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Contingency Theories of Order Management, Capacity Planning, and Exception Processing in Complex Manufacturing Environments

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ABSTRACT

Technological development and market diversification increase the complexity of modern manufacturing environments. Although the popular literature on lean management practices and quality improvement programs describe numerous ways of decreasing the complexity of manufacturing processes, the complete elimination of complexity is seldom possible. Thus, one needs to understand how to mitigate the performance effects of complexity with appropriate management practices. The research questions of this dissertation ask first, what do we already know about operations management under complexity, and second, how the applicability of day-to-day operations management practices depends upon the different dimensions of complexity.

The research question on the existing knowledge about operations management under complexity is answered in two steps. First, I present a comprehensive review of organization-theoretical literature on the concept of complexity. This review results in a number of propositions on different ways of managing complexity. Second, I analyze the evidence for those propositions in a systematic literature review of recent operations management research. The results of that review point to a number of contribution opportunities, which guide the empirical studies that address my second research question.

The research question on the applicability of operations management practices under different kinds of complexity is addressed with three studies within the same focused sample of 163 machinery manufacturing processes. The first study examines how the applicability of different order management practices depends upon the complexity arising from product customization. The second study examines the effects of process complexity on the applicability of different capacity planning methods. The third study examines the effects of different kinds of uncertainties on the applicability of different exception processing routines. As the studied practices begin from the acquisition of orders and end in the delivery of products, they constitute a holistic view of day-to-day operations management in manufacturing firms.

The empirical analyses result in three contingency-theoretical propositions. First, I argue that product configurator tools, available-to-promise verifications, and configuration management practices are only applicable with specific levels of customization in products' configurations and components. Second, I argue that rough-cut capacity planning methods are only applicable with job-shop processes, capacity requirement planning is only applicable with batch-shop processes, and finite loading methods are only applicable with bottleneck-controlled batch shops and assembly lines. Third, I argue that only formal automated exception reporting channels are applicable when urgent glitches are being resolved in production processes. Meanwhile, only formal interpersonal exception reporting channels are applicable when equivocal glitches are being resolved.

The theses have immediate practical implications for managers who are responsible for production processes in complex task environments. The studies show that none of this dissertation's theses are commonly known by practitioners nor discussed in the literature. In addition to the immediate implications for the studied environments, the theses can be theoretically generalized to other environments that satisfy certain boundary conditions. Examples can be found in service production, healthcare operations, and software development. The resulting middle-range theories of operations management in complex task environments can be tested in future studies with random samples of processes from other operations management contexts.

Keywords: complexity, uncertainty, operations management, empirical research, contingency theory, substantive theory

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TIIVISTELMÄ

Teknologinen kehitys ja asiakastarpeiden erikoistuminen lisäävät kompleksisuutta nykyajan teollisuusyrityksissä. Tuotannonohjauksen ammattikirjallisuus tarjoaa lukuisia menetelmiä kompleksisten tuotantojärjestelmien yksinkertaistamiseksi, mutta yleensä kompleksisuuden täydellinen poistaminen ei ole mahdollista. Siksi onkin tärkeää oppia ymmärtämään, miten kompleksisuuden negatiivisia vaikutuksia voidaan vähentää erilaisilla tuotannonohjausmenetelmillä. Väitöskirjani tutkimuskysymykset selvittävät ensinnäkin sitä, mitä nykykirjallisuuden perusteella tiedämme tuotannonohjauksesta kompleksisissa toimintaympäristöissä ja toiseksi sitä, miten erilaisten tuotannonohjausmenetelmien toimivuus riippuu kompleksisuuden eri ilmenemismuodoista.

Tutkimuskysymykseen siitä, mitä jo tiedämme tuotannonohjauksesta kompleksisissa ympäristöissä, vastaan kahden eri vaiheen kautta. Ensiksi esitän organisaatioteoreettisen kirjallisuustutkimuksen kompleksisuuden eri ilmenemismuodoista ja vaikutuksista. Sen lopputuloksena on lista propositioita siitä, kuinka kompleksisuutta voidaan hallita. Toisessa vaiheessa esitän systemaattisen kirjallisuuskatsauksen siitä, kuinka organisaatioteoreettisia propositioita on tutkittu tuotannonohjauksen saralla. Lopputuloksena syntyy joukko tutkimustarpeita ja kontribuutiomahdollisuuksia, joiden perusteella kohdistan toiseen tutkimuskysymykseeni vastaavat empiiriset tutkimukseni.

Tutkimuskysymykseni siitä, kuinka eri tuotannonohjausmenetelmien toimivuus riippuu kompleksisuuden eri ilmenemismuodoista, saa vastauksensa kolmesta tutkimuksesta 163 konepajateollisuusprosessin näytteessä. Ensimmäisessä tutkimuksessa selvitän, kuinka erilaisten tilaustenhallintamenetelmien toimivuus riippuu tuotteiden räätälöinnistä johtuvasta kompleksisuudesta. Toisessa tutkimuksessa selvitän, kuinka erilaisten kapasiteetinhallintamenetelmien toimivuus riippuu ohjattavan prosessin kompleksisuudesta. Kolmannessa tutkimuksessa selvitän, kuinka erilaiset epävarmuustekijät vaikuttavat kommunikaatiorutiinien toimivuuteen, kun tuotantosuunnitelmiin tehdään muutoksia. Empiirisen osan tutkimukset alkavat siis tilausten vastaanotosta ja päättyvät tuotteiden toimitukseen muodostaen siten yhtenäisen kokonaisuuden teollisuusyritysten jokapäiväisessä tuotannonohjauksessa.

Empiirisen osan tutkimukset tuottavat kolme kontingenssiteoreettista teesiä. Ensinnäkin väitän, että tuotekonfiguraattorien, toimituspäivän laskentatekniikoiden ja tuotekonfiguraationhallintamenetelmien hyödyllisyys riippuu siitä, kuinka paljon tuotteiden komponentteja ja konfiguraatioita on räätälöity. Toiseksi väitän, että kapasiteetin karkeasuunnittelumenetelmät toimivat ainoastaan pajaprosesseissa, kapasiteetin tarvelaskentamenetelmät toimivat ainoastaan eräprosesseissa ja kapasiteetin hienokuormitusmenetelmät toimivat ainoastaan pullonkaulaohjatuissa eräprosesseissa sekä kokoonpanolinjoissa. Kolmanneksi väitän, että ainoastaan automatisoidut suunnitelmamuutosten kommunikointirutiinit toimivat, kun muutoksia aiheuttavat epävarmuustekijät ovat luonteeltaan kiireellisiä. Vastaavasti ainoastaan kokousrutiineihin perustuva suunnitelmamuutosten kommunikointi toimii, kun epävarmuustekijät ovat luonteeltaan epäselviä.

Väitöskirjani teesit auttavat käytännön tuotannonohjauksesta vastaavia päätöksentekijöitä valitsemaan toimivimmat tuotannonohjausmenetelmät kompleksisiin toimintaympäristöihin. Tutkimukseni osoittavat, etteivät valinnat eri menetelmien välillä ole millään tavoin ilmeisiä käytännön päätöksentekijöille, eikä niitä ole selvitetty myöskään tuotannonohjauskirjallisuudessa. Väitöskirjan lopussa esitän, kuinka tulokseni voisivat olla yleistettävissä myös tutkitun konepajateollisuuden ulkopuolelle esimerkiksi palvelutuotantoon, terveydenhuoltoon ja ohjelmistokehitykseen. Niinpä teesini ovat perimmiltään kompleksisten toimintaympäristöjen tuotannonohjausteorioita, joita voidaan tulevaisuudessa testata laajemmin satunnaisotoksilla erilaisista tuotantoympäristöistä.

Avainsanat: kompleksisuus, epävarmuus, tuotannonohjaus, empiiriset tutkimusmenetelmät, kontingenssiteoria, substanssiteoria

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I am indebted to many people who have helped me with this dissertation or simply contributed to making my doctoral studies such a joyful experience. First of all, I wish to thank my advisors Mikko Ketokivi and Kari Tanskanen whose contributions to my dissertation project have been complementary but equally critical.

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Yet another absolutely crucial input to the dissertation was made by the 204 informants who filled my questionnaires, agreed to be interviewed, or allowed me to observe how they carried out their daily work. I am particularly grateful to the studied firms' senior executives, whose strong commitment to this research project ensured successful data collection.

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Antti Tenhiälä
Minneapolis, October 30, 2009

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WORKING PAPERS

The contents of this dissertation are based on four article manuscripts that are in different stages of the publication process during the time of this writing. The manuscripts are the following:

Chapters 2 & 3: Tenhiälä, A, "Manifestations and effects of task complexity in operations management research," under preparation to be submitted to a journal

Chapter 5: Tenhiälä, A. and Ketokivi, M., "Order management in the customization-responsiveness squeeze: lessons from make-to-order manufacturing of complex machinery," submitted to a journal

Chapter 6: Tenhiälä, A., "Contingency theory of capacity planning: the link between process types and planning methods," submitted and under the first revision

Chapter 7: Tenhiälä, A. and Salvador, F., "Supply chain glitches, exception processing routines, and organizational reliability: a contingency-theoretical view," submitted to a journal

I list the manuscripts here because I want to gratefully acknowledge the contributions of my two co-authors in the studies that will be presented in Chapters 5 and 7 of this dissertation.

1 INTRODUCTION

The topic of this dissertation is operations management in complex task environments. This chapter briefly introduces the concept and the effects of complexity in manufacturing organizations. It also presents the overall research question of the dissertation and explains the motivations behind its selection. Lastly, the structure of the rest of the dissertation is overviewed.

1.1 CHALLENGE OF COMPLEXITY

1.1.1 Sources and Effects of Complexity

Contemporary management researchers have repeatedly observed that modern manufacturing organizations operate in increasingly complex environments. One driver of complexity is the continuous technological development that increases both the number and the sophistication of features in manufacturers' products (Closs et al., 2008; Narasimhan and Kim, 2002). Another driving force is the increasing diversification of market requirements that is going on in most of today's manufacturing industries (Ketokivi and Jokinen, 2006; Kocabasoglu et al., 2007; Mukherjee et al., 2000). The consequences of these two trends are manifold. First of all, manufacturers are forced to diversify their product offerings or to make adjustments to them at a brisk pace (Tan and Vonderembse, 2006). Furthermore, they also often face demand for more customizable products (Sousa, 2003; Squire et al., 2006). The resulting proliferation of product families, end products, components, and raw materials increase the number of parts in the puzzle of everyday operations management, which makes production planning more complicated and production plans increasingly sensitive to changes (e.g., Salvador et al., 2002; Hegde et al., 2005; Ellis et al., 2008; Williams et al., 2002).

Just as the development of technology and the diversification of market requirements increase the complexity of manufacturers' products, they also increase the complexity of manufacturers' production processes. Along with the advances in manufacturing technologies has come an increased specialization of resources and the need for more specialized skills in operating different kinds of production machinery (Das and Narasimhan, 2001; Swink and Nair, 2007). The challenge is two-pronged: if technology is used to automate and improve the efficiency of production resources, then the processes become more specialized, and if technology is used to improve the flexibility of the production resources, then more specialized skills are required from the process operators (Flynn and Flynn, 1999; Kotha and Orne, 1989; Swink, 1999). While the technological development drives for specialization, the diversification of market requirements reduces manufacturers' possibilities to dedicate resources for specific purposes (Helkiö and Tenhiälä, 2009). Instead, they must face the challenge of making the best use of their specialized resources by wisely arranging and timing the changes from the production of one product to another (Kreipl and Pinedo, 2004; Swink and Nair, 2007). Consequently, there are not only an increased number of parts in the operations management puzzle but also an increased amount of interrelationships and constraints among the individual parts that have to be planned and controlled (e.g., different kinds of routings, diverse skill requirements, variable setup times, etc.)

The increasing complexity propagates even beyond the internal operations of manufacturing firms. When the same technological developments that drive the specialization of production processes and resources are combined with ever more prevalent pressures for efficiency, entire firms are driven to be specialized and focus on specific parts of the value-adding chains (Holcomb and Hitt, 2007; Jacobides, 2005). The disintegration of value chains means that individual firms have less control over the operations that are necessary to produce the goods that they sell. Thus, most manufacturers also face complexity that is manifested as an increasing number of raw material suppliers that have various interrelationships among themselves as well as with the competitors of their customers (Craighead et al., 2007; Hendricks et al., 2009). Furthermore, the geographical distances between individual firms of these supply networks are lengthening as many manufacturers, in hopes of efficiency gains, have relocated parts of their processes in the countries of lower labor costs (Choi and Hong, 2002; Choi and Krause, 2006; Stock et al., 2000). Just like in the case of the products and the processes, the increasing number of entities and their interrelationships not only add to the difficulty of planning operations but also make the supply networks more vulnerable to disruptions (Aron et al., 2008; Hendricks and Singhal, 2003; 2005a).

In all of the above examples, the increased complexity is manifested in a very classic sense. Complexity is typically defined in the literature as the composition of the number of parts in a system and the number of possible interactions among those parts (Simon, 1962; Gottinger, 1983). Also the outcomes of the increased complexity are the same as in the classic literature: the more there are interacting parts and potential interactions in a system, the more difficult it is to plan tasks in advance and to manage disruptions during their execution (Galbraith, 1973; Perrow, 1967; 1984; Thompson, 1967). Consequently, it is not surprising that not much has changed in terms of complexity's overall effects on manufacturing organizations; a recent study by Bozarth et al. (2009) presented relatively strong evidence on negative performance effects resulting from all of the above-described types of complexity: product, process, and supply network.

1.1.2 Persistence of Complexity

Although the evidence on the growing complexity and its negative implications warrants the woes of today's managers, the increasing complexity in the manufacturing sector is certainty not a new phenomenon. Unfortunately, the phenomenon is not likely to be transient either. Already the early organization theorists observed that complexity tends to grow as industries evolve (Aiken and Hage, 1968; Terreberry, 1968). Also the mechanisms of the growth—the technological development and the diversification of markets—were exactly the same as the mechanisms discussed in the contemporary literature:

> "The elaboration of technology usually means that activities which formerly were considered single units of effort are dissected and split into multiple units of effort, each of them specialized and highly developed. With this 'elongation' of the technology comes increasing complexity of the social organization designed to operate it."
> (Thompson and Bates, 1957, p. 326)

> "As the comparison of the three industries in this study suggested, the industrial environment of the future will be both less certain and more diverse. … The differentiation of [organizational] units will be more extreme. Concurrently, the problems of integration will be more complex. Great ingenuity will be needed to evolve new kinds of integrative methods."
> (Lawrence and Lorsch, 1967b, p. 238)

Since the above observations, considerable effort both in academic research and in the development of best practices has been put into the reduction of organizational complexity (e.g., Child et al., 1991; Closs et al., 2008). As the complexity is so inherently related to products and production technologies, it is natural that large parts of the research and development efforts have taken place in the domain of operations management. Understandably, firms have typically pursued the reduction of complexity by trying to restrain the growing diversity rather than the technological development.*

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* Some recommendations have been made in favor of moderating technological development as well (e.g., Stalk and Webber, 1993; Gottfredson and Aspinall, 2005). However, the advice has not been to fall back from competi-

The most obvious countermeasure to the increasing diversity is standardization (Squire et al., 2006). The earliest standardization efforts considered entire products and resulted in single-variant mass products like the paradigmatic black Model T Ford (Abernathy, 1978). Today, the standardization efforts are more subtle because they are typically focused on raw materials (e.g., components' interchangeability and commonality, Sheu and Wacker, 1997; Vakharia et al., 1996), component interfaces (e.g., design rules and modularity, Baldwin and Clark, 2000; Salvador et al., 2002), or production processes (e.g., total quality management programs and ISO certifications, Deming, 1986; Benner and Veloso, 2008; Naveh and Marcus, 2005) instead of the entire end products. In the literature, many of these tools and practices are discussed under the rubric of design for manufacturability (e.g., Boothroyd and Dewhurst, 1988; Youssef, 1994; 1995; Swink et al., 2006). The use of modularity and platform-based product designs has proved to be particularly effective in keeping the diversity-based complexity under control regardless of the increasing product proliferation (Starr, 1965; Ulrich, 1994; Robertson and Ulrich, 1998; Sanchez, 1999; Schilling, 2000; Tu et al., 2001; Koufteros et al., 2002; Salvador et al., 2002; Tu et al., 2004; Fixson, 2005).

Besides product architectures, also management practices can contribute to the reduction of the diversity-based complexity. One of the first arguments in this direction was Skinner's (1974) model of the focused factory. He proposed that plants that are focused on "a limited, concise, manageable set of products, technologies, volumes, and markets" will always outperform their unfocused rivals (Skinner, 1974, p. 114). The evidence behind this bold proposition was largely anecdotal, but further theoretical and empirical work has implied that focused processes may, indeed, be superior in many operating environments (Ketokivi and Salvador, 2007). Skinner's ideas on the importance of maintaining focus in manufacturing operations have also been developed in management paradigms that provide more detailed guidelines on how to implement and use techniques that should keep processes simple. The best-known variants of these paradigms are the rigid flexibility model (Collins and Schmenner, 1993; Collins et al., 1998; da Silveira, 2006), Japanese manufacturing techniques (Schonberger, 1982), world-class manufacturing (Hayes and Wheelwright, 1984; Schonberger, 1986; Flynn et al., 1999), cellular manufacturing (a.k.a. group technology, Burbidge, 1979), quick response manufacturing (Suri, 1998), and lean management

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tors' pace of development but to consider the effects of increased complexity, potential cannibalization, and other byproducts of development when deciding about the pace of designing new products.

(Womack and Jones, 2003; Hines et al., 2004). To a large extent, the contents of these paradigms are the same. The guiding principle in all of them is the relentless pursuit for simplicity, and despite slight differences in emphases, the tools offered are pretty much the same. They include long-term contracts with suppliers to simplify and stabilize supply networks, reduction of parts in product architectures to simplify materials management, cross-training of labor to reduce constraints in production processes, flow-line shop-floor layouts to simplify production planning, visual just-in-time and kanban methods to simplify production control, and strong commitment to quality to reduce problems with variation and rework.

The pursuit for simplicity, its toolkits, and the business literature about it are all certainly invaluable for manufacturing firms. However, fighting complexity by only trying to reduce or eliminate it is not sufficient. After almost three decades of just-in-time, lean management, cellular manufacturing, and other simplification efforts, the complexity in manufacturing has not yet been eliminated. Nor is the elimination likely in the future, since the sources of complexity are permanent by nature. Contemporary observers tend to make the exactly same remarks as Thompson and Bates (1957): the constant development of product and process technologies create new complexities that replace the earlier ones, which may have been successfully remedied (Khurana, 1999; Gottfredson and Aspinall, 2005; Browning and Heath, 2009). The same applies to the other source of complexity: diversification. The strategy literature has long recognized that one way for firms to seek competitive advantage is to try doing different things in different ways than the other firms in the market (Porter, 1985).

By pursuing the differentiation strategy—instead of the efficiency strategy—of value creation, firms run counter to many principles of complexity reduction. For example, offering highly customizable products brings about many kinds of complexities but if the customers really value the customizability, then the resulting higher margins may well offset the increased trouble in the management of the complex production processes (Bozarth et al., 2009). Similarly, instead of pursuing standardization of processes and process technologies, a firm may seek higher customer value by allowing latitude for its labor to improvise and explore new ways of doing business; although the outcome may be chaotic it may well be profitable as well (Hall and Johnson, 2009). Further in the same fashion, reliance on a complex global supply network based on arms-length relationships may be strategically a better option than building long-lasting relationship with few suppliers; the uncontrollability and instability may be offset by flexibility, cost efficiency, or innovativeness of the complex network (Choi et al., 2001; Pathak et al., 2007).

1.1.3 Research Questions

The conclusions from the above introduction are: first, complexity comes from many sources including at least the products, processes, and the supply networks of manufacturing firms. Second, complexity makes a manufacturing firm more vulnerable to disruptions and therefore constitutes a threat to its performance. Third, complexity can be reduced in many different ways as described in the literatures on modular products, just-in-time production control, and lean management, for instance. Fourth, despite the reduction efforts, new complexities tend to arise from constantly developing technologies and firms' pursuits to differentiate themselves from one another. The conclusions lead to the following synthesis: besides pursuing the reduction of complexity, manufacturing firms need to understand how to cope with those sources of complexity that cannot be eliminated.

The objective of this dissertation is to create understanding on how complexity influences everyday operations management in manufacturing firms and what kinds of operations management practices best help alleviate the negative performance effects of complexity. Considering the wide availability of literature on the reduction of complexity, I would argue that this aspect of coping with complexity has not received as much attention as it deserves. Only very recently, the concept of resiliency has surfaced in the business literature. The tenets of the resiliency literature are related to complexity because they give equal emphasis to the avoidance of disruptions—that is, the reduction of complexity which creates ground for disruptions—and to the mitigation of disruptions, which is largely the same thing as coping with the complexity (Sheffi, 2005; Sheffi and Rice, 2005). The resiliency literature calls for more empirical research on the latter aspect (e.g., Kleindorfer and Saad, 2005; Narasimhan and Talluri, 2009) because so far, researchers have only confirmed the relationship between complexity and disruptions and the negative effect of disruptions on firms' performance (Aron et al., 2008; Bozarth et al., 2009; Hendricks et al., 2009). In order to increase understanding in how manufacturing firms can cope with complex task environments[*], I need to address several different research questions:

> RQ1a: What do we already know about operations management in complex task environments?

[*] The concept of task environment refers to both the internal organization of the firm and the immediate external environment in which the firm operates (Thompson, 1967).

RQ1b: Where are the best opportunities to advance the knowledge about operations management in complex task environments?

