside-in (e.g., market-oriented) processes (e.g., Bogers et al., 2017; Cheng & Huizingh, 2014; Papa et al., 2020). The other types of alignment represent specific internal directions for coordination across functions and hierarchies (Malone, 1987). The product structure also requires S&OP's constructive engagement, represented by the active involvement of relevant managers and subordinates. That mechanism implicitly points to enhancing collaboration by establishing incentives, common goals, and mutual trust between managers and subordinates (Tang, 2010).

Third, S&OP creates lateral relations by establishing direct contact between managers, liaisons, permanent teams, and integrative roles. Those mechanisms enable and are enabled by S&OP's dimensions of alignment quality as well (i.e., top-down, bottom-up, and cross-functional alignment).

Fourth, as for the information system support for decision-making, S&OP ensures data currency, data localization, data globalization, the formalization of information flows, and effective human–machine information processing. Those mechanisms are enabled by S&OP's informational quality, particularly the ability to combine data from numerous sources and to provide sufficient visibility into customers' demand for ETO (e.g., tender requests and due dates), products (e.g., customizability and incompatibilities), machine capacity (e.g., machines' performance and constraints), labor capacity (e.g., skills, availabilities, and learning curves), processes (e.g., setup cost dependencies and task requirements), materials (e.g., items' life cycle), and the supply chain (e.g., outsourceable requirements for customization). Beyond that, human–machine information processing also enables and is enabled by the procedural quality of S&OP, including the improved ability to predict variabilities in demand (e.g., the generation of improved forecasts) and product design (e.g., improved forecast aggregation and product life cycles), to develop solutions (e.g., product customization), and validate information (e.g., via what-if and capacity analyses).

The identified mechanisms show that S&OP's core demand–supply balancing potential rests in its alignment quality, which seems to enable and be enabled by several IPMs. Oliva and Watson (2011) have argued that S&OP's alignment quality is more effective than its informational and procedural qualities in many situations. This thesis argues against that proposition, however, by instead emphasizing procedural quality as the most critical dimension. The findings show that S&OP relies heavily on its alignment quality and constructive engagement to address uncertainty in hit rates, usually by simply gathering guesses based on gut feelings and tacit knowledge from sales organizations that claim to have strict alignment with and influence customers' plans. What S&OP needs is to adopt advanced drivers of procedural quality instead (e.g., fact-based quantifiable models to predict hit rates).

The literature on achieving mature alignment quality within S&OP far exceeds the literature on how to increase informational and procedural qualities, at least literature that also considers the pressure of context (Kreuter et al., 2021a; Kreuter et al., 2021b; Kristensen & Jonsson, 2018). Moreover, S&OP's alignment quality is arguably the most prominent dimension examined. In general, findings show that S&OP in ETO operations primarily delivers numerous mechanisms of alignment quality necessary to reduce IPNs and increase information-processing capacity. However, managing increasing uncertainty beyond certain levels and in certain areas with only enhanced alignment quality is arguably not the most cost-effective option. Beyond that, no evidence shows that ETO-oriented manufacturers intentionally direct their S&OP's procedural quality to suit IPNs and information-processing capacity. Although ETO uncertainty increases the pressure on informational and procedural quality in particular, even the highly mature S&OP processes meet only the minimal procedural and informational requirements at best.

### 6.1.4. Medium-term demand–supply balancing through instability management

Following a multidisciplinary approach, the underlying research connected literature from various areas—material requirements planning, supply chain complexity, and process theory—describe the influence of complexity on demand–supply balancing at the tactical–operational interface with an emphasis on instability in material delivery schedules.

Because the focus of this thesis at the tactical–operational interface is material delivery scheduling, many studies on material planning were used to forge a thorough understanding of the material ordering process and to identify factors associated with schedule instability. According to Sivadasan et al. (2013), identifying factors of schedule instability is necessary for experimental research. In response to that call, the research behind this thesis produced an extended synthesis of the operating variables, operating conditions, and dependent variables tackled in the literature. The synthesis features a comprehensive overview compared with the few available frameworks on the topic (Inman & Gonsalvez, 1997; Law & Gunasekaran, 2010; Pujawan et al., 2014; Pujawan & Smart, 2012).

The thesis also responds to the need for empirical research on material delivery scheduling, as called for by Sahin et al. (2013). A set of empirically identified factors is new to literature on the topic, and the proposed factors explicitly specify the type of influence on instability—that is, whether it is causal (i.e., mediating) or amplifying (i.e., moderating). Such clarity is crucial to constructing models with acceptable internal validity (Hayes, 2017) that can be used to test strategies to mitigate instability.

Using Holweg et al.'s (2018) process theory and Dittfeld et al.'s (2018) complexity framework, complemented with numerous insights from research on complexity (e.g., Bozarth et al., 2009; Serdarasan, 2013), the thesis extends the theoretically understanding of the phenomenon of schedule instability. In doing so, it operationalizes several theoretical contributions in research streams concerning both perspectives. For research on complexity, the thesis provides an example of how generic complexity theories can be synthesized and combined into an analytical framework that helps to clarify how a practical industrial problem such as the delivery schedule instability occurs and develops. In addition, the thesis provides a more comprehensive synthesis of drivers of dynamic complexity than any previous study has, one that can serve as a reference framework of constructs of dynamic complexity. Moreover, the thesis's set of empirically identified factors represents drivers new to research on complexity. As for process theory, Papers V and VI specifically operationalize two principles concerning variations and complexity to provide granular detail regarding their underlying moderating and causal factors. Added to that, by adopting process theory's taxonomy of variations, the thesis showcases how the theory helps to investigate the root causes of instabilities within any given process.

Figure 6.1 shows instability-absorbing mechanisms used to manage the complexity affecting demand–supply balancing at the tactical–operational interface. They are the predictability of variability in demand, the scalability of capacity, the detectability and predictability of product life cycles, the traceability of material, supply chains with flexibility in order fulfillment, suppliers' flexibility, and adapted replanning parameters. The findings show that the greater the capability to absorb variations internally, the greater the capability to develop more stable delivery schedules. Building variation-absorptive capability requires balancing the growth of slack resources with the gains achieved from less instability. Creating slack resources is an IPM that reduces uncertainty (Galbraith, 1977), because slack resources enable low enforcement levels for order fulfillment on the supply chain and improve the scalability of capacity. Low enforcement levels on the supply chain mean granting suppliers additional flexibility in fulfilling customers' changing demands (Forslund et al., 2021). Otherwise, selected suppliers should have highly resilient supply chains against disruptions. The scalability of capacity requires substantial investments in the manufacturing infrastructure (Deif & ElMaraghy, 2006) and entails adjusting the capacity more often with less ramp-up delay time, thereby improving the system's performance in volatile demand environments (Kim & Duffie, 2004).

The findings additionally show that material scheduling could benefit from profiling items based on consumption rates. Using data representing other relevant factors, the planners could apply analytics methods such as machine learning to detect items leaving the phased-in or entering the phased-out zones earlier (Jennings et al., 2016)—that is, where items cause additional instability. Material schedulers need to pay closer attention to such items, which are typically slow-moving ones (Wänström & Jonsson, 2006). If possible, then the parameters of designing material scheduling (e.g., planning periodicity) should be customized according to phase-in and phase-out dynamics.

### 6.1.5. Summary of theoretical contributions

This section summarizes how the results of an applied field such as operations management can be used to develop theory (Narasimhan, 2014). The research of this thesis was rooted in practice because the RQs were driven by a phenomenon (i.e., demand–supply balancing in complex manufacturing operations), and because I collaborated with practitioners to collect data (Schwarz & Stensaker, 2014). Using an inductive approach, empirical data through identified patterns allowed numerous theoretical contributions to established bodies of knowledge and theories.

The bodies of knowledge to which this thesis contributes include order management, S&OP, and operations scheduling (see Figure 6.2). Paper I extends previous frameworks for tactically planning orders in ETO operations (Carvalho et al., 2015; Giebels, 2000; Hans et al., 2007), by explicitly highlighting how underlying activities and decisions determine demand–supply balancing. Meanwhile, both Papers I and II contribute to the discussion supporting adaptive managerial responses to various engineering and production decoupling configurations (Cannas et al., 2019, 2020; Gosling et al., 2017). Beyond that, Papers I–IV offer detailed insights into various aspects of complexity embedded in ETO operations, which extend and complement the literature on ETO dynamics (e.g., Alfnes et al., 2021; Birkie & Trucco, 2016; Earl et al., 2003; Lu et al., 2009; Mello et al., 2015; Rauch et al., 2018; Telles et al., 2019).

As for contributions to the literature on S&OP, Papers III and IV provide new insights for theoretical discussions about context-fitted S&OP configurations (Kreuter et al., 2021a; Kreuter et al., 2021b; Kristensen & Jonsson, 2018; Thomé et al., 2014). Oliva and Watson (2011) have suggested four dimensions representing S&OP quality, and Papers III and IV operationalize and extend those dimensions by showing examples of how the S&OP context determines underlying requirements for quality that represent each of the four dimensions of quality. In addition, Paper IV provides insights into evaluating the influence of existing S&OP process configurations and thus enriches the literature on maturity (Danese et al., 2017; Grimson & Pyke, 2007; Lapide, 2005; Snow, 2006) and performance in S&OP (Goh & Eldridge, 2019; Hulthén et al., 2016a; Hulthén et al., 2016b).