RQ2: What practices can be used to facilitate successful operations management in complex task environments?

After Research Questions 1a and 1b have been answered in Chapter 3 of this dissertation, Research Question 2 will be further focused and divided into the following three parts:

RQ2a: How does the applicability of different order management practices depend on the complexity of the manufactured products?

RQ2b: How does the applicability of different capacity planning methods depend on the complexity of the manufacturing processes?

RQ2c: How does the applicability of different exception processing routines depend on the sources of uncertainty in complex task environments?

1.2 WHY STUDY OPERATIONS MANAGEMENT UNDER COMPLEXITY?

1.2.1 Practical Motivation

The main practical motivation to choose the above research questions is the already-mentioned paucity of empirically substantiated prescriptive literature on the management of everyday operations in complex manufacturing environments. In the absence of appropriate guidance, manufacturers that deal with complex products, process technologies, or supplier networks may end up in severe difficulties. Recently, this has been demonstrated by the problems that face the world's leading commercial airliner manufacturers. Despite their boasts of advanced lean manufacturing systems and design-for-manufacturability programs (Holmes, 2007; Lunsford, 2007), both Airbus with its A380 Superjumbo and Boeing with its 787 Dreamliner have found themselves "wrestling with several significant technical and production problems that could create a domino effect if not resolved quickly" (Holmes, 2006). In spring 2009, the domino effects appear to have taken place as both firms are reporting lengthy delivery delays and facing formidable contract penalties (Hollinger and Wiesmann, 2008; Weber, 2009).

In addition to the above examples in the business press, also my personal and business contacts in the industry suggested that there would be demand for research on coping with manufacturing operations under complexity. Further evidence of the practical interest is the fact that the research project was relatively easy to "sell" to the senior executives of the companies from which the data of this dissertation were collected. In addition to the senior executives, also the middle managers, who were the main informants, found the topic relevant and were willing to put their time and resources into the study even though at times, it demanded relatively intensive interaction.

1.2.2 Theoretical Motivation

In addition to the practical relevance of the topic, the effect of complexity on operations management practices has some theoretically interesting aspects as well. The opportunity for theoretical contribution is good because operations management research naturally produces middle-range theories, where grand theories of wide generalizability are applied in specific domains (Ketokivi and Jokinen, 2006; Rungtusanatham and Salvador, 2008). These middle-range theories are not only crucially important steppingstones in making the grand theories relevant to practice but also to further elaborate the contents and the interrelationships of these theories' central constructs (Merton, 1957; Bourgeois, 1979). An example of this kind of a contribution is a study on manufacturing flexibility, which showed that the variables explaining the adoption of manufacturing practices are somewhat different from those that are discussed in the grand theories of technological constructs' relationships (Ketokivi, 2006). This kind of an elaboration of a grand theory is the objective of this dissertation as well. The potential for contribution exists because even today, the majority of complexity-related theorizing occurs at the firm level and considers the applicability of different structural arrangements (e.g., Donaldson, 2001) rather than focusing on individual processes and considering issues that determine the applicability of different daily practices—which are the foci of this dissertation's research questions.

The other factor that shapes the aim of this dissertation is the role of contingency theory—the grand-theory perspective of this dissertation—in the operations management research. Although the contingency theory of organizations has roots in the domain of operations management (e.g., Woodward, 1965), it has not been used very widely or systematically in the contemporary operations management research (Sousa and Voss, 2008). In contingency theory, the fundamental premise is that the effectiveness of organizational arrangements depends on the situations and environments in which they are applied (e.g., Donaldson, 2001). Yet, most operations management researchers have chosen to study universalistic propositions that expect some arrangements (e.g., just-in-time production control, total quality management programs, certain types of enterprise software, quality certifications, etc.) to enhance performance regardless of the situations and environments in which they are applied. This kind of a "best practice" research has recently started to draw criticism (Ketokivi and Schroeder, 2004b; Sousa and Voss, 2008), and thus there is an opportunity to make contributions by developing middle-range contingency theories of operations management.

1.2.3 Economic Motivation

In addition to the opportunities for theoretical and practical contributions, the research on the management of complex manufacturing operations has also an interesting economic aspect to it. During the last couple of decades, manufacturing industries have gone through a strong trend of relocating and outsourcing operations globally in search of lowest operating costs. The trend has naturally had a significant impact on the manufacturing industries of the developed countries (Doig et al., 2001). As the most complex parts of the value-adding processes necessitate more professional workforce with more specialized skills, the easiest operations for firms to outsource are the simplest parts of the processes (e.g., Balakrishnan et al., 2007; Novak and Eppinger, 2001). Following from the shift of focus, the manufacturing industries of the developed countries have become increasingly exposed to the above-mentioned sources of complexity, as observed by contemporary researchers:

> "In an age of increasing product functionality, diversification, customization, and change, novel and complex products are becoming more common, and they account for a significant portion of the economic output of developed countries."
> (Browning and Heath, 2009, p. 24)

The anecdotal evidence on the increasing importance of complex manufactures in the developed countries is also backed up by national economic statistics. As described in detail in Tenhiälä (2006), the manufactures of complex products constitute significantly larger proportions of the total manufacturing output in the developed countries than they do in the developing countries, which have been the beneficiaries of the global outsourcing trend. In comparison to China, for example, the relative economic value of complex manufactures is 240 percent higher in the United States. Moreover, there are several European countries, such as Germany, Austria, and Italy, where the relative difference is far larger. In Finland, for example, the relative economic value of complex manufactures is 450 percent higher than in China. As the trend of the simplest processes being outsourced to the countries of lower labor costs is not likely to change in the near future, the conclusion is that any contribution to increase understanding in the management of complex manufacturing operations is particularly welcome in the developed countries whose manufacturing sectors have shrunk due to the trend.

1.2.4 Guiding Principles and Values

The three motivations above give some indications of the values that guided me in choosing the topic and the methodology of this dissertation. As usual in the operations management research, I assume *realist* ontology and *positivist* epistemology. As a scientific realist, I assume that I can observe reality that exists independently of the social constructions and meanings that are given to it by people (Burrell and Morgan, 1979). As a positivist researcher, I assume that it is possible to create if not objective then at least inter-subjective knowledge, which means that different observers following the same methodology would arrive in similar conclusions about the studied phenomenon (Popper, 1959). These ontological and epistemological stances demand indifference and freedom from personal biases and desires regarding the results and the implications of the research. Nonetheless, despite this principle of value-neutrality, research interests of any researcher are necessarily influenced by some personal values, and thus the aimed and achieved contributions of any study are easier to understand and evaluate if the values are discussed explicitly (Root, 1993).

In this dissertation, the guiding values are quite pragmatic. The research interest is best described as *problem-oriented* yet *descriptive*. The main research impetus is the practical challenge of managing manufacturing operations in complex task environments. It means that the study is designed so that there is a chance of generating prescriptive insight to how practicing operations managers should carry out their everyday work. While this kind of practical orientation is normal to operations management research (Meredith, 2001; Ketokivi and Schroeder, 2004b), it stands out as an exception in the wider field of social sciences, where solely theoretical research interests are usually favored and pragmatic interests are often viewed as threats to the "academic purity" of research (Meredith, 2001). In this dissertation, the pragmatism influences the aimed contribution so that the primary purpose of this work is to develop precise and context-specific—rather than abstract and widely applicable—theory (Ferré, 1988). This tradeoff is, of course, in alignment with the goal of developing middle-range theories (Merton, 1957; Bourgeois, 1979) that I discussed earlier.

The other choice with fundamental impact on the dissertation's aimed contribution is the descriptive approach. My objective is to describe how well different practices work under different conditions of complexity. Thus, my role as a researcher is one of an observer instead of a solution developer. Although this kind of a positivist stance (e.g., Donaldson, 2003) is also typical to operations management research, it is by no means self-evident. Namely, pragmatic research interests are often associated with endeavors to develop entirely new solutions through scientific experimenting (e.g., Argyris et al., 1985; Kaplan, 1998; Holmström et al., 2009). Naturally, taking the role of an observer is more reasonable when the problems of interest already have a number of different solutions that are relatively widely implemented in practice so that they can be observed and compared to one another. It turns out that such is the case with the phenomena of interest in this dissertation.

1.3 STRUCTURE OF THE DISSERTATION

After this introductory chapter, the structure of the rest of the dissertation is as follows: Chapter 2 reviews relevant organization theories to chart the existing theoretical knowledge about the effects of complexity on the management of industrial organizations. The chapter concludes with a number of definitions and propositions that give guidance for the rest of the dissertation, which focuses more closely on the day-to-day management of manufacturing operations. Chapter 3 presents a systematic review on complexity research in the contemporary operations management literature. The objective of the chapter is to find out how the theoretical propositions of Chapter 2 have been studied in the recent volumes of top-tier operations management journals. As a result, it is possible to identify unexplored topic areas so that the studies of this dissertation can be focused for maximal potential of contribution. As already revealed in Research Questions 2a, 2b, and 2c, three different topics are picked for empirical inquiry. They are order management under product complexity, capacity planning under process complexity, and exception processing routines under different kinds of uncertainties. Chapter 4 presents the methodology and data with which the chosen topics are studied. Chapters 5, 6, and 7 present analyses that address Research Questions 2a, 2b, and 2c, respectively. Finally, Chapter 8 provides a synthesizing discussion, and Chapter 9 summarizes the main theses of this dissertation.

Overall, the chapters constitute an entity that resembles the *holistic construal* of Bagozzi and Phillips (1982). First in Chapter 2, I start from the generic “theoretical concept” of complexity and develop it into four more analyzable “derived concepts:” uncertainty, organizational complexity, process complexity, and product complexity. They are further developed into a number of “empirical concepts” that can be measured in an operations management context (e.g., product variety, customization, etc.). In Chapter 3, I review the existing operations management literature to understand how to best contribute by studying complexity in the manufacturing context. After presenting the methodology in Chapter 4, I begin the empirical part of the dissertation that comprises Chapters 5, 6, and 7. In Chapter 8, I discuss the meanings of the empirical results at the level of the theories from which the dissertation commenced. This synthesizing discussion closes the deductive-inductive logic of the holistic construal as shown in Figure 1.

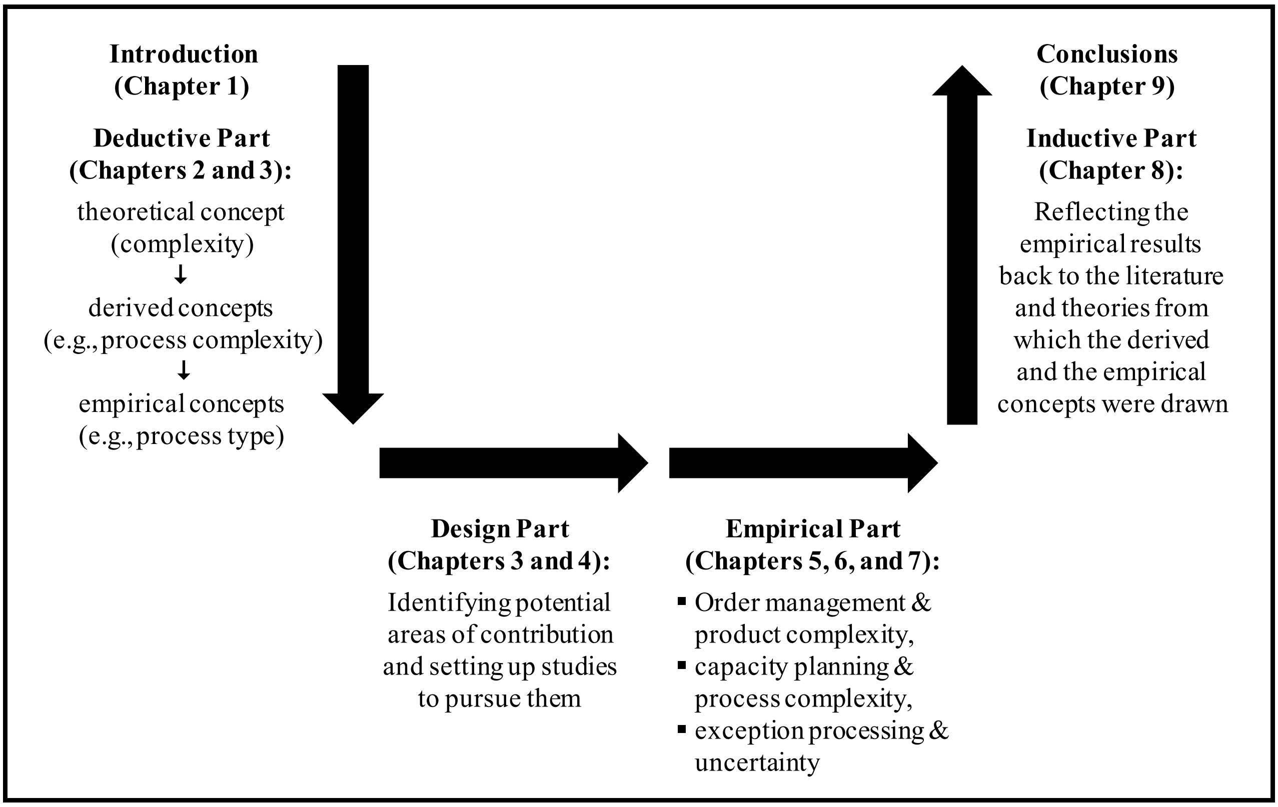

Figure 1: Holistic construal in this dissertation

The contents of the empirical part (Chapters 5, 6, and 7) are based on the outcomes of the theoretical work in Chapter 2 and the literature review of Chapter 3. Also the contents of the empirical part constitute a circular framework. This time, the circle consists of processes that are tied together in the everyday management of manufacturing operations. Figure 2 illustrates the practical connections between the empirical chapters.

1.4 RECAPITULATION

In this chapter, I briefly described how complexity is manifested in the operations of manufacturing firms, where it comes from, and how it influences them. Further, I described how the efforts to reduce and eliminate complexity—despite their doubtless importance—are not sufficient to save manufacturing firms from the negative effects of complexity. Instead, I argued that firms must also develop capabilities to cope with the complexities that they cannot eliminate. Lastly, I presented rationales for the practical, theoretical, and economic importance of improving our understanding in how manufacturing firms can cope with complexity in their everyday operations.

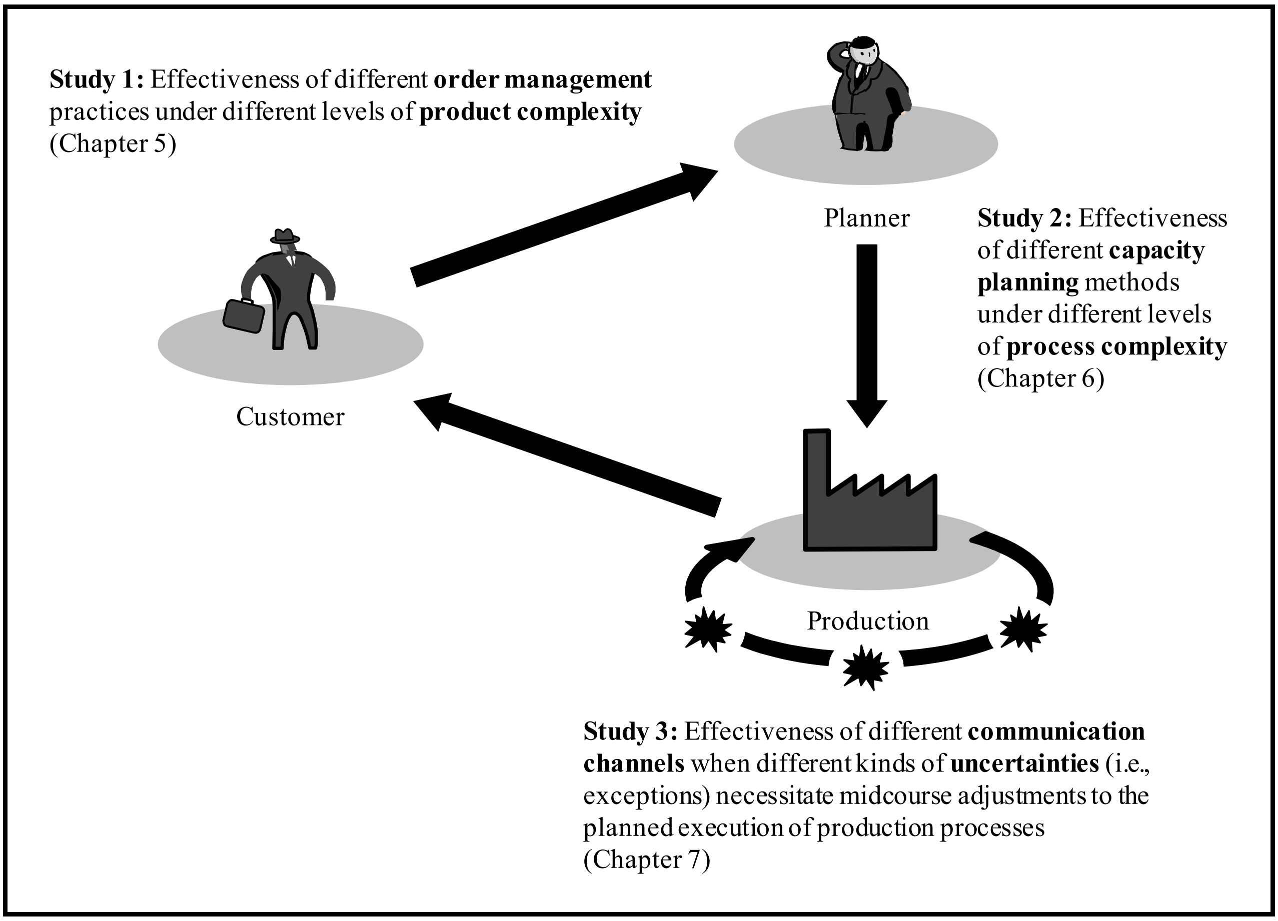

Figure 2: Topics and the interrelationships of this dissertation's empirical studies

2 COMPLEXITY IN MANUFACTURING ORGANIZATIONS

This chapter reviews the existing organization-theoretical literature regarding the effects of complexity. The outcomes of the review are formulated as definitions and theoretical propositions that will guide the analysis of the contemporary operations management literature in Chapter 3.

2.1 SETTING THE FOCUS

The purpose of this chapter is to establish what is already known about the effects of complexity on the management of industrial organizations. In doing so, I will review a selection of organization-theoretical studies and summarize their main theses as definitions and propositions that will guide the review of operations management literature in the next chapter. As for the definitions, it is important to notice that they are not made in any trial to capture the universal meanings of concepts. Such things do not exist because concepts like complexity can be rightfully discussed in different ways depending on what theoretical perspectives are taken. Hence, the definitions are only aimed to outline the concepts from the perspectives of those theories that I believe are the most useful in studying the research questions of this dissertation. Thus, the purpose of the definitions is rather to set the focus of the dissertation than to declare any matters of fact.

One fundamental driver in setting the focus of the theoretical review is my pragmatic research interest in the effectiveness of different operations management practices under complexity. The questions of effectiveness have been discussed mostly in *modern* organization theory, as opposed to the symbolic and the postmodern streams of organization theory that have concerned themselves with other research interests, such as the understanding of how people interpret and construct reality in organizations (Hatch and Cunliffe, 2006).

Another driver of focus is the interest in the management of organizations under complexity. From the vast literature of modern organization theories, I have picked those that most directly address the challenges of managing organizations under complexity. This focus rules out several influential theories of the modern era. The complexity part of the focus reduces the utility of theories based on perfectly rational worldviews (e.g., scientific management, Taylor, 1911) as they tend to assume away the relevant complexities. The management part of the focus, in turn, reduces the utility of theories based on purely natural views of organizations (e.g., human relations school, Mayo, 1933), since they are more concerned with leadership and behavior of individuals than with the management organizational processes. In the place of those streams of literature, the focus is set on the more contemporary theories based on the *open systems* view of organizations (see, e.g., Scott, 2003). They include among others the contingency theory of organizations (Lawrence and Lorsch, 1967b; Donaldson, 2001), normal accidents theory (Perrow, 1984), and high reliability theory (Weick, 1987).

The third driver of focus is the interest in operations management, which I consider to encompass the management of *intra-organizational* operations. This focus excludes those open-system theories that are concentrated on larger units of analysis. They include, for example, population ecology (Hannan and Freeman, 1977) and organization-level social networks theory (Burt, 1982). Another dominant open-system theory that I find inapplicable is the resource dependence theory (e.g., Pfeffer and Salancik, 1978), which is more focused on strategic than operational issues in management of organizations. So in summary, whenever I discuss “organization science” in the following review, I refer to those streams of organization science that somehow concern themselves with organizational effectiveness, complexity, and the operational-level management of individual organizations.

2.2 COMPLEXITY AND UNCERTAINTY

2.2.1 What is Complexity?

Complexity is a focal construct in many fields of science. In organization science, a system—a process, a product, or an organization, for instance—is considered complex if it has a large number of parts that may interact with one another in many different ways; the larger the numbers of parts and different kinds of possible interactions, the higher is the complexity (Simon, 1962; Gottinger, 1983)[*]. The rest of this chapter builds upon the following formal definition:

> D1: Complexity refers to the number of different parts in a system and to the number of different interactions that can occur between the parts.

[*] Here, I choose to focus the dissertation so that complexity is considered as an objective characteristic of a system (Campbell, 1988). Alternatively, complexity could be considered as a subjective experience that depends on the cognitive capacity (e.g., Loy, 1991) and the previous experiences of an individual (e.g., Shaw, 1976). This choice is in alignment with the dissertation’s focus on managerial rather than behavioral issues. It basically means that the objective complexities of this dissertation may be perceived as more or less complex depending on the individuals experiencing them.