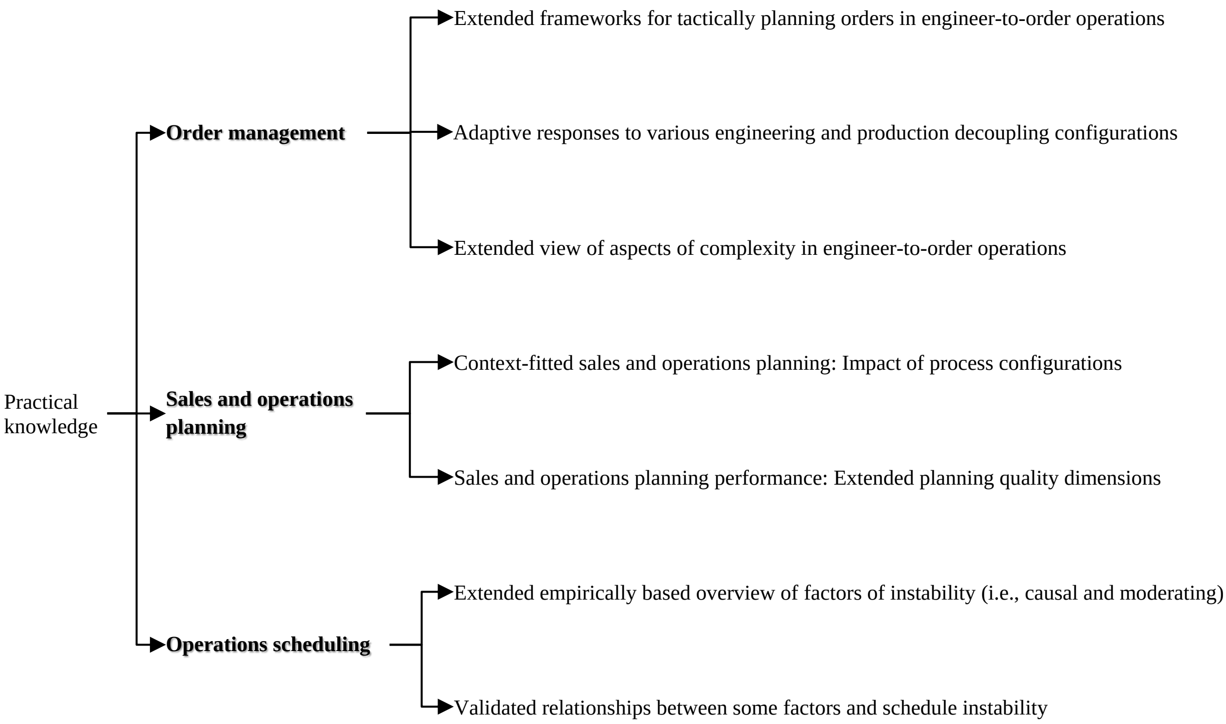
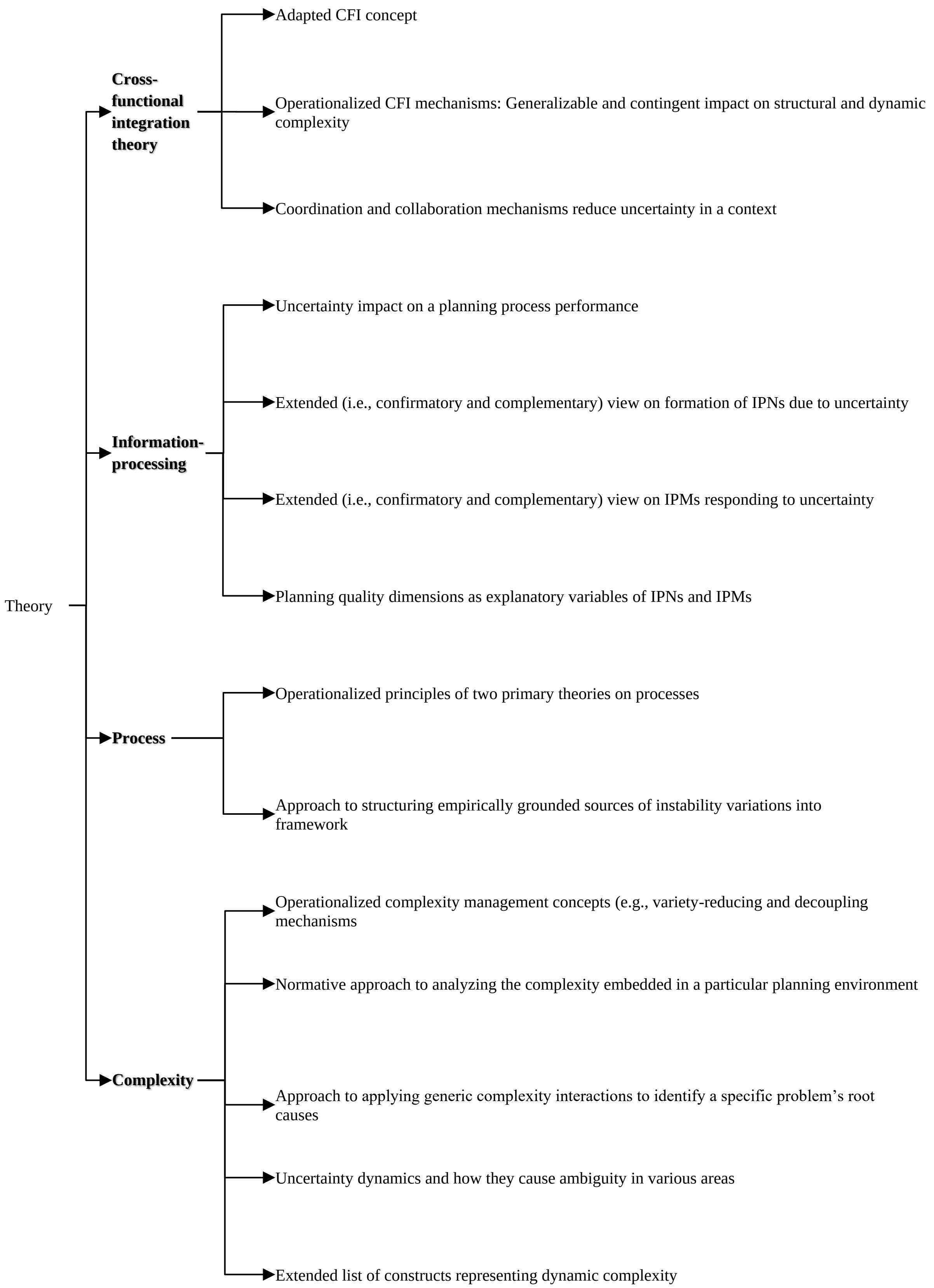