Both the number of parts and the number of different possible interactions are important elements of complexity. Although the two are related so that the total amount of possible interactions often increases as the number of parts increases, it does not mean that all systems with a lot of parts would have to be complex. Instead, the literature distinguishes between complex and *complicated* systems by referring to the latter when a system has many parts but their interactions are predictable (Waldrop, 1992). It means that in a complicated but non-complex system, Event X in any part of the system has always the same effect on the other parts of the system. Meanwhile the behavior of a complex system is less predictable because the interactions between its parts can take many different forms. It means that they can be nonlinear, asymmetric, and temporary (Yates, 1978; Guastello, 1995). A nonlinear interaction takes place if, for example, Event X has a small effect in Part A of the system, which leads to hardly any effect in Part B but to a huge effect in Part C. An asymmetric interaction, in turn, occurs if Event X in Part A leads to Effect Y in Part B but the same Event X in Part B leads to a different Effect Z in part A. Lastly, the temporariness of the interactions means naturally that their nature changes over time.

According to this definition of complexity, a repetitive production process of a standard commodity like a drug or a food product can be very complicated yet fairly non-complex. That is because the interactions between the many different production activities are relatively well known due to the repetitive nature of the process—and in fact, they must be well known and predictable, since the regulators of pharmaceutical and food industries are typically not very tolerant of improvisation. By contrast, a production process of highly customized products like machine tools or industrial instruments can be very complex because whenever a product has many unique specifications, it is impossible to have previous knowledge on all potential interactions between different production activities. The distinction between complicatedness and complexity is illustrated in Figure 3.

An important characteristic of complex systems is that it is not the complexity in itself that is problematic but the interaction between complexity and uncertainty (Duncan, 1972). When a system faces unexpected events, the more it has parts and the more there are different kinds of interactions that can occur between the parts, the more difficult it is to control the effects of the events. That is because the different parts of a complex system may react to the events in many different ways (Lawrence and Lorsch, 1967a) so that the disparate reactions may trigger cascade effects that create new unexpected events as they ripple through the different interconnected parts of the system (Pfeffer and Salancik, 1978). In a merely complicated system, the evolution of cascade effects can be anticipated and thus controlled. Meanwhile in a simple system, the cascade effects are naturally short-lived as they do not have room to emerge and evolve (Perrow, 1984).

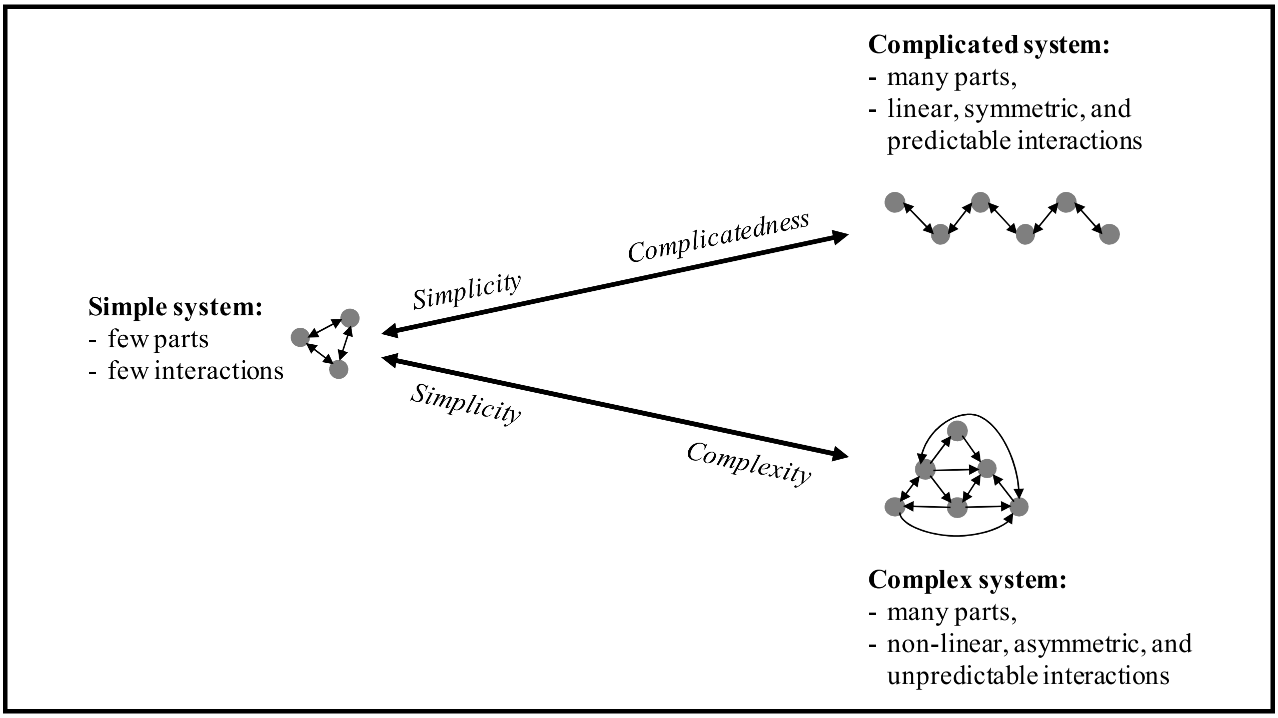

Figure 3: Simplicity, complicatedness, and complexity

In addition to the prospect of cascade effects, complexity increases vulnerability to uncertainty because buffering against unexpected events becomes more difficult when a system has more parts and the interactions that needs to be buffered (Galbraith, 1973). In very complex systems, not only is it necessary to have buffers in many places but also the estimation of the appropriate sizes of the buffers is difficult due to the unpredictability of the interactions between different parts (Thompson, 1967; Perrow, 1984). Here, a buffer refers to any kind of slack or redundancy that can help the system absorb unexpected events without implications for its desired performance level (Bourgeois, 1981). In manufacturing organizations, such buffers include at least safety stock, reserve capacity, and floats or safety lead times in production plans (e.g., Goldratt, 1997; Leach, 2005; Vollmann et al., 2005). Due to the difficulty of buffering, the complex systems are particularly vulnerable to unexpected events, and thus the fundamental nature of complexity can be summarized in the following proposition:

P1: Uncertainty has a negative effect on performance, especially in complex systems (e.g., organizations, processes, or products).

In this proposition, I use the word performance synonymously with what is often discussed as organizational effectiveness (Scott, 1977; Donaldson, 2001). It is "the extent to which an organization as a social system, given certain resources and means, fulfills its objectives without incapacitating its means and resources and without placing undue strain upon its members" (Georgopoulos and Tannenbaum, 1957, p. 535).* Naturally, choosing the objectives is an important strategic decision, and thus the chosen goals may vary widely among different organizations. The most typical objectives for manufacturing organizations are cost efficiency, flexibility, quality, and delivery performance (Ward et al., 1995; Ward et al., 1998). Since there are no theoretical bases to propose that uncertainty would only be detrimental to some but not all of these dimensions, Proposition 1 does not make any distinctions on the bases of how performance is measured.

2.2.2 What is Uncertainty?

In the above, I discuss uncertainty simply as the occurrence of unexpected events. In contrast to such a narrow view, classic organization-theoretical literature offers several generic definitions of uncertainty. For example, Galbraith (1973, p. 5) defines uncertainty as the difference between the amount of information required to perform a task and the amount of information already possessed by the organization. In a classic book, March and Simon (1958, p. 134) define uncertainty as a lack of information about the probability distributions that connect decisions to their outcomes. These generic definitions are aligned with Proposition 1 since it is easy to fathom how the amounts of parts and different kinds of interactions leverage the negative performance implications of the lack of information. Therefore, I first lay down the generic definition of uncertainty:

D2: Uncertainty is lack of information about the task environment.

When going into more detailed nature of uncertainty, I take the introduction of Proposition 1 as a starting point and discuss the manifestations of uncertainty as unexpected events arising from the task environment of an organizational system (Miller and Friesen, 1983; Dess and Beard, 1984). The word "unexpected" is important in this operationalization. Following the logic of Definition 2, a high frequency of predictable events that occur exactly when expected and just as expected is not considered as a manifestation of uncertainty (Miles et al., 1974; Milliken, 1987). In the literature, many words are used synonymously with the frequency of unexpected events. They include *dynamism*, *instability*, and *turbulence* of the task environment (e.g., Baum and Wal-

* With this definition, I adopt a rather classic view of organizations (Scott, 2003). The proponents of some more recent views would argue that organizations as inhuman things cannot have objectives of their own and thus the effectiveness of any organization depends on whose objectives are considered (Cummings, 1977; Weick, 1976).

ly, 2003).[*] Similarly, the unexpected events are also discussed as changes or *exceptions* (Perrow, 1967). Consequently, the following definition can be formulated:

> D3: Dynamism, instability, and turbulence refer to uncertainty that is manifested as frequency of exceptions (or unexpected events or changes) in the task environment.

Another important issue in uncertainty concerns what it takes to recover after an exception has occurred. One could argue that a task environment in which easily solvable, little exceptions occur all the time is uncertain in a different way than a task environment where exceptions occur quite seldom but when they do, the entire system loses its capacity to fulfill its purpose for an indefinite period of time. Obviously, the issue is not whether one or the other of the examples is more or less uncertain than the other, but instead exceptions' frequency and ease of solving appear to be two different dimensions of uncertainty (Perrow, 1967; Daft and Lengel, 1986). This discussion is well aligned with the generic definition of uncertainty as a lack of information (e.g., Galbraith, 1973). When exceptions occur, it is necessary to search for or create new information (e.g., a solution to a problem or a plan to resume normal operations after some parts of the system have unexpectedly become unavailable). The easiest exceptions are such that their solutions can be found by asking a few yes-or-no questions. The most difficult exceptions are such that it is not even clear what the questions could be. This dimension of uncertainty is typically referred to as *equivocality* (Daft and Lengel, 1986; Daft and Macintosh, 1981), *ambiguity* (March and Olsen, 1976), or lack of *analyzability* (Perrow, 1967).

> D4: Equivocality, ambiguity, and unanalyzability refer to uncertainty that is manifested as difficulty of solving exceptions that have occurred in the task environment.

A third important issue in uncertainty is the speed with which the exceptions propagate after their initial occurrence. Colloquial examples of two similar exceptions with very different levels of urgency would be an engine breakdown and an engine fire in a flying aircraft. The former is likely to propagate with a slower (and more predictable) speed than the latter. When the urgency of the exceptions increases, the importance of swift response increases (Perrow, 1984). Interestingly, organization theorists have taken two contradictory perspectives to the means of improv-

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[*] In contrast, terms like task-environmental *velocity* (e.g., Eisenhardt, 1989b) and *volatility* (e.g., Anand and Ward, 2004) typically refer to the mere rate of change without the assumption of unpredictability.

ing the speed of response. Students of one school argue that decentralized and informal decision making is imperative because bureaucracy causes unnecessary delays (Majchrzak et al., 2007). Meanwhile, another school of thought argues that centralized and formal decision making is imperative since it minimizes the psychological effects that cause delays in stressful situations (Tetlock, 1985; Bigley and Roberts, 2001). The organizational and the psychological factors that may delay responses to exceptions are discussed in threat-rigidity theory but the controversy remains unsolved (Staw et al., 1981; Baum and Wally, 2003). However, some researchers have analyzed various hybrid decision-making structures that aim to grasp the benefits of both solutions (e.g., Starbuck and Milliken, 1988; Roberts et al., 1994; Goold and Campbell, 2002; Roberto et al., 2006). In summary:

D5: Urgency refers to uncertainty that is manifested as swift propagation, intensification, or escalation of exceptions, which have occurred in the task environment.

While the frequency, equivocality, and urgency of exceptions appear to be the most commonly utilized dimensions of uncertainty, other operationalizations exist too. One of them is Milliken's (1987) concepts of state, effect, and response uncertainty. In that operationalization, *state uncertainty* refers to the lack of information regarding to the current or future state of the task environment (e.g., what is the demand for Product X in next quarter?). *Effect uncertainty* refers to the lack of information regarding what is going to happen if some specific event occurs (e.g., what will happen to the firm if the demand of Product X is below Y in next quarter?). *Response uncertainty*, in turn, refers to the lack of information about what should be done after the effect has been realized (e.g., what should be done if the demand of Product X falls short of Y in next quarter?). Hence the following definitions:

D6a: State uncertainty refers to the lack of information regarding what is happening and what will happen in the task environment.

D6b: Effect uncertainty refers to the lack of information regarding the consequences if some specific exception occurs in the task environment.

D6c: Response uncertainty refers to the lack of information regarding what should be done if some specific exception occurs in the task environment.

Another approach that differs from the earlier definitions has been suggested by Sutcliffe and Zaheer (1998), whose operationalization distinguishes between *primary* and *secondary* uncertainties. The former refers to natural events (e.g., is it going to start raining?) while the latter is used in reference to the purposeful actions of actors that have deliberative ability (e.g., is Aunt

Annie coming for a visit tonight?). The idea behind this distinction is that the probability distributions, mitigation mechanisms, and response strategies could be very different depending on whether the system is facing primary or secondary kinds of uncertainties. The same distinction has also been made by Williamson (1985), who labeled the dimensions *innocent* and *behavioral*. Hence, I formulate the following definitions:

D7a: Primary or innocent uncertainty refers to the lack of information regarding naturally occurring phenomena.

D7b: Secondary or behavioral uncertainty refers to the lack of information regarding the current and future actions of actors with deliberative ability.

Yet another approach has been taken by Argote (1982), who pointed out that especially in service-providing organizations, a considerable challenge arises from the variability in organization's "input materials" (e.g., patients in a hospital). In comparison to the earlier definitions of uncertainty, the issue with *input uncertainty* is not that something unpredictable would happen, but instead it is that not much can be predicted when a system needs to process a very wide variety of inputs (Larsson and Bowen, 1989; Siehl et al., 1992). Thus, I formulate the last manifestation of uncertainty as follows:

D8: Input uncertainty refers to the lack of information regarding the raw materials that the system needs to process.

2.2.3 Sources of Uncertainty

While the above definitions consider the different manifestations of uncertainty, another important attribute is the source of uncertainty. Many different streams of organizational research have focused on uncertainties from a specific source. For example, socio-technical systems theory has concentrated on events that arise from within the system (Cherns, 1976). Game theory and transaction cost economics have focused on uncertainties that originate from organization's business partners like suppliers and customers (von Neumann and Morgenstern, 1944; Williamson, 1985). Strategic management research has concerned itself with the uncertainties that arise from the moves of an organization's competitors (e.g., Porter, 1985). Disaster management literature has focused on uncertainties that arise from the natural environment (e.g., Dynes, 1970). Lastly, many researchers from different fields have discussed uncertainties that are generated by governmental and regulatory agencies (e.g., Dill, 1958; Duncan, 1972; Bourgeois, 1985). Consequently, Proposition 1 can be further defined to the following six propositions:

P1a: Uncertainty that arises from internal operations has a negative effect on the performance of a complex system.

P1b: Uncertainty that arises from raw material suppliers has a negative effect on the performance of a complex system.

P1c: Uncertainty that arises from customers has a negative effect on the performance of a complex system.

P1d: Uncertainty that arises from competitors has a negative effect on the performance of a complex system.

P1e: Uncertainty that arises from the natural environment has a negative effect on the performance of a complex system.

P1f: Uncertainty that arises from regulatory agencies has a negative effect on the performance of a complex system.

2.3 MANIFESTATIONS OF COMPLEXITY

Now that I have briefly overviewed the organization-theoretical literature regarding the manifestations and sources of uncertainty, I will do the same thing for complexity. Following the framework of Kotha and Orne (1989), I structure the review by making the first division between organizational, process-related, and task-related complexities.

2.3.1 Organizational Complexity

The most traditional view of organizational complexity holds that it stems from the size of the organization. As an organization grows, its subunits tend to become more specialized in specific tasks; in other words, they become *differentiated* (McNulty, 1962). On the organizational level, differentiation typically means specialization in different business functions such as production, marketing, accounting, and so forth (e.g., Thompson, 1967). Although the purpose of this evolution—whether intentional or not—is to make the organization more efficient, as suggested by the classic literature on bureaucracy (e.g., Weber, 1946), it can also work against the organization by increasing its complexity (Blau, 1970). That is because differentiation increases the number of different parts in an organization, which is one of the two elements in the definition of complex systems. However, differentiation does not necessarily lead to complexity, since it is not directly associated with the amount of interactions between the parts, which is the second element of the definition (Simon, 1962; Gottinger, 1983). Thus, it is the number of possible interactions between the different parts that makes a differentiated organization complex.

The number of interactions within a internally differentiated organization is typically discussed as the strength with which its subunits are coupled (Weick, 1976). A *loosely coupled* organization is not very complex or vulnerable to uncertainty, while a *tightly coupled* organization is complex and thus vulnerable to uncertainty. Another albeit less common way to discuss the level of intra-organizational coupling is to discuss the *requisite integration* between differentiated business functions (Lawrence and Lorsch, 1967a). The idea in that approach is that integrative devices are *required* in order to manage a tightly coupled organization successfully. In summary, the manifestation of complexity at the organizational level can be defined as follows:

> D9: Tight versus loose coupling, or the level of requisite integration, refers to the intensity of interactions between functionally differentiated subunits of an organization.

The normal accidents theory of Perrow (1984) addresses directly the challenge of tight coupling. The name of the theory comes from Perrow's argument that accidents are inevitable or "normal" in tightly coupled systems. The primary countermeasure in Perrow's approach is the elimination of the tight links, which can be done by investing in sufficient buffers of time or materials between the differentiated functions (Galbraith, 1973). If that is not possible, and the projected ramifications of the accidents are sufficiently severe, then the only solution that Perrow offers is the abolition of the entire organization. In Perrow's analysis, nuclear power plants for instance fall into this hopeless category. To avoid that destiny, organizations should try to eliminate the tightly coupled links, and so the main tenet of the theory can be summarized as the following proposition:

> P2: Complexity (and thus vulnerability to uncertainty) can be reduced by using buffers of materials or time to eliminate tightly coupled links between functionally differentiated subunits.

2.3.2 Process Complexity

While the above-presented view held that functional differentiation (caused by the growth of an organization) creates complexity, another form of differentiation that can also create complexity; that is, differentiation among the different work units that contribute to the same production process (Thompson, 1967; Adler, 1995). Here, the work units do not refer to functional departments but to resources that are responsible for certain process steps, such as inspection of raw materials, machining, assembly, painting, quality control, and so forth. This form of differentiation originates from technological development that tends to necessitate deeper specialization into specific production tasks (Thompson and Bates, 1957; Lawrence and Lorsch, 1967b; Aiken and Hage, 1968; Terreberry, 1968). For example, in a traditional craftsman's shop, a single person can perform all the process steps that are required to produce the entire product, in contrast to the manufacturing of high-tech products like silicon chips, where both the process operators and the production machinery need to possess such specialized capabilities that work units must be differentiated.

When it comes to the differentiation among work units, the intensity of interactions (i.e., tight versus loose coupling) is no longer a sufficiently accurate measure. Instead, the sequence and the direction of the interactions must be taken into account as well. In the classification of Thompson (1967), the simplest type is called *pooled* interdependence, and it occurs when all work units depend on one another doing their own part of the process, but there are no requirements regarding the sequence or the direction of the interdependence. In the more complex type, the sequence is important and hence it is called *sequential* interdependence. It occurs when work units depend on the outputs of other work units by using them as inputs in their own work. The most complex type in the original classification is called *reciprocal* interdependence and it refers to processes in which the sequence is important but in contrast to the previous type, the direction is not in only one way. Instead, two work units can use each others' outputs as their own inputs, and such iterations can occur several times.

Practical examples of Thompson's (1967) types of interdependence can be found from the book of Woodward (1965). In her pioneering study, she concluded among many other things that production process types constitute a hierarchy of complexity, in which a job-shop process type is simplest, a line-flow process type is the second most complex, and a batch production process is the most complex. These process types match well to the pooled, sequential, and reciprocal types of interdependence.

The original classification of Thompson (1967) has later been complemented with one even more complex type, which is known as *team* interdependence (Van de Ven et al., 1976). It refers to situations where different work units must do their parts of the process exactly at the same time. So in summary, the different types of process-level complexity can be summarized in the following definitions:

D10a: Pooled interdependence refers to the least complex type of process interdependence because in pooled processes (e.g., in job shops), the sequences and the directions of interactions are not predetermined.

D10b: Sequential interdependence refers to the third most complex type of process interdependence because in sequential processes (e.g., in assembly lines), the sequences of interactions are predetermined but unidirectional.

D10c: Reciprocal interdependence refers to the second most complex type of process interdependence because in reciprocal processes (e.g., in batch shops), the sequences of interactions are not only predetermined but they can also create iterative loops.

D10d: Team interdependence refers to the most complex type of process interdependence because in team-interdependent processes (e.g., in teamwork), the work units must interact exactly at the same time.

The first remedy against the process-level complexity is the same as against the organization-level complexity: reduction of the interdependence (Thompson, 1967; Galbraith, 1973). That is possible if the differentiation of work units can be reduced, for example, by replacing specialized production resources with computer-integrated multipurpose machinery (Dean and Snell, 1991) and by cross-training the workforce to perform multiple tasks (Manz and Stewart, 1997). Typically, also changes to product designs are necessary but it will be discussed in the next section of this chapter. Anyway, the remedy can be formulated as follows:

P3a: Complexity (and thus vulnerability to uncertainty) can be reduced by decreasing the specialization of the work units that constitute the production processes.

If the process-level complexity is very high like in the reciprocal processes of batch shops, the classic operations management literature offers two additional ways to make the interdependences more manageable. Both of them work by restricting the direction of interactions between work units, which essentially means moving from reciprocal interdependence towards a sequentially interdependent assembly line.

The first solution is called bottleneck control. In the literature, it is discussed under several rubrics, such as the theory of constraints, bottleneck control, and optimized production technology (Goldratt and Cox, 1984; Vollmann, 1986; Schragenheim and Ronen, 1990). The basic idea in all of them is to invest in sufficient excess capacity in the less expensive work units so that the work unit with most expensive resources constitutes a bottleneck in the process. Consequently, the process becomes sequential around the bottleneck and the excess capacity ensures that possible unexpected events in the reciprocal parts of the process do not disrupt the entire process.

Another solution is to divide and rearrange the work units and the machines of a batch shop as manufacturing cells, where all productive resources that are needed for the production of one product (or a product family or a semi-assembly) are put together in small groups that are typically organized in U-shaped layouts, which enable individual operators to multitask (e.g., Burbidge, 1979; Singh, 1993; Suri, 1998; Hyer and Wemmerlöv, 2002). The reciprocal interdependences become sequential when the productive resources of a batch shop are arranged in cells according to the routings of the products (Garza and Smunt, 1991; Yang and Deane, 1994).

Both the bottleneck control and cellular manufacturing typically necessitate other complexity reduction efforts than the mere reorganization of work units and process layouts (Venkatesan, 1990; Wemmerlöv and Johnson, 1997). Thus, they are often accompanied with several methods that are discussed in the next subsection of this chapter. However, the process-level effect can be formulated as the following proposition:

P3b: Complexity (and thus vulnerability to uncertainty) can be reduced by decreasing the amount of reciprocal interdependences in the production processes.

If the process complexity is extreme like in the case of team-interdependent processes, the simultaneous interactions can be sometimes eliminated by partitioning work or otherwise redesigning the process steps (Van de Ven et al., 1976). That way, the process can be first made reciprocal and thereafter, additional steps can perhaps be made to simplify the process further. Hence the following proposition:

P3c: Complexity (and thus vulnerability to uncertainty) can be reduced by decreasing the amount of team interdependences in the production processes.

2.3.3 Task Complexity

While the first two manifestations of complexity are ultimately caused by the differentiation of organizational units (i.e., functional subunits in the case of organizational complexity and specialized work units in the case of process complexity), the third one, task complexity, results from the *variety of activities* that must be mastered within the organizational units (Child, 1972; Dess and Beard, 1984). In the exact same way as the differentiated organizational units may constitute complexly interconnected systems, the different activities conducted in one organizational unit may be interconnected in multiple different ways and thus constitute complex systems of their own (Wood, 1986). This sort of complexity can be labeled action variety* and defined as follows:

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* Here, I use the somewhat rarer term "action variety" instead of "task variety" to avoid confusion. Although some authors (e.g., Wood, 1986) have used the latter term for the purpose at hand, some others (e.g., Daft and Lengel, 1986) have used it in referring to dynamism (i.e., the frequency of unexpected events).

D11: Action variety refers to task complexity in the form of the overall variety of tasks that must be mastered in an organizational unit.

For example, a machining resource which is used to process parts that are of different shapes and materials faces more action variety than a machining resource that is dedicated to the processing of only certain shapes or materials. Here, at least two mechanisms contribute to task complexity. First, the number of different interactions between jobs increases because the execution of each a job can vary depending on the previous jobs. For example, different deburring, cleaning, and setup activities can be required depending on the differences between the materials and the shapes of the consecutive machining jobs. Second, wider action variety increases the amount of different failure modes that can occur during the task, which increases the unpredictably of the interactions between different jobs. For example, certain sequences of jobs can increase the likelihood of different failures, such as jamming, overheating, and contamination.

The most obvious solution to reduce the task complexity that results from action variety is to focus on only executing certain tasks. As described in Skinner's (1974) model of focused factory, this solution means that organizational units are focused on serving certain market segments with similar needs. The solution can be formulated as the following proposition:

P4a: Complexity (and thus vulnerability to uncertainty) can be reduced by focusing on serving specific market segments.

Another obvious solution to reduce the task complexity resulting from action variety is to introduce *redundancy* (Landau, 1969; Lerner, 1986). In the above-presented example, the redundancy could be implemented by duplicating the machining resources and dedicating each of them to the processing of certain kinds of materials and shapes. Building redundancies into a system is a fundamentally similar solution to the buffering, which was discussed in the contexts of Propositions 2 and 3b (Galbraith, 1973; Thompson, 1967). Thus, the following proposition is in essence the manifestation of buffering at the task level:

P4b: Complexity (and thus vulnerability to uncertainty) can be reduced by investing in redundant resources.

In addition to the redundancies, there are also several other solutions to reduce task complexity that arises from action variety. These solutions can be derived from Ashby's (1956) "law of requisite variety". It says that in order to transform inputs into predetermined outputs, the variety of inputs must be matched with an equal variety of activities. Therefore, to keep the action variety within bounds is the same as to keep the variety of inputs under control. In manufacturing organizations, *standardization* is a classic way of controlling the variety of inputs (Taylor, 1911). The most obvious subject of standardization is the raw materials. By defining and then systematically controlling the dimensions and other measurable properties of raw materials, the productive work units can be sheltered from the escalation of action variety (Shewhart, 1931). In addition to the specifications of materials, work procedures and entire processes can be standardized (e.g., March and Simon, 1958; Galbraith, 1973; Lillrank, 2003). The effect on action variety is the same. When different work units produce outputs that are used as inputs by other work units, the standardized work procedures and process flows reduce the need for the units to adapt to the different ways, forms, and conditions in which the other units may deliver their outputs. In conclusion, I present the following overall proposition on standardization without going into its various possible subjects:

> P4c: Complexity (and thus vulnerability to uncertainty) can be reduced through standardization.

Besides standardizing raw materials, the variety of inputs for a task can be reduced simply by decreasing the amount of different raw materials (MacDuffie et al., 1996). If for example, a work unit uses Raw Materials A, B, and C, then standardization would mean that it would only receive raw material variants A_1, B_1, and C_1 instead of A_1, B_1, C_1, A_2, B_2, C_2, A_3, B_3, C_3, and so on. The reduction of raw materials, on the other hand, would mean that it would only receive Raw Materials A and B, and not C. Standardization and the reduction of raw materials influence action variety and thus task complexity in exactly the same ways. Due to the sheer amount of raw materials, producing a commercial airliner is a much more complex task than producing a box of matches but the task of producing the commercial airliner would be even more complex if none of the raw materials were standardized. The sort of task complexity that can be measured as the number of distinct parts in a single product can be labeled *component variety* and defined as follows:

> D12: Component variety refers to task complexity in the form of variety of raw materials that must be handled in the production.

This sort of task complexity can be remedied in at least two ways. First, the organization may outsource non-core production activities and purchase its raw materials at a more value-added stage, which naturally reduces the variety of materials that must be dealt with within the organization (Kotha and Orne, 1989). Another approach is to simplify the product structures by developing products that would share many of the same parts (Child et al., 1991; Collins et al., 1998). This solution is called component commonality (Baker, 1985). Thus, the following propositions can be formulated:

P4d: Complexity (and thus vulnerability to uncertainty) can be reduced by outsourcing non-core production activities.

P4e: Complexity (and thus vulnerability to uncertainty) can be reduced by increasing component commonality.

On an even more basic level, the task complexity can be increased by increasing the number of different product lines that are offered to the customers (Kotha and Orne, 1989). Naturally, the action variety is lesser if an organization produces only commercial airliners or matchboxes than if the organization produced both. Thus, product variety must be considered as well:

D13: Product variety refers to task complexity in the form of variety of outputs that the organization must be able to produce.

In most organizations, the task complexity that arises from product variety is particularly controllable because the diversification of product lines is often a strategic decision. The organization may choose to enter into new market segments or to serve customers with a wider product varieties so that they can better find the products that best fit to their needs (Kekre and Srinivasan, 1990; Kahn, 1995). However, since the product variety increases task complexity, organizations must often seek a balance, and thus it can be proposed as follows:

P4f: Complexity (and thus vulnerability to uncertainty) can be reduced by decreasing the variety of the offered products.

Two other causes of task complexity operate in much similar manner as the product variety. First, instead of diversifying product lines, organizations may choose the strategy of reaching for new customers by maintaining a quick pace of *new product introductions* (Fine, 1998). The challenge with that strategy is that it does not leave much time to learn about the interactions between different production activities (Kotha and Orne, 1989). The other similar strategy is to offer *customizability* so that customers can choose from different options and features instead of complete end products (Kotha, 1996). Naturally however, the customizability of products increases the amount of different activities that must be mastered in the production and also the number of unknown interactions between the activities. Thus, the following two definitions can be formulated:

D14: Rate of new product introductions, refers to task complexity in the form of quick pace of change in activities that must be mastered in the production.

D15: Product customization refers to task complexity in the form of the required production activities varying from one order to another.

High rates of new product introductions impose several challenges in addition to the increased complexity. They include cannibalization of earlier products, difficulties in maintaining and servicing all product generations, and costs of marketing and training of front-end personnel (Stalk and Webber, 1993). Therefore, the moderation of new product introductions is often recommendable and it also works to reduce task complexity. Thus, it can be proposed as follows:

> P4g: Complexity (and thus vulnerability to uncertainty) can be reduced by decreasing the pace of new product introductions.

Similarly as above, the most obvious remedy against customization-based task complexity is to moderate the offered level of customizability. In fact, several authors have argued that firms in many industries have gone overboard with the customizability (Agrawal et al., 2001; Zipkin, 2001). Thus, it can be proposed as follows:

> P4h: Complexity (and thus vulnerability to uncertainty) can be reduced by decreasing the customizability of the offered products.

The other main remedy against customizability-based task complexity is discussed in the handbooks of mass customization (e.g., Pine, 1993). That stream of literature has the almost paradoxical objective of describing ways in which diversity can be offered with relatively standard sets of production activities. The primary ways to reach that objective—in addition to the above-mentioned component commonality—are *modularity* (Starr, 1965) and *product platforms* (Robertson and Ulrich, 1998). In both solutions, the idea is to create diversity by combining and swapping relatively standard parts and thus to reduce the variety of activities that must be mastered in the production. This remedy can be summarized in the following proposition:

> P4i: Complexity (and thus vulnerability to uncertainty) can be reduced by increasing the use of modularity and platform structures in products.

2.4 COPING WITH COMPLEX TASK ENVIRONMENTS

Now that the above propositions have been laid out, it is probably worth reminding that one should not err to think that the elimination of complexity would be the foremost priority in all organizations. Although complexity increases vulnerability to uncertainty, we observe that not all industrial activity is organized as a craftsman’s job shop. Nor is every firm only producing a single standard product. On the contrary, complex production processes and products prevail in contemporary industrial organizations as discussed in Chapter 1 (e.g., Bozarth et al., 2009; Browning and Heath, 2009). The reason for accepting the complexity of the task environment is often that it is a technical necessity. For example, it may not be economically viable to implement sufficient buffers for drum-buffer-rope production control or comprehensive cellular manufacturing systems that would turn an intensive reciprocal process into a completely sequential process (Hyer and Wemmerlöv, 2002; Johnson and Wemmerlöv, 2004); or it may not be possible to simplify the product structures of swiftly evolving high-tech products (Closs et al., 2008). Consequently, many organizations choose to try and cope with the complexity of their task environments.

2.4.1 Reduction of Uncertainty

While the above propositions concentrated on the avoidance of complexity, the organization may also pursue the avoidance of uncertainty. Considering Definition 2 about uncertainty being essentially lack of information (Galbraith, 1973), the first solution to this challenge is quite intuitive. It is the active collection of information from organization's task environment (Leblebici and Salancik, 1981). In manufacturing contexts, the collection of information typically refers to forecasting efforts or supply chain collaboration (e.g., Forrester, 1958). They can be exercised in many different ways ranging from making occasional consumer studies to the systematic large-scale data mining and the utilization of sophisticated actuarial methods. Regardless of the sophistication of the methods, their desired effect can be summarized in the following proposition:

> P5a: Uncertainty can be reduced (and thus the performance of complex systems improved) by increasing the collection of information from the task environment.

Another equally intuitive solution is to try and change the task environment altogether. The researchers of strategic management have long ago dismissed the idea of the task environment being an externally given contingency factor which the organization must either adapt to or decease. Instead, the task environment is seen to be dependent upon the market segments that the organization chooses to serve (Child, 1972; Bourgeois, 1984; Clark et al., 1994). Therefore, uncertainty can also be reduced by choosing to operate in stable markets. Thus, the following proposition can be presented:

> P5b: Uncertainty can be reduced (and thus the performance of complex systems improved) by choosing to operate in stable markets.

There is yet another intuitive approach. It is simply being careful in uncertain task environments. The issue is discussed in depth within the high reliability theory (or the theory of high reliability organizations) of Weick (1987). In Weick's theory the carefulness is discussed as the culture of *collective mindfulness* (Weick et al., 1999). In such culture, the highest priority is always given to the preservation of reliability (instead of efficiency, for instance). The term “collective mindfulness” means that everyone in the organization understands the ways in which their own actions are part of complex interactions that can either accelerate or suppress a swiftly emerging failure mode that has been triggered by some exception in the process (Weick and Roberts, 1993). The specific propositions of high reliability theory consider at least the following: members of the organization should always be preoccupied with the avoidance of failures (Weick, 1988; Weick et al., 1999); members of the organization should exhibit reluctance to minimize weak signals about exceptions (Marcus and Nichols, 1999); organizations should empower members to take actions against potential exceptions without unnecessary authorization requests (Roberts et al., 1994); organizations should allow bypassing formal communication channels when exceptions are detected and need swift reaction (Vaughan, 1990); and lastly, organizations should develop capabilities to learn from “near misses” (March et al., 1991). In a trial to keep balance between the different streams of literature, I summarize the propositions of high reliability theory as follows:

> P5c: Uncertainty can be reduced (and thus the performance of complex systems improved) by cultivating an organizational culture of collective mindfulness where the predominant value is reliability.

Uncertainty is also discussed in the literature on transaction cost economics, whose basic tenets are that externally-induced uncertainties can be reduced by either internalizing the sources through *vertical integration* or by using contracts and alliances to provide the potential sources of uncertainty with incentives not to cause trouble (Williamson, 1975; 1985). The latter can be achieved through *contracts* and *alliances*, for instance (Williamson, 2000). Thus, the following propositions can be formulated:

> P5d: Uncertainty can be reduced (and thus the performance of complex systems improved) through vertical integration.

> P5e: Uncertainty can be reduced (and thus the performance of complex systems improved) by enforcing contracts and forming alliances.

Lastly, organizational uncertainty can be viewed from more mathematical perspectives as well. The wide literature on *queuing theory* proposes various laws and theorems about the stochastic interplay between throughput times, external sources of variation (i.e., uncertainty), and performance (e.g., Hopp and Spearman, 2000). On the most basic and intuitive level, the relationship between throughput time and uncertainty is such that the more there is time for exceptions to occur, the more there will be exceptions (Stalk and Hout, 1990). Thus, the following proposition can be put forward:

> P5f: Uncertainty can be reduced (and thus the performance of complex systems improved) by reducing the throughput times of production activities.

2.4.2 Mitigation of Uncertainty

Just as it is not always possible or meaningful to try eliminating all complexity, it may not be possible to eliminate all uncertainty. Thus, organizations need to possess mitigation capabilities, or in other words, become resilient to uncertainty (Hamel and Välikangas, 2003; Kendra and Wachtendorf, 2003; Sheffi and Rice, 2005). In fact, firms like Zara and Nokia show that in very uncertain task environments, it may be even possible to build a competitive advantage on uncertainty mitigation capabilities (Lee, 2004; Sheffi, 2005).

Many organization theorists have discussed the act of *coordination* being central to the mitigation of the negative performance effects of exceptions in complex organizations (e.g., Weber, 1946; March and Simon, 1958; Stinchcombe, 1959; Cyert and March, 1963; Lawrence and Lorsch, 1967a; Emery, 1969; Van de Ven et al., 1976) but the different coordination mechanisms are synthesized in the information processing theory of Galbraith (1973). He proposes that the different coordination mechanisms form a hierarchy, where the basic mechanisms are in the order of sophistication: *rules* (e.g., if X happens, do Y), *hierarchical referral* (e.g., if anything happens, ask instructions from your supervisor), and *goal setting* (e.g., whatever happens, pursue the goal Z). The rules should work in the simplest organizations but when complexity increases then hierarchical referral (in moderately complex organizations) and goal setting (in most complex organizations) are needed as well. Thus the following propositions can be made:

> P6a: The negative effect of uncertainty on the performance of a lowly complex organization can be mitigated by setting rules about operating procedures that are to be executed when exceptions occur.

> P6b: The negative effect of uncertainty on the performance of a moderately complex organization can be mitigated by depending on hierarchical referral when exceptions occur.

> P6c: The negative effect of uncertainty on the performance of a very complex organization can be mitigated by setting goals that should be pursued regardless of any exceptions.

In addition to the basic mechanisms, Galbraith (1973) proposed that coordination can be improved also by two formal information processing solutions: the implementation of information systems and the establishment of employee positions for the coordination purposes (see also, Tushman and Nadler, 1978). In the original theory, the two formal processing solutions were described as equally effective but later studies have suggested that their applicability depends on the type of uncertainty that the organization faces. The media richness theory of Daft and Lengel (1986) proposes that *human coordinators* (teams or individuals) are more effective when equivocality is high (see Definition 4). On the other hand, the threat-rigidity theory of Staw et al. (1981) proposes that centralized information processing, and thus the use of information systems, is most effective when the urgency is high (see Definition 5). So, in summary:

P7a: The negative performance effect of uncertainty in a complex organization can be mitigated by using formal information processes for coordination.

P7b: The negative performance effect of equivocal exceptions in a complex organization can be mitigated by using individuals and/or teams as coordinators.

P7c: The negative performance effect of urgent exceptions in a complex organization can be mitigated by using an information system for coordination.

2.4.3 The Role of Best Practices

The propositions of this chapter may give an impression that so much is already known about dealing with complexity that it should be pretty straightforward to implement the most effective countermeasures in all organizations. In reality however, choosing the best methods to reduce complexity and uncertainty or to mitigate their effects is typically anything but obvious. The reason for that is what Simon (1978) calls *bounded rationality*. It refers to human limits in the ability to process as much information as it would take to perfectly analyze each choice and come up with an optimal solution. It also means that in most cases, it is not possible to collect complete information about the decision-making situation so that one could know with certainty whether the chosen solution is optimal or not. Furthermore, it also means that humans are constantly in various decision making situations and therefore it does not make sense to devote extensive time to the collection and processing of information to ensure an optimal, or even near-optimal, decision regarding any single choice. Reaching a satisfactory solution must suffice in most situations (Simon, 1978).

Like all human decisions, the choices between coordination mechanisms or solutions to reduce complexity or uncertainty are subject to bounded rationality. In fact, those choices are especially susceptible to bounded rationality because as the complexity of the task environment increases, the bounds of rationality get narrower (Taylor, 1975). When a manager of a complex organization needs to make a decision and is not quite sure about his or her understanding of the situation, one reasonable solution is to see and mimic what other organizations are doing (Cyert and March, 1963; Haveman, 1993). Sometimes when this kind of benchmarking is conducted intentionally, the solutions are referred to as *best practices* (Marcus and Nichols, 1999). Quite often however, the mimicry is conducted somewhat unconsciously as people convey ideas when they move from one organization to another and because certain ways of doing things often reach a status of being the legitimate ways of doing them (DiMaggio and Powell, 1983). Alternatively, the *isomorphism*, or trend towards similarity, may result from evolutionary reasons if the task environment is so complex that only those organizations that have made good choices have survived (Hannan and Freeman, 1977). Regardless of the mechanism of the isomorphism, it can be proposed as follows:

> P8: In complex task environments, organizations have a tendency to start resembling one another.

2.5 RECAPITULATION

The purpose of this chapter was to review the organization-theoretical literature on complex task environments. The review resulted in a number of definitions and propositions, which will next guide us in the review of the contemporary literature on operations management. I deem such guidance essential because it helps to identify new findings and findings that are specific to operations management from all possible results that are already included in the grand-theoretical body of knowledge. Another purpose of the theoretical definitions and propositions is to bring structure to the systematic review. Tables 1 and 2 summarize the definitions and the propositions, respectively.

Table 1: Definitions from the organization-theoretical literature

	Definition
1	*Complexity* of a system refers both to the number of different parts and to the number of different interactions that can occur between the parts.
2	*Uncertainty* is lack of information about the task environment.
3	*Dynamism* (instability, turbulence) refers to uncertainty that is manifested as frequency of *exceptions* (unexpected events/changes) in the task environment.
4	*Equivocality* (ambiguity, unanalyzability) refers to uncertainty that is manifested as difficulty of solving exceptions, which have occurred in the task environment.
5	*Urgency* refers to uncertainty that is manifested as swift propagation (intensification, escalation) of exceptions, which have occurred in the task environment.
6a	*State uncertainty* refers to the lack of information regarding what is happening and what will happen in the task environment.
6b	*Effect uncertainty* refers to the lack of information regarding the consequences if some specific exception occurs in the task environment.
6c	*Response uncertainty* refers to the lack of information regarding what should be done if some specific exception occurs in the task environment.
7a	*Primary* (innocent) *uncertainty* refers to the lack of information regarding naturally occurring phenomena.
7b	*Secondary* (behavioral) *uncertainty* refers to the lack of information regarding the current and future actions of actors with deliberative ability.
8	*Input uncertainty* refers to the lack of information regarding the raw materials that the system needs to process.
9	*Tight* (versus *loose*) *coupling* (requisite integration) refers to complexity that occurs at organizational level as the intensity of interactions between functionally differentiated subunits.
10a	*Pooled interdependence* refers to the least complex type of process inter-dependence because in pooled processes (e.g., in job shops), the sequences and the directions of interactions are not predetermined.
10b	*Sequential interdependence* refers to the third most complex type of process interdependence because in sequential processes (e.g., in assembly lines), the sequences of interactions are predetermined but unidirectional.
10c	*Reciprocal interdependence* refers to the second most complex type of process interdependence because in reciprocal processes (e.g., in batch shops), the sequences of interactions are not only predetermined but they can also create iterative loops.
10d	*Team interdependence* refers to the most complex type of process inter-dependence because in team-interdependent processes (e.g., in team-work), the work units must interact exactly at the same time.
11	*Action variety* refers to task complexity in the form of the overall variety of tasks that must be mastered in an organizational unit.
12	*Component variety* refers to task complexity in the form of variety of raw materials that must be handled in the production.
13	*Product variety* refers to task complexity in the form of variety of outputs that the organization must be able to produce.
14	*Rate of new product introductions* refers to task complexity in the form of quick pace of change in activities that must be mastered in the production.
15	*Product customization* refers to task complexity in the form of the required production activities varying from one order to another.