**Figure 6.2.** The thesis's contributions to bodies of practical knowledge

As for the thesis's contributions to the literature on operations scheduling, Papers V and VI elaborate the development of instabilities within material delivery scheduling that have received tremendous quantitative attention. In particular, Paper V extends the overview of the potential factors of instability in material delivery scheduling presented in previous studies on material requirements planning (Inman & Gonsalvez, 1997; Law & Gunasekaran, 2010; Pujawan et al., 2014; Pujawan & Smart, 2012) using empirical evidence. The identified factors were divided into causal and moderating factors, a delineation that is crucial to constructing models with acceptable internal validity (Hayes, 2017). Responding to Sahin et al.'s (2013) call for empirically based research on instability in material requirements planning, Paper VI goes a step further by testing whether such instability can be explained by any of the factors identified in Paper V.

The theories applied as lenses in this thesis include cross-functional integration theory, information-processing theory, process theory, and complexity theory (see Figure 6.3). Papers II–IV provide several generalizable insights into mechanisms of cross-functional integration. In particular, Paper II explicitly addresses the concept of cross-functional integration by adapting a widely accepted definition and underlying constructs suggested by Kahn (1996a). The paper also operationalizes mechanisms of cross-functional integration presented in previous studies (e.g., Daft & Lengel, 1986; Hirunyawipada et al., 2010; Troy et al., 2008; Turkulainen & Ketokivi, 2012) and identifies underlying mechanisms and their generalizable, contingent impacts on structural and dynamic complexity. Similarly, Papers III and IV indirectly contribute to cross-functional integration theory by identifying mechanisms of coordination and collaboration that help to reduce uncertainty in given contexts.




*Note.* CFI = cross-functional integration, IPN = information-processing needs, IPM = information-processing mechanisms

**Figure 6.3. The thesis's contributions to theory**

As for information-processing theory, Galbraith's (1977) perspective is considered in all of the papers, which helps to analyze the pressure that uncertainty places on the performance of planning processes. However, Papers III and IV explicitly apply information-processing theory and thus contribute to knowledge about the formation of IPNs due to uncertainty and the IPMs that respond to those needs. Paper III in particular provides rich, empirically based insights into how uncertainty develops into IPNs, namely by confirming and complementing results from previous studies (e.g., Busse et al., 2017; Daft & Macintosh, 1981; Rogers et al., 1999; Simon, 1978; Srinivasan and Swink, 2018; Tushman & Nadler, 1978). Next, Paper IV identifies secondary IPMs underlying the four primary ones suggested by Galbraith (1977) and thus confirms and complements results from previous studies (e.g., Foerstl et al., 2018; Gattiker, 2007; Schlegel et al., 2020). On top of that, Papers III and IV integrate the dimensions of planning quality identified by Oliva and Watson (2011) as explanatory variables of IPNs and IPMs, respectively.

As for process theory, Paper V operationalizes two of the theory's chief principles suggested by Holweg et al. (2018) and therefore provides empirical detail on related concepts such as dynamic complexity. In addition, the paper presents an approach based on process theory for structuring empirically grounded sources of variations contributing to a specific problem of instability—that is, material delivery instability.

Last, the thesis has a limited focus on complexity within a specific area of performance: medium-term demand–supply balancing. Papers I and II operationalizes concepts of managing complexity (e.g., variety-reducing and decoupling mechanisms) proposed by Fernández Campos et al. (2019) and thus describe a simplified normative approach to analyzing the complexity embedded in a particular planning environment. Such an approach allows predicting the consequences of low-level decisions instead of only high-level strategies.

Papers III–V contribute to the concept of dynamic complexity. In particular, Papers III and IV implicitly deliver such contributions by focusing on dynamics of uncertainty—that is, the essence of dynamic complexity (Serdarasan, 2013)—and how they cause ambiguity in various areas. Paper V adapts and operationalizes Dittfeld et al.'s (2018) complexity framework by compiling fragmented insights from previous studies (e.g., Bozarth et al., 2009; Fernández Campos et al., 2019; Serdarasan, 2013; Turner et al., 2018; Wiengarten et al., 2017) and extending the constructs representing the dimension of dynamic complexity. The paper also describes an approach to applying generic complexity interactions to identify the root causes of specific problems such as schedule instability.

## 6.2. Managerial implications

This subsection presents the thesis's primary managerial implications for practitioners such as capacity planners, demand planners, supply chain planners, operations managers, S&OP coordinators, master production planners, and material controllers. Table 6.1 shows an overview of the implications, sorted into three categories corresponding to the three business processes addressed in the thesis: customer order fulfillment, S&OP, and material delivery scheduling.