Table 2: Propositions from the organization-theoretical literature

Proposition		Sources
1	In a complex system (e.g., an organization, a process, or a product), uncertainty has a negative effect on performance.	(Duncan, 1972; Galbraith, 1973; Pfeffer and Salancik, 1978; Bourgeois, 1981; Perrow, 1984)
1a	Uncertainty that arises from internal operations has a negative effect on the performance of a complex system.	(Cherns, 1976)
1b	Uncertainty that arises from raw material suppliers has a negative effect on the performance of a complex system.	(von Neumann and Morgenstern, 1944; Williamson, 1985)
1c	Uncertainty that arises from customers has a negative effect on the performance of a complex system.	(von Neumann and Morgenstern, 1944; Williamson, 1985)
1d	Uncertainty that arises from competitors has a negative effect on the performance of a complex system.	(Porter, 1985)
1e	Uncertainty that arises from the natural environment has a negative effect on the performance of a complex system.	(Dynes, 1970)
1f	Uncertainty that arises from regulatory agencies has a negative effect on the performance of a complex system.	(Dill, 1958; Duncan, 1972; Bourgeois, 1985)
2	Complexity can be reduced by using buffers to eliminate tightly coupled links between functionally differentiated subunits.	(Perrow, 1984)
3a	Complexity can be reduced by decreasing the specialization of the work units that constitute the production processes.	(Dean and Snell, 1991; Manz and Stewart, 1997)
3b	Complexity can be reduced by decreasing the amount of reciprocal interdependences in the production processes.	(Goldratt and Cox, 1984; Vollmann, 1986; Schragenheim and Ronen, 1990; Burbidge, 1979)
3c	Complexity can be reduced by decreasing the amount of team interdependences in the production processes.	(Van de Ven et al., 1976)
4a	Complexity can be reduced by focusing on specific market segments.	(Skinner, 1974)
4b	Complexity can be reduced by investing in redundant resources.	(Landau, 1969; Lerner, 1986)
4c	Complexity can be reduced through standardization.	(Taylor, 1911)
4d	Complexity can be reduced by outsourcing non-core production activities.	(Kotha and Orne, 1989)
4e	Complexity can be reduced by increasing component commonality.	(Baker, 1985; Child et al., 1991; Collins et al., 1998)
4f	Complexity can be reduced by decreasing product variety.	(MacDuffie et al., 1996)
4g	Complexity can be reduced by decreasing the rate of new product introductions.	(Stalk and Webber, 1993)
4h	Complexity can be reduced by decreasing the customizability of the offered products.	(Agrawal et al., 2001; Zipkin, 2001)
4i	Complexity can be reduced by increasing the use of modularity and platform structures in products.	(Starr, 1965; Pine, 1993; Robertson and Ulrich, 1998)
5a	Uncertainty can be reduced by increasing the collection of information from the task environment.	(Forrester, 1958)
5b	Uncertainty can be reduced by choosing a strategy of operating in stable markets.	(Child, 1972; Bourgeois, 1984; Clark et al., 1994)

(to be continued on the next page)

Table 2 (continued)

5c	Uncertainty can be reduced by cultivating an organizational culture of collective mindfulness where the predominant value is reliability.	(Weick, 1987)
5d	Uncertainty can be reduced through vertical integration.	(Williamson, 1975; 1985)
5e	Uncertainty can be reduced with contracts and alliances.	(Williamson, 2000)
5f	Uncertainty can be reduced by shortening throughput times in production.	(Stalk and Hout, 1990)
6a	The negative effect of uncertainty on the performance of a lowly complex organization can be mitigated by setting rules about operating procedures that are to be executed when exceptions occur.	(March and Simon, 1958; Cyert and March, 1963)
6b	The negative effect of uncertainty on the performance of a moderately complex organization can be mitigated by depending on hierarchical referral when exceptions occur.	(Weber, 1946; Emery, 1969)
6c	The negative effect of uncertainty on the performance of a very complex organization can be mitigated by setting goals that should be pursued regardless of any exceptions.	(March and Simon, 1958; Stinchcombe, 1959)
7a	The negative performance effect of uncertainty in a complex organization can be mitigated by coordination via formal information processes.	(Galbraith, 1973)
7b	The negative performance effect of equivocal exceptions in a complex organization can be mitigated by using human coordinators.	(Daft and Lengel, 1986)
7c	The negative performance effect of urgent exceptions in a complex organization can be mitigated by using an information system for coordination.	(Staw et al., 1981)
8	In complexity task environments, organizations have a tendency to start resembling one another.	(DiMaggio and Powell, 1983; Haveman, 1993)

3 SYSTEMATIC LITERATURE REVIEW

This chapter presents a systematic review of the contemporary research literature on operations management in complex task environments. The definitions and propositions of Chapter 2 are used to help in grouping and understanding the contemporary findings. The outcomes of the review help identify research opportunities from which the research questions of this dissertation are selected.

3.1 INTRODUCTION

3.1.1 Objective

The objective of this dissertation is to develop new knowledge on how complexity influences everyday operations management in manufacturing firms and how to best alleviate the negative performance effects of complexity. To achieve that objective, it is imperative to first build a solid understanding of what is already known about operations management in complex task environments. That is what I aim to do in this chapter. I believe that the most thorough understanding of the existing body of knowledge can be created with the method of systematic literature review (Tranfield et al., 2003). The "systematicness" of the method means that a specific sample of literature is chosen and all published articles are reviewed to find out exactly how the topic of interest is addressed.

3.1.2 Sampling

I chose to review articles from four journals that are in my opinion—as well as according to the impact factors of ISI Web of Knowledge (Thomson, 2009)—the leading outlets of empirical operations management research. They are *Journal of Operations Management*, *Production and Operations Management*, *Management Science*, and *Decision Sciences*.[*] From these journals, I created two samples: the primary sample was all articles published in Journal of Operations Management during the period from the beginning of 1999 until the end of 2008. After reviewing

[*] According to the statistics of 2007, which were the most recent at the time of this writing, the only other operations management journal that reaches even close to these four in impact factors is Operations Research. However, it was excluded since it does not publish empirical research at all.

those articles and identifying the ones that are relevant to the topic, I tested what set of keywords would reveal all of the relevant articles but a minimal number of other manuscripts. I found the best keywords to be “complexity”, “complexities”, “uncertainty”, “uncertainties”, “diversification”, and “standardization”. That result converged from 18 different words in 24 iterations.* I used the keywords to create the secondary sample from the three other journals.

I chose Journal of Operations Management for the primary sample because the journal is dedicated solely to empirical research and was thus likely to yield most results. The main reason to choose the ten-year time frame and not any longer period of time was to keep the workload within reason. Another reason not to start from any earlier point of time was the fact that the quality of empirical operations management research has improved significantly over time. Therefore, an excessively long time range would have probably yielded a sample in which the methodological and theoretical quality of studies had varied very much. I used the same ten-year time frame also to create the secondary sample.

The primary sample consisted of 407 articles out of which 18 were literature reviews and 14 were non-empirical research papers.† Altogether 278 articles were not related to complexity or uncertainty, which left me with 97 empirical studies on complexity and/or uncertainty. The population of the secondary sample was 2149 papers, which was sampled down to 1297 papers with the keyword search. From that amount, 59 items were non-research papers (e.g., editorials, calls for papers, special issue introductions, errata, etc.). 41 literature reviews and 686 non-empirical studies were excluded from the 1238 research papers, which left me with 511 empirical papers. In 388 articles, the keyword(s) were not used in the actual study but only in conventional discussion. For example, the *complexity* of statistical analyses or the *standardization* of variables was discussed in many articles. After the exclusion of those, the total number of relevant articles in the secondary sample was 180. Table 3 provides an overview to both samples and shows that the se-

* Due to the conservativeness requirement (i.e., all relevant articles had to be found with the keywords), the result is not very efficient. The search yielded 345 papers, which means that the keywords excluded only 42 percent of the population, and only 28 percent of the resulting papers are relevant. In addition, it turned out that the database had a problem with two relevant papers, which could not be found with any search terms.

† Non-empirical papers include all articles that are solely based on either analytical modeling or simulation without empirical data. Simulation studies on the bases of empirical data are counted as empirical studies.

lected journals give us a broad view to empirical research by emphasizing different research methodologies a little bit differently.

Table 3: Samples of the systematic review

	Journal of Operations Management	**Production and Operations Management**	**Management Science**	**Decision Sciences**
Source	Elsevier ScienceDirect	ProQuest and Atypon	Highwire Press INFORMS	Wiley InterScience
N(1999-2008)	598	456	1358	335
Search results	598[a]	260	968	69
Non-research[b]	191	13	44	2
Total: research	**407**	**247**	**924**	**67**
Literature reviews	18	16	22	3
Non-empirical	14	114	542	30
Total: empirical	**375**	**117**	**360**	**34**
Conceptual	15	11	6	3
Single case	3	9	3	2
Multiple cases	20	4	9	1
Survey	41	9	30	10
Secondary data	7	6	30	1
Simulation	1	1	5	1
Lab. experiment	2	2	10	4
Field experiment	2	2	3	0
Multiple methods	6	1	16	0
Meta-analysis	0	0	1	0
Total: on topic	**97**	**45**	**113**	**22**

[a] Primary sample: all articles included; [b] e.g., editorials, calls for papers, special issue introductions, etc.

3.2 RESULTS

3.2.1 Operationalizations of Complexity

Table 4 shows how complexity was operationalized in the reviewed articles (see Table A-1 in the appendix for details and references). In addition to listing the articles, the columns of the table show how many times each operationalization was used in a statistical test and how many times a statistically significant relationship was found with some theoretically interesting dependent variable. (The dependent variables are discussed later in this chapter.) The idea behind counting the statistically significant results was to find out if some of the operationalizations had been more effective in statistical analyses than others. Obviously, the significance levels of the variables depend on many issues that are specific to each study, such as the actual metrics that are used and the statistical power of the analysis. However, if some operationalizations appear to be considerably more often insignificant, then one should probably try to avoid such operationalizations in the future research. This information was also used to guide the selection of operationalizations in this dissertation.

Table 4: Operationalizations of complexity

	Definition	Total	Used in a statistical test	Significant effect found
1	Complexity as the number of different parts and possible interactions between them	22	9	9
9	Organizational complexity as tight coupling	17	9	8
10	Process complexity as (a) pooled, (b) sequential, (c) reciprocal, (d) team interdependence	4[a]	1	1
11	Task complexity as action variety	4	4	4
12	Task complexity as component variety	25	15	13
13	Task complexity as product variety	25	15	13
14	Task complexity as rate of new product introductions	10	6	5
15	Task complexity as customization	18	12	11
	Just “complexity”	22	12	7
	Organization’s size	25	25	16
	Distance between different parts of a system	9	7	5
	Diversification (e.g., business segments, countries, technologies, etc.)	8	8	8
	Process type	8	6	5
	Number of parts in a system	7	6	4
	Lack of routines or process standardization	6	4	4
	Difficulty of a task	5	4	4
	Number of information cues	3	3	3
	Cognitive complexity	2	2	2
	Number of suppliers	2	2	2
	Others	19	14	6

See Table A-1 in the appendix for details and references.

[a] Only one study includes (d) team interdependence. The others use a-c.

The table shows that 117 from 244 (48%) operationalizations were something else than what were defined in the organization-theoretical review of the previous chapter. In a way, this observation makes a lot of sense because generic grand-theoretical constructs must often be given a more specific meaning before they can be studied in the context of operations management. A good example of this is the use of process type as a measure of process complexity. Interviewees and survey respondents are probably more likely to understand the question and provide more reliable information if they are asked about the types of their processes instead of whether their processes are characterized by pooled, sequential, or reciprocal interdependences. Interestingly, however, only one of the studies that operationalized complexity as different process types made a connection between them and task interdependence (Ketokivi and Schroeder, 2004b), and even that one did not elaborate how the process types relate to the different *types* of task interdependence. The others made references to Hayes and Wheelwright (1979a) and based their arguments on the volume of production, which obviously varies with the different process types. Therein may lie an opportunity for contribution since the work of Woodward (1965) has shown that the relationship between volume and complexity is not linear, as discussed in the theoretical review.

Another rationale for the varying operationalizations is the use of secondary data as proxies of the theoretical constructs. Good examples of such proxies are organizations' size and diversification. These examples also show that relying on proxies is somewhat risky as the former turned out to have significant effects relatively seldom while the latter proved to be significant in every study where it was used. Theoretically, the use of such proxies is defendable because both size and diversification are antecedents of complexity as discussed earlier. Their riskiness is based on the argument that they should only lead to complexity if they are accompanied by interdependence.

What becomes to the more frequently used operationalizations, one peculiarity lies in the use of component variety and customization. None of the statistical studies that used either of the two variables used them both to measure complexity. This is indeed interesting considering that component commonality was identified as the most important facilitator of customization in many conceptual and qualitative papers (e.g., Duray et al., 2000; Salvador et al., 2002) as well as in one of the statistical analyses (Tu et al., 2004). Thus, one opportunity to advance the field is perhaps in the reconciliation of these two perspectives to task complexity. One could argue, for example, that the challenge of product customization is not only easier but fundamentally different in the presence of component commonality than it is otherwise.

3.2.2 Operationalizations of Uncertainty

Table 5 lists the operationalizations of uncertainty. The classic operationalizations are slightly more common as they account for 122 out 205 (60%) operationalizations. Several observations can be made from these results. First, it seems relatively common to keep unpredictability and variability as separate dimensions of uncertainty. As discussed in Chapter 2, Dess and Beard

(1984) have suggested in the name of parsimony that the two should be combined in a single construct of dynamism. In their reasoning, predictable variability and unpredictable but rare changes are special cases of organizational uncertainty, and thus they should be measured only when the theoretical interest is explicitly in such special cases. However, when it comes to the statistical significance levels of the operationalizations, it seems that studying unpredictability and variability separately is a far more successful approach than combining them into a single dynamism variable. The two studies that used both variables simultaneously (Anand and Ward, 2004; Childerhouse et al., 2002) pointed out that in the context of operations management, it actually makes a lot of sense to keep the dimensions separate. That is because the problems related to the two dimensions are very different: variability—even when it is predictable—causes challenges with capacity management, while the problems with unpredictability are more related to stock outs and obsolescence costs. Considering this rationale, it seems that one should really give thought to the operationalization of uncertainty in quantitative operations management studies.

Table 5: Operationalizations of uncertainty

Definition		Total	Used in a statistical test	Significant effect found
2	Uncertainty as lack of information	43	21	16
3	Dynamism	55	33	17
4	Equivocality	18	8	6
5	Urgency	1	0	
6	(a) State, (b) effect, (c) response uncertainty	8[a]	4	4
7	(a) Primary, (b) secondary uncertainty	2	0	
8	Input uncertainty	5	2	2
	Just "uncertainty"	14	6	6
	Variability	22	11	10
	Unpredictability	11	9	7
	Individual exceptions	13	12	12
	Hostility	11	11	8
	Risk	5	2	2
	Errors	3	2	2
	Others	4	4	1

See Table A-2 in the appendix for details and references. [a] Only one instance of the full scale.

Other widely—and in a statistical sense effectively—used operationalizations of uncertainty are the occurrence of individual exceptions and the hostility of competition. The lesson from the former could be that maybe the dynamism variable could be made more effective if the questions about it are formulated so that they refer to the frequency of specific events instead of the overall rate of change in the task environment. As for the hostility of competition, it should be pointed out that a majority of the studies using the operationalization were found from Management Science, which publishes also research on business strategy, entrepreneurship, marketing, and other fields where the construct has traditionally played a central role (Khandwalla, 1972; Miller and Friesen, 1983). In the domain of operations management, however, the effects of hostility are not that obvious. That is, in fact, epitomized by the only study where it was used as a regressor of a more traditional operations management subject; the study showed that hostility is negatively related to lead times (Salomon and Martin, 2008). In other words, the manufacturers in more hostile competitive environments scored on average higher in operational performance than the manufacturers in less hostile environments, which is an observation that runs counter to Proposition 1 about the fundamental influence of uncertainty. Thus, it is probably advisable that operations management researchers consider their arguments carefully before operationalizing uncertainty as the competitive hostility.

What becomes to the less utilized operationalizations, one remarkable observation is that only one study had taken the urgency perspective to uncertainty. Considering that organization theorists have found the urgency aspect very important (e.g., Perrow, 1984; Majchrzak et al., 2007), it may be that introducing the concept to the field of operations management would provide valuable new insights.

3.2.3 Sources and Effects of Uncertainty

Table 6 presents the sources of uncertainty analyzed in the reviewed studies. Not surprisingly, the sources that are used most often include internal operations, suppliers, and customers. Namely, it could be argued that those sources have much closer relationship to operations management than competitors and regulatory agencies, for instance. One frequently, but in statistical studies relatively unsuccessfully, used source of uncertainty appears to be technological uncertainty. Here, the reason could be that the pace of the overall technological development is currently so swift that this kind of a variable is not sufficiently accurate. Another operationalization that cannot be recommended on the bases of this review is the kind of an overall variable which either leaves the source of uncertainty unspecified or combines several sources. Such variables appear to have seldom explanatory power in statistical analyses.

Table 6: Performance effects of uncertainties from different sources

Proposition		Total	Studied statistically	Significant effect found
1a	Internal uncertainty reduces performance	24	12	12
1b	Supplier uncertainty reduces performance	14	6	6
1c	Customer uncertainty reduces performance	30	16	14
1d	Uncertainty caused by competitors reduces performance	5 +1	5 +1	3 +1
1e	Uncertainty caused by the natural environment reduces performance	2	1	1
1f	Uncertainty caused by regulatory agencies reduces performance	4	2	1
	Technological uncertainty reduces performance	16 +1	13 +1	6 +1
	Overall environmental uncertainty reduces performance	12 +2	10 +2	4 +2
	Other kinds of uncertainty reduce performance	3	1	1

See Table A-3 in the appendix for details and references. Plus signs indicate studies on the positive performance effects of uncertainty.

Interestingly, four studies showed positive relationships between uncertainties and performance measures. As mentioned above, Salomon and Martin (2008) found out that pressure from competitors is associated with reduced manufacturing lead times. The results of Dröge et al. (2003) show that technological uncertainty is related to increased levels of knowledge creation and application, which in turn are positively related to firm’s performance. Jansen et al. (2006) found out that their measure of overall environmental uncertainty has a positive relationship with performance in “exploratively innovative” firms. In the study of Im and Rai (2008), the overall uncertainty has a direct positive effect on performance but the authors do not comment that result in any way.

In summary, the classic sources of uncertainty seem to be the usual suspects in influencing the performance of manufacturing firms. Some opportunities may lie in exploring competitors, regulators, or the natural environment as the origin of uncertainty but the most consistently negative sources seem to be internal operations, suppliers, and customers.

3.2.4 Reduction of Complexity

Table 7 presents the perspectives to the reduction of complexity. Here, the most striking finding is that many of the previous chapter’s propositions have been studied very little. With the exception of product modularity and component commonality, the reduction of complexity appears to be far less studied than what could be expected on the bases of the amount of textbooks devoted to the topic (e.g., Askin and Goldberg, 2002; Suri, 1998; Schonberger, 2001; Womack and Jones, 2003). One explanation for this finding could be that the topic is already so old that it is no longer considered as an interesting subject.

Yet another explanation is also possible. Namely, it seems that lean manufacturing and other simplicity-oriented management paradigms are still studied in the contemporary literature but often their effects are analyzed irrespectively of any complexity constructs. Instead, the studies seem to focus on explaining either the direct performance effects of lean manufacturing practices or the contents and dimensions of those practices (e.g., Browning and Heath, 2009; Shah and Ward, 2003; 2007; Ward and Zhou, 2006). Such studies are based on the premise that modern manufacturing firms are so inherently complex that efforts towards simplicity are universally beneficial. One research opportunity would be to challenge that premise. However, it would be risky because if the premise happens to hold, then the results would not bring anything new to the field. Thus, a safer conclusion is probably to consider the reduction of complexity as a less interesting subject and move forward to the reduction and mitigation of uncertainty.

Table 7: Reduction of complexity

Proposition		Total	Studied statistically	Significant effect found
2	Reduction of tight coupling	6	3	3
3a	Reduction of specialization	1	1	0
3b	Reduction of reciprocal interdependences	2	1	1
3c	Reduction of team interdependences	0		
4a	Focusing on specific market segments	1	0	
4b	Redundant resources	0		
4c	Standardization	4	2	2
4d	Outsourcing	5 +1	3 +0	3
4e	Component commonality	7	2	2
4f	Reduction of product variety	6	4	4
4g	Reduction of new product introductions	0		
4h	Reduction of customization	4	1	1
4i	Use of modularity	22	12	12
	Reduction of supplier base	5	3	2
	Others	9	0	

See Table A-4 in the appendix for details and references. The plus sign indicates a study suggesting that outsourcing increases complexity.

3.2.5 Reduction of Uncertainty

Table 8 lists different ways to reduce uncertainty. The information processing theory of Galbraith (1973) appears to have gotten the most attention but also the strategic, cultural, and economic perspectives to the reduction of uncertainty seem to be relatively well represented. Not surprisingly, operations management subjects like forecasting, planning, quality control, and decision support systems came up as well. As there are no obvious gaps in the research it is difficult to identify any obvious contribution opportunities from the uncertainty reduction perspective.

Table 8: Reduction of uncertainty

Proposition		Total	Studied statistically	Significant effect found
5a	Collection of information	24	12	12
5b	Strategic aversion of uncertainty	3	1	1
5c	Culture of reliability	5	2	1
5d	Vertical integration	1	1	1
5e	Contracts and alliances	8	1	1
5f	Reduction of throughput times	5	1	1
	Forecasting	4	1	1
	Increasing supplier base	3	1	1
	Planning	2	1	1
	Others	14	7	7

See Table A-5 in the appendix for details and references.

Nonetheless, one interesting issue in this topic could be the paradox between the reduction of complexity and the reduction of uncertainty. Specifically, outsourcing and the use of time buffers represent on the one hand mechanisms for the reduction of complexity but on the other hand, insourcing and the reduction of throughput times are mechanisms for the reduction of uncertainty. Similarly, shrinking one's supply base reduces complexity whereas widening it reduces uncertainty. Exploring these paradoxes in the future research could be fruitful.

3.2.6 Mitigation of Uncertainty

Table 9 shows the approaches taken to the mitigation of uncertainty in complex organizations. Here, the most striking observation is that only one study discussed the contingent applicability of the different coordination mechanisms (i.e., Faraj and Xiao, 2006). It only used qualitative methods and thus did not test the contingency propositions. Nor did it cover all of the mechanisms that were discussed in the theoretical review. Therefore, I have put the contingency parts of the propositions in parentheses in Table 9.

Table 9: Mitigation of uncertainty

	Proposition	Total	Studied statistically	Significant effect found
6a	Coordination by rules (for lowly complex organizations)	6	3	3
6b	Coordination by hierarchical referral (for moderately complex organizations)	6	2	2
6c	Coordination by goals (for highly complex organizations)	3	1	1
7a	Coordination via formal information processes	8	5	5
7b	Coordination by human coordinators (with equivocal uncertainty)	14	8	7
7c	Coordination via information systems (with urgent uncertainty)	6	3	2
	Planning	14	3	3
	Flexibility	10	5	4
	Feedback	4	3	2
	Configuration management practices (formal documentation & reviews)	4	4	4
	Quality control	4	4	4
	Experience	3	3	3
	Knowledge management	3	2	2
	Cross-training of employees	2	2	2
	Others	14 +1	9 +1	8 +1

See Table A-6 in the appendix for details and references. The plus sign indicates a study where an intended mitigation mechanism was found to amplify the negative effect of uncertainty.

The lack of studies on the contingency effects of the coordination mechanisms is truly striking because they are central to the contingency theory of organizations (e.g., Lawrence and Lorsch, 1967a; Thompson, 1967; Galbraith, 1973; Tushman and Nadler, 1978; Donaldson, 2001). The theorists have argued that different coordination mechanisms are only effective in certain situations or with certain kinds of uncertainty. Yet, the reviewed studies did not analyze such effects but focused only on the main effects of the coordination mechanisms in uncertain environments. I believe that this is the most important gap found in this review.

In addition, it can be observed that topics specific to operations management such as flexibility and production planning are again well represented. Yet, similarly as in the case of the coordination mechanisms, it would be interesting to study how the applicability of different kinds of planning methods and flexibilities depend on the context of their utilization.

3.2.7 Other Effects of Complexity

In addition to complexity's combined effects with uncertainty, the theoretical review included institutional theorists' proposition about organizations starting to resemble one another in complex task environments. As seen in Table 10, also that proposition receives support from the reviewed articles. However, the table also shows that the vast majority of the articles had focused on examining complexity's effects on issues that are more specific to the domain of operations management. A closer examination of those articles yields four observations with major implications for the research on complexity.

Table 10: Other effects of complexity

Proposition		Total	Studied statistically	Significant effect found
8	Leads to isomorphism	4	2	2
	Reduces performance	38	32	22
	Increases performance	8	7	7
	Influences strategic decisions	12	5	5
	Influences the effects of strategic decisions	4	4	4
	Leads to the use of certain practices	13	9	6
	Influences the effects of certain practices	13	8	8
	Increases the benefits from knowledge management efforts	5	5	3
	Decreases the benefits from knowledge management efforts	1	1	1
	Increases learning	3	3	3
	Decreases learning	4	3	2
	Increases the use of information technology	2	1	1
	Decreases the use of information technology	1	1	1
	Improves the positive effects of information technology	5	5	4
	Reduces the positive effects of information technology	1	1	1
	Increases information sharing	1	0	
	Decreases information sharing	1	1	1
	Increases the benefits of integration	3	3	3
	Decreases the benefits of integration	2	2	2
	Reduces integration	1	1	1
	Influences process design	3	1	1
	Influences relative power of organizational entities	2	2	2
	Influences the applicability of different kinds of flexibilities	3	1	1
	Others	15	10	10

See Table A-7 in the appendix for details and references.

First, a lot of studies have tried to establish a direct link between complexity and organizational performance without giving any consideration to uncertainty. The outcomes of those studies have been mixed. Some of them suggest a negative relationship while others indicate that the relationship would be positive. Many of the statistical analyses have resulted in insignificant coefficients. This finding is not at all surprising in the light of previous chapter's theoretical review, which maintained that the detrimental nature of complexity lies in its interaction with uncertainty (e.g., Duncan, 1972). Thus, one would need to study an inherently uncertain task environment to be able to find a consistently negative relationship between complexity and performance. Otherwise, the amount of uncertainty must be included into the equation.

The second finding is even more important. It is the mixed results of those studies that have focused on complexity's effects on different kinds of practices and organizational arrangements. For example, some studies have found that complexity increases the effectiveness of information technologies while others have come up with the exactly opposite conclusion. As seen in the table, the mixed results cover a wide variety of phenomena ranging from the benefits of organizational integration to the effectiveness of knowledge management efforts. I believe that these mixed results are a manifestation of the fact that the concept of complexity is actually a very complex issue in itself. In other words, it may be impossible to propose anything general about the effects of complexity (apart from such grand-theoretical propositions as the isomorphism argument of P8). Instead, consideration must be given to details such as what kind of complexity is being analyzed and in conjunction with what kind of uncertainties and against what performance dimensions. Thus, in my opinion, the mixed results indicate that one fundamental characteristic of complexity is that it operates on the context-specific levels of analysis. Consequently, in order to capture its effects one must really engage in middle-range theorizing (Merton, 1957; Bourgeois, 1979) as discussed in the introduction of this dissertation.

Third, earlier I identified opportunities in studying complexity's effects on the applicability two specific operations management practices, namely the applicability of different kinds of flexibilities and production planning methods. Now, it seems that the subject has already been explored with regard to the different kinds of flexibilities (Anand and Ward, 2004; Jack and Powers, 2004; Ketokivi, 2006). However, similar contingency analyses have not been conducted on different planning methods. As planning was the most often proposed mechanism to mitigate the effects of uncertainty and yet relatively seldom studied with statistical methods (see Table 9), it seems that an opportunity lies in examining whether the level of task environment's complexity influences the applicability of different planning methods in the same way as it influences the applicability of different kinds of flexibilities.

Fourth, it is interesting to observe how many researchers have taken purely descriptive views in their analyses and explored how complexity is associated with the implementations or the utilization of certain strategies or practices. From those contributions, we have learned for example, that complexity is associated with internet retailers' reduced inventory ownership (Randall et al., 2006), internalization of sales and other front-end operations in multinational manufacturing firms (Campa and Guillen, 1999), and more frequent quality inspections of suppliers' shipments and facilities (Mayer et al., 2004). The descriptive studies turned out to be more prevalent than the studies that examined the effectiveness of different operations strategies and practices. It is in my opinion quite peculiar because the deterministic logic harshly downplays the role of managerial decision making. Moreover, the descriptive studies give very little guidance regarding what strategies and practices managers *should* pursue and implement in order to gain competitive advantage—which is the kind of prescriptive guidance that many people think that operations management research should produce (e.g., Ketokivi and Schroeder, 2004b).

3.2.8 Other Effects of Uncertainty

Table 11 lists the findings regarding the other effects that uncertainty has in addition to its performance effects. The results reinforce two of the observations that were just made about the other effects of complexity. First, in the same way as the complexity above, also the effects of uncertainty seem to constitute such a complex phenomenon that it allows studies to arrive in completely opposite conclusions about the effectiveness of the very same practices, for instance. Thus, I think that middle-range theorizing is imperative also when it comes to understanding how is it exactly that uncertainty influences the applicability of different practices. The other reinforced observation is the prevalence of descriptive studies. Similarly as in the case of complexity's effects, a majority of articles made propositions about how uncertainty leads to the application of certain strategies or practices instead of explaining how it influences the applicability of those strategies and practices.

3.3 RESEARCH OPPORTUNITIES SUMMARIZED

3.3.1 Operationalizations

The findings regarding the conceptualizations and measurement of complexity suggest that many different operationalizations may yield interesting results. However, one specific issue stuck out

Table 11: Other effects of uncertainty

Proposition	Total	Studied statistically	Significant effect found
Influences strategic decisions	17	10	8
Influences the effects of strategic decisions	2	2	2
Leads to the use of certain practices	11	8	7
Reduces the use of certain practices	1	0	
Influences the effects of certain practices	3	1	0
Increases the benefits from knowledge management efforts	2	1	1
Influences partner selection	3	2	2
Increases flexibility	2	2	0
Reduces outsourcing	2	1	1
Has a curvilinear (∩) relationship with outsourcing	1	0	
Increases integration	2	2	2
Reduces integration	1	1	1
Increases the benefits of integration	1	1	1
Influences customers' priorities	1	1	1
Increases the use of information technology	1	1	1
Increases the benefits from information technology	1	1	1
Decreases the benefits from information technology	1	1	1
Increases the search of information	2	1	1
Increases information sharing	1	1	1
Reduces information sharing	1	0	
Influences process designs	2	1	1
Others	13	10	9

See Table A-8 in the appendix for details and references.

of the studies. It was the dominance of relatively narrow operationalizations in statistical studies. For example, qualitative studies routinely discussed product customization and component commonality—two aspects of task complexity—as two tightly interrelated variables. Yet, none of the statistical studies employed the variables in the same analyses. Thus, there seems to be an opportunity to come up with more accurate predictions by using different operationalizations in the same analyses.

Another opportunity to contribute through reconciling different perspectives in operationalizations is to combine classic variables with the ones that are specific to operations management. The review showed that both variables can be meaningful and yield interesting results. Consequently, it may be possible to explore ways that would enable reaping the benefits of both approaches. For example, many of the reviewed articles made use of the process type as a measure of process complexity. However, they did not draw much from the organization-theoretical bodies of knowledge that would have explained how and why the different process types should have effects on anything (e.g., Thompson, 1967; Woodward, 1965).

Third opportunity lies in the urgency dimension of uncertainty. Although some studies referred to it in the discussion parts of the manuscripts (e.g., Speier et al., 2003), only one of the reviewed articles had included it in the theoretical parts, and even that study did not test its effects with any empirical data (Faraj and Xiao, 2006). This state of affairs can be certainly considered as a shortcoming in the contemporary literature. Equivocality appeared to be slightly more popular variable but also underrepresented in comparison to dynamism, which clearly prevailed among the classic operationalizations. Once again, using different perspectives simultaneously could prove fruitful. The results on dynamism are mixed, so perhaps they could be explained with the other dimensions. Also, it was observed that maybe the predictive validity of the dynamism operationalization could be made more tangible by referring to the frequency of specific exceptions instead of referring to the overall rate of change in the task environment.

3.3.2 Reduction versus Mitigation of Complexity and Uncertainty

Regarding the reduction of complexity, the main finding was that the issue is not the most popular topic in the research literature. Not only were the studies relatively scarce (with the exception of studies in product modularity) but neither did I encounter any calls for research in the subject. As for the reduction of uncertainty, various ways of collecting information prevailed in the analyses, which was to be expected as the issues like forecasting and supply chain collaboration have long belonged to the core of operations management. Also many other perspectives to the reduction of uncertainty were well represented. Thus, it might be that the best opportunities for new contributions lie in the mitigation—and not in the reduction—of task environmental complexity and uncertainty. This impression is also backed up by the practitioner literature, which has frequently expressed its interest for more research in the area of coping with complexities and uncertainties (e.g., Rice and Caniato, 2003; Sheffi and Rice, 2005; Hamel and Välikangas, 2003).

A special prospect can be seen in the contextual fitness of different mechanisms that are supposed to mitigate the effects of uncertainty in complex organizations. Only one exploratory study in such mechanisms incorporated contingency effects in its theorizing (Faraj and Xiao, 2006). I find this outcome very peculiar considering that most of the mitigation mechanisms originate from the contingency theory that concerns itself with the contextual applicability of organizational arrangements. Hence considerable opportunities may lie in contingency analyses of different coordination mechanisms such as information systems, face-to-face coordination, and planning methods.

Furthermore, I believe that studying planning methods could be particularly valuable, since planning and scheduling is one of the most central activities in operations management (Kouvelis et al., 2005). To me it seems that universalistic ideas prevail in the operations management literature on planning methods; that is, the studies do not take into account the environment in which the methods are applied. While some of the reviewed articles had analyzed the contingent applicability of different kinds of flexibilities, none had studied the contextual fitness of different planning methods. According to the basic tenets of bounded rationality (Simon, 1978), complexity should specifically influence the effectiveness of planning in any organizations, let alone manufacturing firms where planning plays such a crucial role.

3.3.3 Descriptive versus Prescriptive Research Interests

One of the main observations from the other effects of complexity and uncertainty was that most often, the constructs had been studied as the determinants of what practices or strategies organizations tend to use. While that is by all means a legitimate research interest, it does not necessarily yield much prescriptive insights that could help practitioners. More practical insights can be derived if the foci of the analyses are on how complexity and uncertainty influence the effects—and not the utilization—of the different practices or strategies. Such studies existed and presented very interesting results, however, they represented a minority from the reviewed articles.

Regarding the descriptive studies, an additional motivation for more prescriptive approaches comes from the institutional effect that was predicted in Proposition 8. The isomorphism that was expected to be found among complex manufacturing organizations was supported in the reviewed studies. Since the institutional theory suggests that the resemblance can be explained by many other causes than rational reasons, it becomes even more important to understand whether the different practices and strategies that firms employ to cope with complexity and uncertainty, are indeed effective, and under what circumstances. It may be that the real “best practices” are in fact those that are not used by many but only by few organizations. Others may only rely on the most recent fads in the practitioner literature and business press (Abrahamson, 1991). Therefore, finding the truly effective practices would be very valuable in a practical sense.

3.3.4 Middle-Range versus Context-Independent Theorizing

Lastly, one implication arose from the overviews to the other effects of complexity and uncertainty than what were proposed in the theoretical review. The review showed that the concept of complexity is such a complex phenomenon in itself that it is necessary to go into details when analyzing its effects on anything. Otherwise, one can find evidence on complexity having completely opposite effects on the effectiveness of different practices, for instance. This observation emphasizes the role of middle-range theorizing in studying complexity (Merton, 1957; Bourgeois, 1979). The opportunity that lies in it is the fact that the applicability of middle-range theorizing in the context of operations management is not necessarily limited to the domain of operations management. Instead, by identifying the theoretical boundary conditions of the eventual findings, one can also make theoretical propositions to other contexts where the same conditions exist.

3.4 RECAPITULATION

The purpose of this chapter was to review samples of contemporary operations management literature with aim of identifying research opportunities that could be addressed in this doctoral dissertation. The main opportunities that I identified are summarized in Table 12, and they will be discussed further in the beginning of the next chapter.

Table 12: Main research opportunities identified in the systematic review

	Opportunity
1	Exploring the simultaneous effects of different aspects of complexity; e.g., exploring how task complexity is influenced by the combined effect of customization and component variety
2	Using classic operationalizations in combination with those that are specific to operations management and thus generating practically relevant yet theoretically grounded propositions
3	Analyzing the urgency dimension of uncertainty along with the other classic dimensions
4	Improving the dynamism operationalization with references to tangible events instead of referring to the overall rate of change in the task environment
5	Studying how firms mitigate or try to cope with complexity and uncertainty instead of the mechanisms that are used to reduce them
6	Studying how complexity influences the applicability of different production planning methods
7	Studying how complexity and uncertainty influences the effects of different practices and strategies instead of describing how complexity and uncertainty lead to them
8	Developing middle-range theories on the effects of complexity (instead of trying to capture the effects of complexity in generic grand-theoretical propositions)

4 RESEARCH DESIGN

This chapter presents the chosen research questions and how they are going to be studied in three separate analyses. The methodology is presented for those parts that are common to all three analyses. Lastly, the collection of the empirical dataset is described.

4.1 RESEARCH QUESTIONS

In Chapter 1, I presented a two-pronged research question on what is already known about operations management in complex task environments (RQ1a) and what would be the best ways of contributing to that knowledge (RQ1b). The purpose of Chapters 2 and 3 was to address those questions, and thus at this point, it is possible to take a closer look at Research Question 2, which is about the *practices* that facilitate successful operations management in complex task environments. First of all, I chose to focus on operations management practices instead of strategic or infrastructural aspects of operations management. That choice was based mainly on my personal interests. However, the research opportunities identified in Chapter 3 guided me in the selection of the specific practices and the contingency variable that I assume to influence their applicability. Hence I refined the generic Research Question 2 into the following sub-questions:

RQ2a: How does the applicability of different order management practices depend on the complexity of the manufactured products?

RQ2b: How does the applicability of different capacity planning methods depend on the complexity of the manufacturing processes?

RQ2c: How does the applicability of different exception processing routines depend on the sources of uncertainty in complex task environments?

The planning aspect of Research Question 2b is the central practice in this dissertation. I chose it because the systematic review revealed specific opportunities for contribution in that area (Opportunity 6 in Table 12). I chose the other two practices because they nicely complement the planning aspect. The order management practices of Research Question 2a provide the inputs for the planning activities while the exception processing routines of Research Question 2c are used to control all mid-process changes to the plans. Thus, the three practices constitute the continuum of processes that was illustrated in Figure 2 on page 13.

In Research Question 2a, I aim to take heed of Opportunity 1, which is the use of several complexity dimensions in conjunction with one another. Here, I assume that the task complexity, which results from the nature of the manufactured products, does not depend solely on the level of product customization but also on the level of component commonality. These variables can be expected to influence the order management processes because in the production of all complex products, they are the core process that are responsible for transforming customers' requirements into product specifications and delivery schedules as well as for ensuring that the end products are eventually delivered to the customers in time and according to specifications (e.g., Forza and Salvador, 2002a; Zorzini et al., 2008; Danese and Romano, 2004). In addition, the recent review of Sousa and Voss (2008) did not reveal any studies in which the order management practices would have been analyzed in the light of complexity.

In Research Question 2b, I plan to seize Opportunity 2 regarding the operationalizations of process complexity. I believe that the process type can be as an effective contingency variable as it seemed to be in the literature review. However, I also think that it could prove to be even more valuable if its effects are considered from the perspective of the classic literature on the different types of interdependences that can occur between the work units that constitute the processes (Thompson, 1967; Woodward, 1965). As already mentioned, Opportunity 5 about the lack of contingency studies on the effectiveness of different planning methods guided me to choose production planning as the practice of interest. I further focus on capacity planning methods because that is where the variance is in the different solutions. The material planning methods that contemporary manufacturers use are relatively similar in all contexts (Vollmann et al., 2005).

In Research Question 2c, I am guided by Opportunities 3 and 4. I believe that the urgency dimension of uncertainty is important and it can vary depending on the sources of uncertainty. Also, I think that in order to make the dynamism operationalization meaningful to practice, I need to refer to the occurrence of some tangible events in contemporary manufacturing environments. Thus, I will follow a similar strategy as in addressing Research Question 2b. That is, I measure the uncertainties according to such tangible variables as the frequencies of exceptions from different sources of uncertainty. However, I will theorize on the bases of the fundamental nature of the uncertainties that come from the different sources. In the spirit of Opportunity 7, I choose to study how the nature of the uncertainty influences the effectiveness of different ways to communicate unexpected events in an organization, that is: exception processing routines. In the selection of these communication practices, I am also guided by the recent studies suggesting that intra-organizational communications may play a significant role in organizations' resilience against uncertainties (Craighead et al., 2007; Zsidisin et al., 2005).

Lastly, I could point out some other common themes among the operations management practices that I selected for the study. First, following the guidance of Opportunity 5, all selected practices belong to the coping mechanisms rather than the reduction mechanisms of complexity and uncertainty. Second, they are all logical subjects to contingency effects, as required by Opportunity 7. It means that I will argue that completely different order management practices, capacity planning methods, and exception processing routines should be applied depending on the nature of complexity and uncertainty of subjects' task environments. In the case of some other practices, the contingency effects could be less dramatic. For example, the systematic review showed that quality management practices are beneficial in all organizations but they are only slightly less beneficial in very complex organizations (Cua et al., 2001; Hendricks and Singhal, 2001). Third, in order to cover a wider area in the domain of complexity, I selected such practices that can be expected to be related to different aspects of complexity. I will study order management practices in relationship with product complexity, capacity planning methods' relationship with process complexity, and exception processing routines' relationship with the uncertainty aspect of complexity. Fourth, all three topics fall into the category of developing middle-range theories, which was identified as Opportunity 8. The boundary conditions and the theoretical generalizability of the findings will be discussed in Chapter 8. Table 13 summarizes the definitions and propositions of the theoretical literature that are represented in the chosen research questions.