Three implications pertain to the customer order fulfillment process. First, the outline of tactical planning at the strategic–tactical interface and of the influence of the embedded decisions on complexity (i.e., highlighted in Paper I) serves as a formal reference for designing and implementing customer order fulfillment, one that ensures consistent, transparent consideration of decisions' consequences on performance. Second, the substantial influence of selecting customers' inquiries and suppliers and of the aggregate reshuffling of resources on complexity implies that those activities require major support. More specifically, decision-makers need tools that enable intuitive, efficient, and valid scenario planning, because they need to seamlessly assess the consequences of selecting individual orders and suppliers and of moving resources between projects in order to identify constraints and criticalities. Third, the influence of mechanisms of cross-functional integration within customer order fulfillment (i.e., highlighted in Paper II) implies that specific organizational changes and management approaches may improve overall performance because they realize effective integration strategies. For instance, Paper II shows that balanced cross-functional teams become increasingly significant for processing complex inquiries from customers, especially in order customization and workload analysis. Firms may lack explicit policies that require dedicating such teams as the complexity of customers' orders increases. Nevertheless, if individual managers apply such a mechanism in an ad hoc fashion, they may still sense its effect on performance. Therefore, when introducing managerial and organizational changes, planners need to ensure and maximize their benefits and escalate the downsides from the perspective of integration.

Table 6.1 also shows four implications pertaining to the S&OP process. First, the identified IPNs within S&OP representing the uncertainty affecting demand–supply balancing (i.e., highlighted in Paper III) imply that determining the requirements for efficient and effective S&OP needs an accurate delineation of critical areas of uncertainty. The starting point for developing a context-fitted S&OP is pinpointing and including all areas of uncertainty that the S&OP process has to handle. Those areas need to at least explicitly appear on the S&OP agenda. Second, the required quality of S&OP to reduce uncertainty affecting demand–supply balancing implies the need for investing in S&OP configurations able to deliver the effects of enhanced visualization, problem-solving, coordination, and collaboration. Third, as highlighted in Paper IV, the S&OP configurations represented by IPMs that influence the uncertainty affecting demand–supply balancing indicate S&OP's qualitative performance. Accordingly, S&OP teams could establish corresponding appraisals as part of an agenda of continuous improvement instead of constantly addressing qualitative performance—that is, the "soft," elusive side of S&OP that cannot be measured. Fourth, the areas of uncertainty, the requirements for quality S&OP (i.e., presented in Paper III), and the quality of existing S&OP processes (i.e., presented in Paper IV) can guide practitioners in ETO operations toward defining contextualized S&OP requirements. The identified areas of uncertainty may serve as a comprehensive reference, while the requirements for quality S&OP are targets for continuous improvement. The quality of existing S&OP processes showcases the current state of practice, and given that state and the targets defined by the context requirements, gaps in S&OP quality can be identified and resolved.

Two primary managerial implications pertain to scheduling material deliveries. First, Paper V shows that the instability emerging in material delivery schedules is primarily driven by internal complexity interactions. In response, the internal capability that reduces such instability can involve strategies and programs that develop the scalability of capacity and suppliers' flexibility and grant flexibility in order fulfillment to the supply chain. Building such capability requires balancing the growth of slack resources with the gains achieved from minimized instability. Second, the impact of slow-moving items (i.e., due to low consumption rates or life cycle phases) on schedule instability, as emphasized in Paper V and tested in Paper VI, implies that supply chain managers need to identify those items in material requirements planning systems and have material controllers monitor the related inaccuracies closely. Beyond that, some parameters of the scheduling process such as planning periodicity need to be adapted to accommodate those items' demand dynamics. Last, the possibility for collecting, recalling, and comparing data related to slow-moving items has to be established, automated, and preferably made easy to visualize.

**Table 6.1.** Overview of managerial implications

| Practice | Managerial implications | Support in the thesis |
|---|---|---|
| Customer order fulfillment | The customer order fulfillment process requires formalized guidance that ensures consistent and transparent consideration of the decision consequences on the performance. | Proposed tactical planning framework and influence of embedded decisions on complexity (i.e., Paper I) |
| | Reviewing aggregate customer order fulfillment activities requires ultimate scenario-planning support that identifies criticalities drawing on available data and assumptions. | Impact of order and supplier selection and aggregate reshuffling of resources on complexity (i.e., Paper I) |
| | Introducing organizational changes and new management approaches to customer order fulfillment may improve overall performance because they realize effective integration, even unintentionally. | Impact of mechanisms of cross-functional integration embedded in the customer order fulfillment process on complexity (i.e., Paper II) |
| Sales and operations planning | Determining the requirements for an efficient, effective sales and operations planning process needs the accurate delineation of critical areas of uncertainty. | Information process needs within sales and operations planning representing the uncertainty affecting the balance between medium-term demand and supply (i.e., Paper III) |
| | Adapting the sales and operations planning configurations to uncertainty requires investments in visualization, problem-solving, coordination, and collaboration. | Requirements for sales and operations planning quality to reduce the uncertainty affecting the balance between medium-term demand and supply (i.e., Paper III) |
| | Configurations of the sales and operations planning process determine its qualitative performance. | Information processing mechanisms representing configurations of the sales and operations planning process that impact uncertainty affecting the balance of medium-term demand and supply (i.e., Paper IV) |
| | Engineer-to-order operations require advanced process configurations of sales and operations planning. | Areas of uncertainty in engineer-to-order operations (i.e., Paper III)<br>Requirements for quality in sales and operations planning in engineer-to-order operations (i.e., Paper III)<br>Quality of sales and operations planning processes in engineer-to-order operations (i.e., Paper IV) |
| Material delivery scheduling | The internal capability that reduces material delivery schedule instability can encompass strategies and programs that build capacity scalability, suppliers' flexibility, and order fulfillment flexibility in the supply chain. Building such capability requires balancing the growth of slack resources with the gains achieved from minimized instability. | Complexity interactions within internal operations driving instability in material delivery schedules (i.e., Paper V) |
| | Identifying consumption rates and the item life cycle is necessary for understanding inaccuracies in delivery schedules. Some material delivery scheduling process parameters, including planning periodicity, need adaptation to fit an item's demand dynamics. The possibility to collect, recall, and compare data related to those items has to be established, automated, and preferably made easy to visualize. | Impact of slow-moving items on schedule instability (i.e., Paper V)<br>Item's consumption rate and life cycle as potential determinants of schedule instability (i.e., Paper VI) |