4.2 METHODS AND DATA

4.2.1 Methodology

The research questions are analyzed in three separate studies with the same set of data. The studies are reported in Chapters 5, 6, and 7. In all three studies, I use multiple sources of data to ensure proper triangulation (Jick, 1979). The main sources are a survey, interviews, and process data but in addition to them, I also performed 34 site visits which enabled work observation and access to reporting data. Furthermore, I presented the results to my informants in three different workshops, which enabled them to comment or challenge my findings and conclusions in the spirit of a member review (Locke and Velamuri, 2009). Although at times, the workshops triggered lively discussions, the validity of the results and the substantive conclusions was not questioned.*

* I mention this because criticism regarding the results of the research is a known challenge in member reviews. However, I believe that it is more of a problem in solely qualitative studies, where methods can be more easily

Table 13: Cross-tabulation of the outcomes from the reviews and the chosen research questions

Definition		RQ2a	RQ2b	RQ2c
D1	*Complexity* as the number of different parts and possible interactions between them	×	×	
D2	*Uncertainty* is lack of information about the task environment			×
D3	*Dynamism* as the frequency of *exceptions*			×
D4	*Equivocality* as difficulty of solving exceptions			×
D5	*Urgency* as swift propagation of exceptions			×
D10	Process complexity as (a) *pooled*, (b) *sequential*, and (c) *reciprocal* interdependences between work units		×	
D12	Task complexity as *component variety*	×		
D15	Task complexity as *product customization*	×		
P1	Effects of (a) *internal*, (b) *supplier*-originated, and (c) *customer*-originated exceptions			×
P3	Effects of reducing (b) *reciprocal* interdependences in production processes		×	
P4	Effects of (e) increasing *component commonality*, (h) decreasing products' *customizability*, and (i) increasing *modularity*	×		
P7	Effects of (a) *formal information processes* under uncertainty, (b) *human coordinators* with *equivocal exceptions*, and (c) *information systems* with *urgent exceptions*			×
O1	Simultaneous effects of different aspects of complexity	×		
O2	Combining classic and operations-management-specific operationalizations		×	
O3	Effects of the urgency dimension of uncertainty			×
O4	Making the dynamism operationalization of uncertainty more tangible			×
O5	Ways of coping with (instead of reducing) complexity and uncertainty	×	×	×
O6	Effects of different planning methods in complex task environments		×	
O7	Effects of complexity and uncertainty on the effectiveness of different practices (instead of the effects on their utilization)	×	×	×
O8	Middle-range theorizing	×	×	×

In each of my three studies, I combine the use of hypothetico-deductive (Popper, 1965) and inductive inference (Glaser and Strauss, 1967; Eisenhardt, 1989a). Following the logic of middle-range theorizing (Merton, 1957; Bourgeois, 1979), I begin with grand-theoretical arguments and use them to formulate hypotheses in which the theories are adapted to the context of everyday operations management. I test the hypotheses statistically with quantified survey data and use the process data to establish the criterion validity of my main dependent variable, which is delivery

criticized without formal methodological training, than in mainly quantitative studies.

performance. The inductive parts of the studies begin after the statistical analyses as I draw from the interviews to explain and further elaborate the meaning and implications of the statistical results. Consequently, the conclusions of each study can be read as new propositions for further theoretical development. Apart from middle-range theorizing, this kind of a research design has also been called elaboration of theory (Ketokivi, 2006), abductive reasoning (Hartshorne and Weiss, 1934), and inference to best explanation (Harman, 1965).

4.2.2 Formulation of Hypotheses

As discussed above, all of my research questions take a form in which the effect of a certain practice (order management, capacity planning, and exception processing) depends on a contingency factor (product complexity, process complexity, and source of uncertainty, respectively). Such contingency hypotheses can be formulated in a number of different ways. I use the guidelines of Venkatraman (1989) to choose the most appropriate operationalization for each study. The theoretical arguments and the data differ so much between the studies that the hypotheses are formulated differently in every one of them. When the applicability of different order management practices are hypothesized to depend on product complexity, the two-dimensional nature of the contingency factor (i.e., product customization and component commonality) leads to an operationalization that is labeled *fit as gestalts* (Venkatraman, 1989, p. 432). When the applicability of different capacity planning methods is hypothesized to depend on process complexity, the categorical nature of the variables (i.e., process type and planning method) leads to an operationalization called *fit as matching* (p. 430). Lastly, when the effectiveness of different exception processing routines is hypothesized to depend on the different kinds of uncertainties, the two continuous variables (i.e., the use of a specific routine and the frequency of exceptions from a certain source) work best with a *fit as moderation* operationalization (p. 424).

4.2.3 Data Collection

In order to study the research questions and test the hypotheses derived from them, I had to create a sample with appropriate variance in product complexity, process complexity, and the sources of uncertainty. Also, all of the organizations had to be relatively flexible because that way I could fix the effect of flexibility, which the systematic review showed to be a known mitigating factor for the effects of complexity and uncertainty. Consequently, I chose to conduct the studies in the machinery manufacturing industry and approached seven large machinery manufacturers. For reasons of convenience, five of these corporations were headquartered in Finland but in order to mitigate the possible biases resulting from the common origin, I also included two foreign corporations. The other selection criterion was to choose corporations from different sectors of machinery manufacturing. It was necessary to avoid the problems involved in studying firms that engage in direct competition with one another. However, it also maximized the scope of the dataset and thus reduced the risk of proposing generalizations from sector-specific idiosyncrasies.

Once the senior executives of the selected corporations agreed to participate in the research project, I used their help in identifying all plants in their supply chains that made good candidates for the study. A majority plants in each corporation's internal supply chain were chosen for the study, which mitigates concerns regarding self-selection on the bases of performance, for instance. I also specifically asked the executives to avoid concentrating on their best performers. The main reason to exclude plants from the study was that many of them produced relatively simple auxiliary components for the end products. Another reason was that a plant was just being ramped up or otherwise going through changes and the executives did not want to disrupt their management with this study. Lastly, also some plants were excluded because the executives though that language barriers would compromise data collection on the level of production planners. This part of the sampling led to a total of 73 manufacturing plants located in 18 different countries.

In the chosen plants, I decided to focus solely on the *make-to-order* (MTO) production processes because only they can have the desired variance in all three contingency factors: product complexity, process complexity, and sources of uncertainty. First of all, the MTO products of machinery industry can range from perfectly tailor-made products to relatively standardized goods that are made to order only because of their low volumes, high values, or high obsolescence costs. They also exhibit variance in component commonality, since manufacturers typically try to make use of modularity and product platforms to simplify the customization efforts. Second, most MTO production processes of machinery products pose a *capacity* planning challenge that is necessary for Research Question 2b. Meanwhile, make-to-stock manufacturing process of commodity products can be planned entirely with rate-based *material* planning methods (Vollmann et al., 2005). Yet, the MTO production processes have the necessary variance in processes types. Third, the MTO production of industrial machines is susceptible to all three main uncertainties that were identified in the systematic review: internal, supplier-originated, and customer-originated. In the MTO production, the customer-originated exceptions, such as changes in orders' specifications or delivery dates, occur in a similar manner as the other two types of exceptions (e.g., machine breakdowns and delayed raw material shipments). That is, they are very well-defined in comparison to customer-related uncertainties in make-to-stock environments, where the uncertainty is not manifested as individual exceptions but instead as the extent of forecasts being accurate or wrong.

The managers of each manufacturing plant helped me to indentify a total of 180 MTO production processes that were managed separately from one another. Also, the plant managers gave me the contact information of each processes' responsible production planner. These production processes were to be the units of analysis and their planners were to be the respondents of the survey.

With the help of the executives and the plant managers, I also chose 30 people to be interviewed from different plants in six countries. I conducted semi-structured interviews to gain a better understanding about the practical challenges faced in the studied environments and to explore the rationales that had led to the use of certain operations management practices. The interviewees were seasoned practitioners who averaged 15 years of work experience in complex manufacturing environments. At the time of the study, 14 of the interviewees worked as production planners similarly as the respondents of the survey. Five interviewees had previously worked as production planners but had then switched to other positions such as quality managers and process developers. Seven interviewees were or had recently been plant managers and thus had experience on supervising the work of production planners. The remaining four interviewees worked in the sales departments and thus provided complementary insights from the perspective of the customer interface. In one way or another, each of them had also previous experience from the management of the manufacturing processes (e.g., through the participation in the implementation of an ERP system).

Altogether 17 interviewees were conducted before the survey while 13 of them were done during the collection of the survey data. On average, each interview lasted one hour and 15 minutes. Almost all interviewees provided some sorts of company documents to illustrate their experiences and observations. A wide array of topics was covered in the interviews but in the empirical chapters, I will focus on those parts of the qualitative dataset that explain or elaborate the results from the statistical analyses of the survey data. This focus is due to my choice of methodology, where inferences are primarily based on the testing of hypotheses.

Beside the collection of qualitative data, I used the first 17 interviewees to help in the development and testing of the survey instrument. After the pilot tests, the questionnaire was implemented with a Web-based survey tool and it was made available in Finnish, English, and German. That enabled 92 percent of the respondents to answer in their native tongues. The remaining eight percent responded in English. The English and German versions of the questionnaire were translated from the Finnish versions, and the translations were back-translated by two different persons to ensure the similarity across the versions.

Due to the strong senior executive support for this research project, I obtained 163 valid responses, which translates to a response rate of 91 percent. Consequently, non-respondent bias is negligible. The general characteristics of the sample are described in Table 14. As shown in the table, the sample for Research Question 2b is smaller than the sample that was used to study the other research questions. That is because some of the chosen processes in the downstream of the studied supply chains only carried out such labor-intensive assembly and installation operations that did not require capacity planning efforts in the form that they are normally performed.

Table 14: Sample overview

Supply chain **Products**	**Geographic scope of ops**	**Studied plants**	**Production processes**	**Interviews**
Air defense artillery Cannons, fire control units, & related electronics	Global	14 (8)	20 (14)	4 (3)
Aero-derivative power turbines Turbines and auxiliary equipment for power generation and the secondary recovery of oil & gas	Global	11 (8)	27 (20)	3 (2)
Factory automation Flexible manufacturing systems, robotized production cells, & loading/deburring/measuring stations for machine tools	Europe & the U.S.	10 (7)	27 (21)	3 (2)
Heavy-capacity industrial cranes Process cranes for waste mgmt, paper, & steel industries, gantry cranes for shipyards, & container cranes for harbors	Global	14 (6)	33 (18)	5 (3)
Reactive power compensation systems Capacitor banks, static compensators, & harmonic filters	Global	6 (3)	12 (3)	3 (2)
Remote-refrigerated display cabinets for grocery retailers Refrigerators, freezers, combination cabinets, & deli bars	North & East Europe	11 (5)	25 (10)	5 (3)
Special-purpose elevators Elevators for skyscrapers & ships, and luxury elevator cars	Global	7 (4)	19 (12)	7 (6)

Unit of analysis: *production process*; the numbers in parentheses apply to RQ2b
Total survey sample (RQ2a/c) = 180; usable responses (RQ2a/c) = 163; response rate (RQ2a/c) = 91%
Total survey sample (RQ2b) = 98; usable responses (RQ2b) = 89; response rate (RQ2b) = 91%

The empirical sample is obviously not randomly selected. The downside of the focused sampling is that the results cannot be *statistically* generalized to any specific population. However, the purpose of this dissertation is not to produce universally precise estimates for the effects of interest but to find out in general what the effects are. Thus, the studies of this dissertation are more exploratory by nature than survey studies usually are. Hence also the aimed contribution is to produce *theoretically* generalizable findings (e.g., Yin, 2003) that can be proposed to apply in other contexts that are similar to the studied processes. Theoretical generalizations can indeed inform the broader theory as demonstrated by the study of Woodward (1965) in which she examined the relationship between organizational structures and technologies in a very narrow context (i.e., manufacturing firms in 1950's South Essex, England) and yet produced highly generalizable theoretical insights that are still applicable today.

The focused sampling also had its benefits regarding the measurement. The relative homogeneity of the task environments ensured that the questions of the survey were interpreted in similar ways and perceived as contextually fitting in all of the sampled processes. For example, an issue like product customization would have had a very different meaning in a process where product customization is done solely by software. Yet another benefit of the focused approach was that it allowed the questions to be tailored according to the terminologies of the respondents' everyday work. For example, the pretests of the questionnaire indicated that surprisingly few production planners associated their ERP systems with the term "ERP system". In the questionnaire, the word had to be replaced with the brand of software used at each plant (e.g., SAP, Lawson, Lean, etc.) in order to ensure that the questions were understood correctly.

So in summary, the main benefits of the focused sampling are that it provides the necessary variance in the variables of interest while keeping the other possibly influential contextual variables relatively fixed. In addition, it helps to reduce biases and random inconsistencies that can result from the generic questions that are necessary in non-focused samples (Fowler, 1992; Podsakoff et al., 2003).

4.2.4 Measures

I tried to base the measures of the three studies on existing research where possible. However, it turned out that majority of empirical survey-based research is conducted at the levels of plants or firms, which rendered the questionnaire items inapplicable at the level of everyday management of production processes. Thus, I had to develop almost all of the measurement frameworks on my own. The measures include both reflective scales (Nunnally and Bernstein, 1994) and formative indices (Bollen and Lennox, 1991). The construct validity and reliability of the reflective scales are tested with confirmatory factor analyses, and the results are discussed in detail later in this dissertation. As for the formative indices, the measurement items do not need to be internally consistent and thus factor-analytical validity tests and correlation-based reliability tests are not applicable (Bollen, 1984). Instead, the construct validity of the items has to be evaluated on a purely theoretical basis (Jarvis et al., 2003; Shah and Goldstein, 2006).

As mentioned earlier, I also collected process data on the delivery performance of the studied production processes. For that purpose, I was given sufficient data from 38 different production processes. In that subsample, the correlation between the perceptual variable and the objective measure was .61 (significant at the level of $p < .001$). The result suggests adequate *criterion validity* for the delivery performance and serves as a proxy for the other constructs that could not be tested in the similar manner. It is probably worth mentioning that although the correlation of 61 percent may sound relatively low to someone, the interviewees considered it almost surprisingly high. However, the reason why they expected it to be lower was not that they would not have trusted the perceptual measures; instead they did not have complete trust in the "objective" measure. For example, sometimes delivery dates may be renegotiated with the customers and the revised dates may or may not end up into the reporting systems. As this example was only one among the many possible sources of error in the "objective" measure, the interviewees actually considered the perceptual measure to be more valid than the "objective" measure.

Naturally, one potential concern with perceptual measures is the reliability of the respondent: does the person really know what he or she is describing in the answers. One way of ensuring this was that each respondent was handpicked in collaboration with the managers of the participating companies. The other way, was to statistically test the rater reliability. I did this by collecting a second opinion from a deputy production planner in one process from each of the seven supply chains. The second points of view enabled calculating *inter-rater reliability* (IRR) statistics, which were quite convincing: all IRR coefficients were significant ($p < .001$) and their average was .88. There were no differences between the "consistency" and the "absolute agreement" definitions of IRR.

4.2.5 Dependent Variables

As the theoretical literature proposes that the main negative effects of complexity and uncertainty are directed against organizational reliability (Perrow, 1984; Weick et al., 1999), I decided to use two of its dimensions, *product conformance* and *delivery performance*, as the dependent variables of my analyses. In the selected context of MTO manufacturing, these two dimensions represent the most important facets of organizational reliability, since the MTO manufacturers operate under the pressures of conforming to customers' unique product specification and yet fulfill their orders swiftly and timely (McCutcheon et al., 1994; Salvador and Forza, 2004). Furthermore, the more complex and uncertain the task environment is, the more there are chances to make errors or miss some critical details and thus compromise products' conformance to their specifications. In the selected sample, the conformance to specifications is paramount because the capital-intensive machinery that is manufactured in the studied processes has to be aligned with the quality criteria and technical standards of the customers.*

While product conformance covers the scope aspect of reliability, delivery performance covers the main elements of its time aspect (Szwejczewski et al., 1997). Delivery performance is equally important in the studied context because delays and lengthy delivery times can be very costly to customers. The delays may be particularly harmful because customers must often run down their own value creation processes to prepare for the installation of the studied firms' products (Yeo and Ning, 2002). Yet, the manufacturers must also be responsive to the requested delivery dates because it is likely that customers have strong preferences regarding the timing of the new machinery' commissioning. For example, customers' demand seasons can make certain periods considerably more preferable than others. Lastly, also the delivery lead times of the manufacturers must be competitive or otherwise the customers take their business to the competitors. Although logical tradeoffs exist between these three facets of delivery performance (e.g., promising only long delivery lead times could help hitting the promised delivery dates), market pressures tend to invalidate the tradeoff positions, and thus the three items tend to be correlated in empirical inquiries (Szwejczewski et al., 1997). This view has also received support in recent operations management research (Swink and Nair, 2007).

As shown in Table 15, both dependent variables were operationalized with three reflective items in which the respondents were asked to evaluate their production processes' performance in comparison with those of their three most important competitors. The answers were given using five-point Likert scales from "much worse" to "much better."

* Originally, I planned to use a scale of product quality. However, the interviewees, who pilot-tested the survey, were quite unanimous that it would be too narrow and would not capture the essential aspects of conforming to customers' technical standards and unique requirements. Thus in the spirit of spanning the domain of interest (Little et al., 1999, p. 207), I developed a scale of my own and labeled it as product conformance.

Table 15: Confirmatory factor analysis of the performance measures

"How well do you perform in comparison to [three most important competitors]…" ***1: much worse, 2: somewhat worse, 3: about similarly, 4: somewhat better, 5: much better***	***Standardized item loading***
Delivery performance (composite reliability = .85, average variance extracted = .65)	
"…in the ability to confirm delivery dates for customers' first requirement dates"	.88*
"…in the ability to deliver on the confirmed delivery date"	.81*
"…in the average lead time from order acquisition to delivery"	.73*
Product conformance (composite reliability = .80, average variance extracted = .58)	
"…in the quality of products"	.82*
"…in the technical performance of the products"	.80*
"…in the ability to satisfy customers' requirements for the products"	.65*
χ^2 = 13.22, degrees of freedom = 8, p = .104, χ^2/d.f. = 1.65, CFI = .985, NFI = .965, RMSEA = .064 Standardized covariance between *delivery performance* and *product conformance* = .25 (p < .05)	* p < .001

The confirmatory factor analysis of Table 15 as well as all the other factor analyses of this dissertation were conducted with the full-information maximum likelihood estimation with missing data procedure (Arbuckle, 1996), which is embedded in the AMOS 16.0 structural equation modeling software. The full-information estimation was used although the amount of missing data was not a serious cause for concern in any of the analyses. It ranged from three to eight percent at the item level.

It turns out that only the order management practices of the study on Research Question 2a have effects on the product conformance dimension. Thus, Chapters 6 and 7 will only discuss the delivery performance dimension. This outcome was actually to be expected because only the order management practices consider the scope of the ordered products. The capacity planning and the exception processing routines (i.e., the creation of the original production schedules and the management of schedule changes) are only involved with the time aspect of reliability.

4.3 INTRODUCTION TO THE EMPIRICAL PART OF THE DISSERTATION

The main research questions of this dissertation are addressed in three separate empirical analyses. This chapter presented the data of those analyses as well as the analytical methods for those parts that are common to all three studies. Next, Chapters 5, 6, and 7 presents the analyses on Research Questions 2a, 2b, and 2c, respectively. In addition to the analyses, each chapter includes its own small literature review, which is necessary for the development of hypotheses. Each chapter also includes its own discussion section, which is necessary to come up with the theoretical conclusions regarding each topic of interest. Later, in Chapter 8 all theoretical and practical implications will be synthesized and discussed together.

5 CONTINGENCY THEORY OF ORDER MANAGEMENT

This chapter presents the analysis of Research Question 2a on how the effectiveness of different order management practices depends on the complexity of the manufactured products. The premise of the analysis is that complex products can be customized either at the configuration or component level, or both. This gives rise to three customization gestalts: mass customizers, custom producers, and mass producers. I will first develop hypotheses on how the gestalts influence the effectiveness of three different order management practices: the use of product configurators, available-to-promise verifications, and configuration management methods. Then, I identify the gestalts in the data and test the hypotheses. Lastly, I discuss the statistical results in the light of the interviews. The results show that some seemingly old-fashioned practices, such as available-to-promise verifications, are effective but commonly neglected in many organizations. The findings also challenge some of the conventional wisdoms about mass customization. For example, systematic configuration management methods, which are conventionally associated only with project business environments, appear to be important in all customized manufacturing, mass customizers included.

5.1 INTRODUCTION

Manufacturers of complex customized products need to pursue multiple and often conflicting competitive priorities. One fundamental challenge is that the production times of customized products can be significantly longer than their desired delivery times. This challenge has been labeled the *customization-responsiveness squeeze* (McCutcheon et al., 1994), and it has been researched widely from different points of view, including at least the literatures on mass customization (Pine, 1993), product architectures (Salvador et al., 2002), process design (Tu et al., 2001), supplier relationships (Krajewski et al., 2005), customer involvement (Duray et al., 2000), and supply chain structures (Randall and Ulrich, 2001). Different authors have framed the customization-responsiveness challenge in different ways and proposed different solutions for addressing it.