# 7. Conclusion

This chapter presents the concluding remarks and limitations of the research underlying this thesis and closes with suggestions for future studies on tactical planning in complex manufacturing operations.

## 7.1. Concluding remarks

The research presented herein addressed demand–supply balancing and planning in complex manufacturing operations. In five studies that resulted in six papers, the three RQs of the thesis were answered, as discussed in Chapter 5, and an extended framework was proposed (see Figure 6.1).

By answering RQ1, the influence of complexity on tactical planning configurations, represented by activities and cross-functional integration within the customer order fulfillment process, in ETO operations has been identified. Accordingly, complexity in ETO operations requires planning activities at the strategic–tactical interface, including order screening, customization, workload analysis, review, and contracting. Order screening, review, and contracting require two mechanisms of cross-functional integration: formalized procedures and adequate data management infrastructure. Order customization and workload analyses encompass procurement, product and process engineering, resource loading, and cost and duration estimation. Those activities require four cross-functional integration mechanisms: balanced cross-functional team composition, adequate task design, concurrent engineering, and information system support to product and production design modeling and optimization.

By answering RQ2, the influence of complexity, represented by uncertainty and corresponding IPNs within S&OP, on tactical planning configurations in ETO operations has been identified. Accordingly, complexity in ETO operations reduces the predictability and visibility of numerous demand- and supply-related variations. It also makes customer demand increasingly multifaceted. Therefore, planning at the tactical level needs to capture numerous dynamic, difficult-to-measure variables characterizing individual orders through IPMs. The research addressed four primary mechanisms: creating slack, creating lateral resources, creating self-contained tasks, and investing in information system support. First, creating slack resources translates to capacity-oriented order selection and centralization. Second, creating self-contained tasks takes the form of interdepartmental planning within large functions and cross-functional planning between functions. Third, creating lateral relations manifests in various forms: direct contact between managers, liaisons, permanent teams, and integrative roles. As customizations require higher interdependency between functions, shifting from direct contact between managers to liaisons becomes necessary, and as the number of interdependent functions increases, coordinating the consequent cross-functional interactions comes to require permanent teams. Moreover, as conflicts and decisions of consequence increase, integrative roles need to be established. Fourth, investing in information system support translates to combinations of human–machine information-processing capacities that effectively enable significant qualitative data processing. Such combinations have to ensure data availability, data currency, and data formatting for various decision-makers across functions and hierarchies. It also needs to ensure consistent, reliable results from analysis.

By answering RQ3, the influence of complexity, represented by complexity interactions and corresponding process variations, on instabilities within material delivery schedules in CTO operations was identified. Accordingly, from a complexity-oriented perspective, complexity in CTO operations produces instabilities in material delivery schedules through dynamic (i.e., horizontal) interactions within internal operations. Only two drivers of structural complexity are relevant, whereas the supply chain does not have a direct impact. Instabilities in master production schedules represent the only driver with a direct effect within the fixed period that is moderated by several factors. Factors leading to instability in production schedules are numerous. From a process-oriented perspective, complexity in CTO operations generates instabilities through contextual variations and aspects of process design. Variations occur in terms of quality (i.e., conditions causing disruptions in production), quantity (i.e., low actual demand and discrepancies in inventory stock), and timing (i.e., uncertain item life cycles, late increases in demand, late changes to end-item specifications, misaligned supply chain operation times, short frozen production schedules, switching suppliers, and the visibility of underdeveloped master production schedules). Aspects of process design include the insufficient buffering of time (i.e., changing transport lead times and uncertainty about suppliers' inventory), of inventory (i.e., suppliers' limited flexibility and inadequate safety stock policy), and of capacity (i.e., high enforcement levels for order fulfillment). Other dimensions of process design include bottlenecks in the system (i.e., full-truckload optimization requirements), scale (i.e., low pickup frequency, suppliers' lot sizing, inadequate replanning periodicity, and large packaging), and scope (i.e., item variety and limited capacity scalability). Last, the schedule horizon statistically explains the effect of slow-moving items and modularized product configurations on instability. At the same time, the severity of schedule inaccuracy does not necessarily explain the effect of relevant variables on instability.

## 7.2. Limitations and directions for future research

The research behind this thesis featured three primary limitations concerning external, construct, and content validity. The limitations provide clarity for future paths of research (see Figure 7.1). However, they do not substantially limit the findings of the underlying studies on how medium-term demand–supply balancing is influenced by complexity in manufacturing operations.

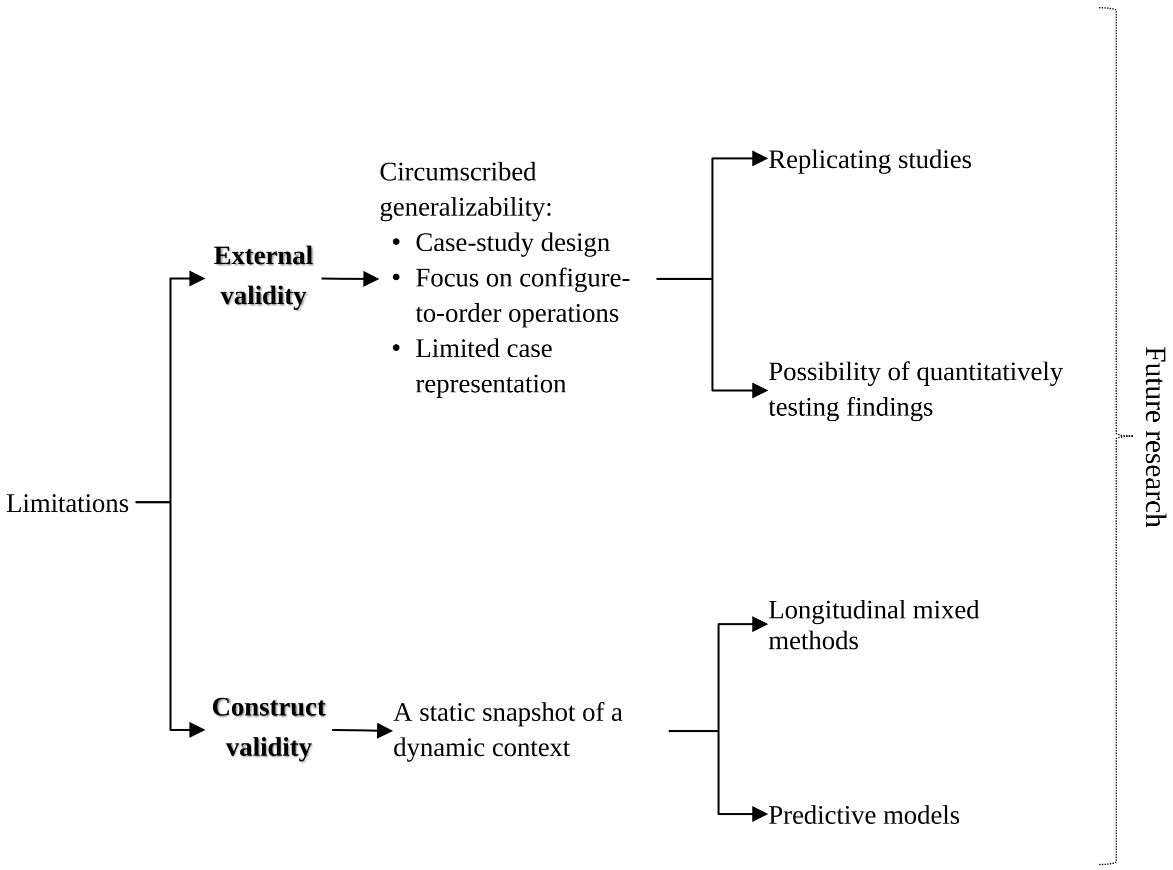



**Figure 7.1.** Limitations and related future research

The findings' external validity (i.e., generalizability) is somewhat circumscribed because four of the five studies had a case-study design. In-depth analyses were needed due to the lack of theoretical syntheses supporting the understanding of the applied concepts central to the multidisciplinary settings of tactical planning in the thesis. Three studies departed from the notion that ETO operations feature considerable complexity for balancing long- and medium-term demand and supply. Therefore, numerous findings are relevant to customization and engineering capability that do not apply to MTO operations, for example, that may also reflect complexity from other areas. For instance, retail operations do not need customization activities; however, they still have to handle enormous assortment varieties and underlying risks such as short shelf life, obsolescence, extremely tight delivery lead times, and vulnerability to disruptions (Ekinci & Baykasoğlu, 2019). In addition, the selected cases represent various, but not all of the possible, engineering and production decoupling configurations with ETO operations (Cannas et al., 2019).

Therefore, further research that validates, extends, and complements the case studies' findings is needed in multiple directions. First, the developed frameworks could be a starting point for replicating studies involving cases representing various ETO, CTO, MTO, and MTS operations. Second, because the frameworks proposed in this thesis concerning demand–supply balancing and planning in complex manufacturing operations are now available, data collection and analysis may become more structured and narrower, thereby allowing for broader samples. In other words, further research using quantitative methods to test the findings is arguably possible given the established understanding resulting from the case studies.

As for construct validity, inferring the influence of decisions, mechanisms, and activities on measures of complexity (e.g., uncertainty, detail, structural complexity, and dynamic complexity) was primarily based on practitioners' opinions and previous studies. Although those contributions are based on firms' historical incidents and records as well as secondary data from previous studies, they do not qualify as irrefutable proof. The collected data may, in numerous areas, represent a static snapshot of a dynamic context. Put differently, the captured complexity may not depict its evolutionary behavior. Therefore, future research needs to adopt a longitudinal mixed-methods approach with a sequential exploratory design or a concurrent triangulation design to study the influence on complexity. Such designs need to establish adequate measurement instruments and to test and refine the identified causal relationships evolving from qualitative analysis using hard evidence (Creswell & Clark, 2017). Another significant benefit from such quantitative analyses is the ability to predict how much the complexity will increase or decrease, which allows ranking the practices under study based on their influence on complexity.

As for the content validity of the findings, the units of analysis and concepts used in the studies undergirding this thesis partly represent the phenomenon of demand–supply balancing. For instance, tactical planning is represented by one process (i.e., S&OP) and two overlapping processes. In practice, however, tactical planning does not always exist as formalized cross-functional processes such as S&OP. Beyond that, customer order fulfillment and material delivery scheduling are not the only processes overlapping with the tactical level. Sales and operations execution, budgeting, human resource management, supply chain development, and product development are other examples of processes within tactical-level planning activities. The same limitation applies to the identified mechanisms of cross-functional integration, areas of uncertainty, IPMs, and factors of schedule instability. Accordingly, saturating the identified categories by deepening the understanding of the forms and influences of individual categories is recommended for future studies.

Several findings in this thesis highlight directions for future research, as summarized in Figure 7.2.

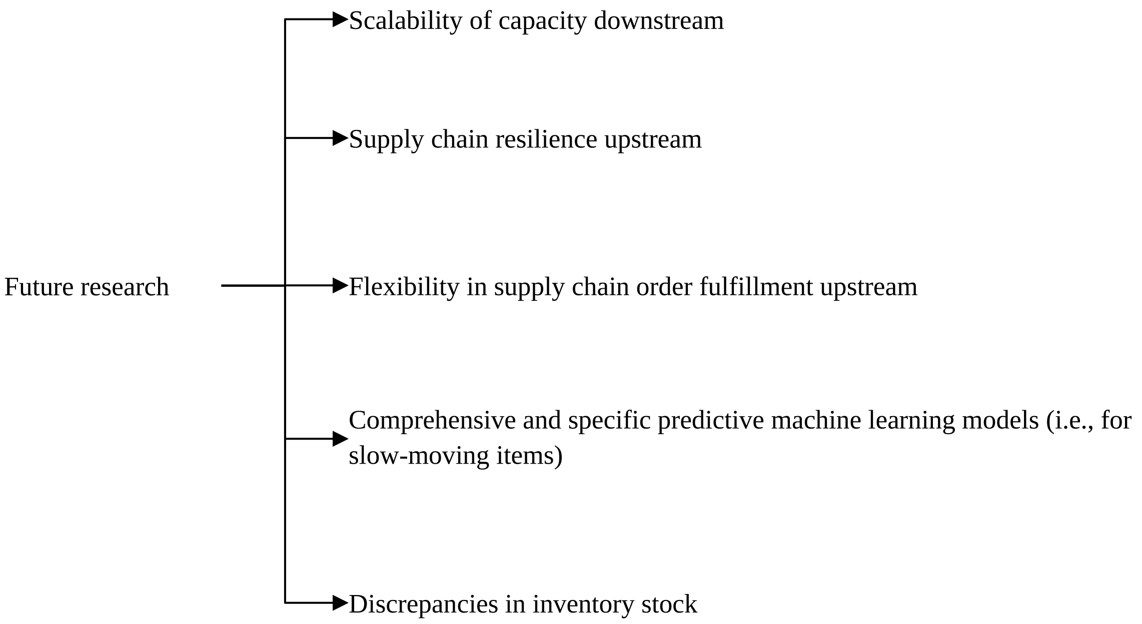



**Figure 7.2.** Directions for future research based on the thesis's findings

First, because the time spent on performing critical engineering competencies within tendering and execution was found to depend on how they are assigned, modeling and optimization studies may address the possibility of equivalently combining various levels of seniority and skill sets without compromises. Such optimization may consider options based on critical and non-critical resource availability and configurability. Second, the influence of numerous identified mechanisms and practices on complexity was found to depend upon variables in the system and its environment. Further research may statistically explain how changing individual contingency variables moderates the influence of those mechanisms on complexity.

Third, the slack capacity in internal operations and the supply chain was found to be crucial for absorbing complexity. Such capacity takes various forms, including as the effect of the capacity scalability of the supplier's flexibility downstream on the upstream supply chain and order fulfillment flexibility granted to the supply chain. Accordingly, future research on how those capabilities need to be developed to ensure high performance despite the complexity is highly recommended. Fourth, recognizing the actual phase of products on their life cycle, especially slow-moving products, is crucial to minimizing instability. Developing predictive (e.g., machine learning) models for that purpose is a highly recommended endeavor for future research. In complement, experimental studies may explore the value of reconfiguring the parameters of the planning and scheduling process in line with specific product characteristics (e.g., slow-moving items). However, planning those products with particular horizons and frequencies, for example, may or may not be effective.

Fifth, discrepancies in inventory stock and low actual demand are significant causes of planning inaccuracy. Advancing forecasting accuracy requires more research on predictive (e.g., machine learning) models that can track more relevant variables, including the variables identified in this thesis. Last, as for discrepancies in inventory stock, future research needs to explore the possibilities of tracking consumption and movement after material is unloaded on the shop floor at the item level, even if the items are relatively small.

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