In this chapter, I examine the customization-responsiveness squeeze from the perspective of day-to-day order management. In particular, I study how different order management practices contribute to responsive and reliable MTO manufacturing. The order management practices of interest include the use of *product configurator* (PC) software, *available-to-promise* (ATP) verifications, and *configuration management* (CM) methods. In contrast with much of the extant work on order management that tends to use analytical methods (e.g., Ramdas, 2003), the methods of this analysis are purely empirical. To be sure, the analytical research has helped us understand the dynamics of using different methods in delivery date promising, for instance (Bertrand et al., 2000; Barut and Sridharan, 2005; Venkatadri et al., 2006). However, the applications that have been found best in such research have been scarcely implemented in practice (e.g., Krishnan and Ulrich, 2001).

The benefit of the empirical approach is the possibility to gain understanding in what practices are effective in the boundedly rational (Simon, 1978) reality of managers who do not have time or incentives to pursue the optimal solutions of the order management techniques advocated by the analytical studies. The results of this analysis will show that the effectiveness of different order management practices depends on the nature of products' customization and also that some effective order management practices may be neglected in contemporary manufacturing firms.

5.2 LITERATURE REVIEW AND THE RECEIVED VIEW

The essential information in MTO manufacturing is recorded in customer orders that specify what must be produced and when the products must be finished. The core process of any MTO manufacturing system is thus *order management*. It can be divided into two phases: *order acquisition* and *order fulfillment* (Forza and Salvador, 2002a). The challenges of the first phase are in the customer interface, where the task is to configure producible solutions that conform to the heterogeneous needs of the customers (Salvador and Forza, 2004). In addition to addressing technical feasibility, the first phase includes the determination of delivery dates that are feasible in terms of manufacturer's available capacity (Bixby et al., 2006; Zorzini et al., 2008). In the order fulfillment phase, the challenge is to cope with potential modifications to order delivery dates and specifications, which are endemic to most MTO manufacturing environments (Danese and Romano, 2004). The following literature review and theory development is structured according to these two generic phases. First, I derive the hypotheses of the "received view," that is, the hypotheses that articulate the current understanding on the effects of order management practices based on the extant literature. Subsequently, I elaborate these hypotheses on different practices' universal effects by deriving contingency hypotheses on where and when each practice should and should not be effective.

5.2.1 Order Acquisition

MTO manufacturing starts to manifest its idiosyncratic characteristics at the time of the sales transaction. The goal of the transaction is to elicit customer needs and to communicate the available options. Typical risks include customers becoming confused with the offered variety and the manufacturer making mistakes in configuring the products (Huffman and Kahn, 1998; Hegde et al., 2005). From an organizational perspective, functional integration is crucial: sales personnel must be able to ensure both the technical viability of the configurations they offer and the feasibility of the delivery dates that they promise. This requires effective information flows between sales, engineering, and manufacturing functions (Lawrence and Lorsch, 1967a; Salvador and Forza, 2004). Without appropriate investments in information processing tools, order acquisition is prone to errors and waste of resources (e.g., Forza and Salvador, 2006).

Product configurator (PC) tools offer one solution to the information processing challenges of the order acquisition phase. They help ensure technical product feasibility by formalizing the rules about how products can be configured and by providing user interfaces that help sales personnel translate desired features into technical specifications (Forza and Salvador, 2002a). These tools are often embedded in *enterprise resource planning* (ERP) systems (e.g., SAP, 2009b), but they can be also purchased as stand-alone software (e.g., i2, 2009). Case studies (e.g., Forza and Salvador, 2002b) have demonstrated that configurators are indeed effective in ensuring technical performance and conformance to customer requirements. These benefits, in turn, should lead to higher product quality and other performance improvements (Forza and Salvador, 2002a). The received view on product configurators thus suggests:

> *H1a: Use of product configurator software in order acquisition is positively associated with MTO manufacturer's ability to meet customers' product requirements.*

While the PC tools help the sales personnel ensure technical feasibility, they seldom help determine feasible delivery dates (Forza and Salvador, 2006). Yet, the determination of delivery dates is particularly crucial in MTO manufacturing, where the capacity utilization at the time of the order acquisition has considerable influence on the delivery lead times (Zorzini et al., 2008). In the MTO context, the use of fixed lead-time quotes *always* results in ineffective delivery date promises (Proud, 2007). Under high capacity utilization the promise is too optimistic and under low utilization, less responsive than it could be.

Various *available-to-promise (ATP)* techniques enable dynamic delivery date determination based on the present and projected capacity utilization. These techniques are sometimes called *capable-to-promise (CTP)* or *advanced available-to-promise (a-ATP)* verifications, depending on their features (Pibernik, 2005). However, I will use the generic label ATP in reference to all of these techniques. Although empirical research on the use of ATP tools is scarce, the tools themselves are widely applied in practice (Stadtler, 2005; Kilger and Schneeweiss, 2005). For example, ERP systems typically feature several alternative techniques for conducting ATP verifications (e.g., SAP, 2009c). The pioneering case study of Bixby et al. (2006) showed that the use of ATP verifications can facilitate integration of sales and manufacturing and thus enhance delivery performance. Therefore, the basic proposition with regard to ATP is:

H1b: Use of available-to-promise verifications in the order acquisition is positively associated with MTO manufacturer's delivery performance.

5.2.2 Order Fulfillment

Once the order fulfillment phase begins, the primary challenge in order management is to respond to the changes in order specifications and delivery dates. Research on MTO industries has discovered that customers frequently request amendments to product configurations and delivery dates after the initial placement of orders (Riley et al., 2005). Unfortunately however, such mid-process changes are often hastily accepted as such, at the cost of other orders. Hasty approvals of change requests lead to capacity and materials shortages, which in turn have a direct impact on manufacturer's reliability (Hanna et al., 2004). Despite the risk of such adverse performance effects, MTO manufacturers feel pressure to approve the changes because freezing the product configurations and delivery schedules in the order acquisition phase is generally considered unacceptable customer service (Danese and Romano, 2004).

In order to avoid the negative effects of customer change requests, all amendments should be evaluated based on their effects on the overall delivery plans of the manufacturer (Lyon, 2004). For example, the delivery date of an order with a change request to its configuration may have to be postponed to ensure that the execution of other orders is not disturbed (e.g., Guess, 2002; PMI, 2006). The evaluations of requested changes necessitate effective procedures where order documents are updated and transferred between the sales and the manufacturing functions.

Surely there may be MTO manufacturers to whom change requests from customers are not a major concern. The ability to accommodate mid-process changes is, however, important to these manufacturers as well. This is because changes may also result from causes other than the changing customer needs, such as procurement delays, machine breakdowns, and quality problems (Koh et al., 2005). In general, MTO manufacturers tend to be considerably more vulnerable than make-to-stock manufacturers to typical manufacturing uncertainties (Koh and Simpson, 2005). Managing uncertainties is more difficult in MTO manufacturing because materials are often order specific and consequently, there are limited possibilities to replace missing, deficient, or scrapped parts. Use of inventories as buffers against temporary capacity shortages is constrained for the same reason. These difficulties can, however, be alleviated with diligent management of order documents: if the glitches in manufacturing are systematically communicated by updating the order documents, sales personnel will get advance information about the forthcoming delivery problems and consequently, will have extra time to negotiate alternative delivery dates and arrangements with the customers.

The practices of recording and approving changes in the order documents of customized products are discussed under the rubric of *configuration management, CM* (Guess, 2002; PMI, 2006). The CM literature postulates that the initial configurations and delivery schedules of all orders are documented in standardized forms. In addition, all changes to the initial documents are subject to approval in formal review procedures that are triggered by issuing standardized order deviation documents. The principles of CM originate in project business environments (e.g., Harter et al., 2000; Shenhar, 2001), but recent literature has shown that they can be applied in the manufacturing context as well (Lyon, 2004). Formal management of order documents is beneficial in customized manufacturing because it creates transparency in the collaboration between sales and manufacturing. Thus, the following hypothesis can be formulated:

> *H1c: Use of configuration management practices in the order fulfillment is positively associated with MTO manufacturer's delivery performance and ability to meet customers' product requirements.*

5.3 THEORY DEVELOPMENT AND THE CONTINGENCY VIEW

While Hypotheses 1a–1c described the received view of the extant literature, I next elaborate these universal hypotheses into a more detailed form by presenting different product customization gestalts, which I argue to have influence on the effectiveness of the different practices (PC, ATP, and CM). The resulting hypotheses can be labeled broadly as a contingency theory of order management. In the following, I first conceptualize product customization as a two-dimensional construct and subsequently theorize how the dimensions of customization are associated with the order management practices.

5.3.1 Contingencies: Configuration-Level and Component-Level Customization

Customization of complex products can occur on two levels. First, products can be tailored to customer needs by switching and swapping the constituent components (Salvador et al., 2002); I label this customization at the configuration level. Second, individual components comprising the configurations may be customized as well; I label this component-level customization. The separation of the dimensions became important after the introduction of the modular product architectures (Starr, 1965), and since then, the configuration-level customization has assumed an important role in industrial practice (McCutcheon et al., 1994; Pine, 1993).

Limiting product customization to the configuration level increases responsiveness through three different mechanisms. First, when components are not order specific, their procurement lead times do not influence end product delivery times (Sheu and Wacker, 1997). Second, processing times of all component-level manufacturing operations become irrelevant to delivery lead times (Feitzinger and Lee, 1997; Su et al., 2005). Third, component commonality reduces the required level of production resource specialization, which in turn reduces the need for internal buffers in the manufacturing processes (Fisher and Ittner, 1999). I use the label *mass customizers* in reference to manufacturers that produce customized configurations from standardized components.

Standardization of components may not, however, be desirable or even possible in all manufacturing environments. Customer needs may be so sophisticated and idiosyncratic and their applications for the products so diverse that customization must be extended to component level (e.g., Robertson and Ulrich, 1998; Hegde et al., 2005). This applies in the studied context in particular: in complex task environments, manufacturers typically seek to restrict customization to the configuration level as much as possible, yet they often find configuration-level customization to be insufficient to meet all customer requirements. Complete modularization may be impossible if the product is to be integrated into a broader system at the customer's facility; an industrial robot that is integrated to a customer's production line is a good example of a product whose interfaces may be so complex that component-level customization is required. In most cases, the grippers of the robot need to be customized for the customer's products, the handling platforms needs to be customized for the customer's jigs, and so forth. Manufacturers of capital-intensive goods such as machinery, industrial instruments, construction materials, and luxury craft products, are other examples. In sum, there are valid reasons for some MTO manufacturers to remain purely *custom producers*, which assemble customized configurations from at least partly customized components.

Finally, there is also the alternative that MTO products are simply not customized at all. Both configurations and components may be standard for all customers, but the products are still made to order simply because they have so many different variants or they are so valuable that the manufacturer cannot commit to producing them until a customer order is received. This applies particularly in business environments where demand is sporadic, products are perishable, or have very short life cycles (Weng and Parlar, 2005). I label MTO manufacturers that produce standard configurations from standard components as *mass producers*.

Although much of the extant literature has treated product customization as a unidimensional variable (e.g., Safizadeh et al., 2000; Sousa and Voss, 2001; Sousa, 2003), there are also studies that recognize its multi-dimensional nature, albeit only implicitly (e.g., Duray et al., 2000; Klein, 2007; Swafford et al., 2006). Contemporary literature is limited in the sense that the different ways of customizing products have not been used to explain the boundaries of applicability of various operations management practices (Sousa and Voss, 2008). This is in stark contrast with the classical organization-theoretical literature, where *product variety* (a construct similar to product customization) was incorporated decades ago as one of the most important contingency variables (e.g., Woodward, 1965; Hickson et al., 1969; Hayes and Wheelwright, 1979b). In the following, I try to correct this shortcoming by complementing the received-view hypotheses with the contingency effects of the product customization gestalts.

5.3.2 Hypotheses: Applicability of the Different Order Management Practices

First of all, the PC tools are relevant primarily to *mass customizers*. *Mass producers* do not configure their products and hence, have no use for PC tools. Further, *custom producers* should not benefit from the PC tools either, because the non-standard components in their case may have a virtually unlimited variety of interfaces and thus, it is in most cases impossible to maintain reliable configuration rules (Forza and Salvador, 2006). Basic proposition H1a is thus elaborated into the following contingency hypothesis:

> *H2a: Use of product configurator software is positively associated with mass customizers' ability to meet customers' product requirements.*

Second, information systems that feature ATP verifications require that products' routings and resource-specific processing time parameters are known in advance and maintained diligently within the software (SAP, 2009c; Vollmann et al., 2005). This cannot be done with sufficient accuracy if some components are unique. Therefore, ATP verifications are less beneficial for *custom producers* than *mass producers* and *mass customizers*. Basic proposition H1b is thus elaborated into the following contingency hypothesis:

> *H2b: Use of available-to-promise verifications is positively associated with mass producers and mass customizers' delivery performance.*

Third, the CM practices are designed for environments where product configurations are diverse across the customer base (Guess, 2002; PMI, 2006). Consequently, CM is not useful for the *mass producer* whose configurations are standard. Basic proposition H1c is thus elaborated into the following contingency hypothesis:

> *H2c: Use of configuration management practices is positively associated with custom producers and mass customizers' delivery performance and ability to meet customers' product requirements.*

The three archetypes of product customization and the contingency hypotheses are summarized in Figure 4. The southeast quadrant of the matrix can be hypothesized to be empirically void because it is difficult to fathom a context where standard product configurations are built from customized components.

5.4 MEASURES

Configuration-level and component-level customization were both operationalized with three-item scales of reflective indicators. Table 16 shows the results of the confirmatory factor analysis that was conducted to evaluate the validity and reliability of the hypothesized dimensions of product customization.

The validity and reliability of measurement appears adequate. First, the statistics are satisfactory in terms of convergent validity; all items load significantly on their hypothesized factors, and the standardized loadings are reasonable. Second, the composite reliability indices of all scales range from .73 to .74, indicating no problems with measurement reliability. Third, inter-construct discriminant validity is supported; the average variance extracted (AVE) for the scales range from .48 to .49, and thus each construct's AVE index is considerably greater than the

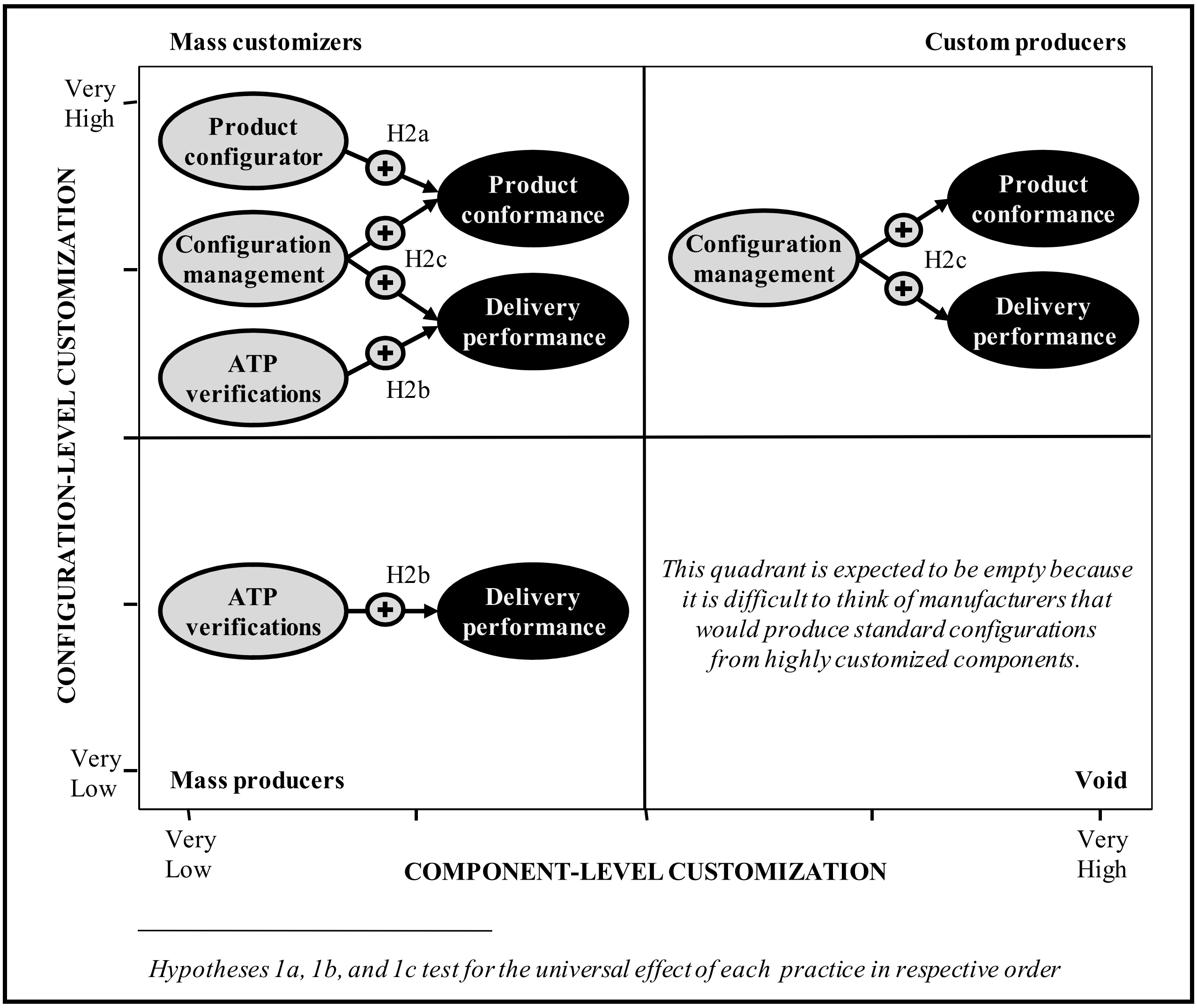


Figure 4: Hypothesized contingency effects of order management practices

Table 16: Confirmatory factor analysis of the customization measures

"How do the following statements describe the operations of your business unit?" ***1: very poorly, 2: somewhat poorly, 3:moderately, 4: quite well, 5: very well***	***Standardized item loading***
Component-level customization (composite reliability = .73, average variance extracted = .48)	
"Our products are made of standard components" (reverse coded)	.59*
"Our products are configured from modules" (reverse coded)	.78*
"We can use inventories as buffers against peaks in demand" (reverse coded)	.69*
Configuration-level customization (composite reliability = .74, average variance extracted = .49)	
"Our production planning is based on product-specific customer orders"	.81*
"Our products are designed according to customers' specifications"	.82*
"Our products have to be adapted to customers' applications"	.64*
χ^2 = 14.82, degrees of freedom = 9, p = .096; χ^2/d.f. = 1.65, CFI = .969, NFI = .930, RMSEA = .063	* p < .001

squared correlation between that construct and any other construct (Fornell and Larcker, 1981). Fourth, the non-significant chi-square-statistic indicates that the overall model fit is adequate.

The three order management practices were operationalized using a total of seven formative indicators. They are listed in Table 17. The formative-indicator mode (Bollen and Lennox, 1991) was used because the individual elements that are associated with each order management practice are not necessarily used in conjunction with one another. The descriptive statistics and inter-correlations of all scale items are shown in Table 18.

Table 17: Order management measures

"How do the following statements describe the order management at your business unit?" ***1: very poorly, 2: somewhat poorly, 3:moderately, 4: quite well, 5: very well***	
Order acquisition practices	
"We use product configurator software"	(Product configurator)
"Delivery dates are confirmed on the bases of available manufacturing capacity"	(ATP verification 1)
"Availability of raw materials is ensured before delivery dates are confirmed"	(ATP verification 2)
"Suppliers' capacity utilization is considered when delivery dates are confirmed"	(ATP verification 3)
Order fulfillment practices	
"Order fulfillment processes are managed as projects"	(Configuration mgmt 1)
"All changes to project plans are documented"	(Configuration mgmt 2)
"Deviations from project plans are managed in a variation management process"	(Configuration mgmt 3)

The questionnaire item addressing the use of PC tools had a U-shaped distribution as the majority of respondents did not use PC tools at all while the second largest group of respondents used PC tools very much (values 1 and 5 in the Likert scale). Consequently, I transformed the measure into a categorical variable, where the Likert values 2, 3, and 4 represented the *occasional users of PC tools*, value 5 the *systematic users of PC tools*, and value 1 the *non-users of PC tools*. The resulting groups were approximately equal in size.

To test the contingency hypotheses, I grouped the sample into three gestalts according to the product customization scores of each observational unit (Venkatraman, 1989). Both dimensions of customization were split at the middle of the scale so that distinct groups of mass producers, custom producers, and mass customizers could be identified. I did not use median split, and therefore the categorization is based on theoretical, rather than empirical, considerations. The contingency effects were tested by first estimating a regression model for each gestalt and subsequently comparing the results of these gestalt-specific regression models.

Table 18: Descriptive statistics and inter-correlations of all questionnaire items

Variable	μ	σ	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 Delivery performance 1	3.01	.86																		
2 Delivery performance 2	3.08	.92	.71*																	
3 Delivery performance 3	2.87	.88	.65*	.61*																
4 Product conformance 1	3.66	.79	.18†	.20†	.13															
5 Product conformance 2	3.78	.78	.12	.11	.02	.67*														
6 Product conformance 3	3.86	.94	.29*	.23*	.12	.52*	.52*													
7 Component cust. 1 (r)	3.45	1.06	.07	.19†	.13	-.14	-.22*	-.27*												
8 Component cust. 2 (r)	2.94	1.10	.09	.17†	.20†	-.08	-.13	-.21*	.48*											
9 Component cust. 3 (r)	1.97	.99	-.06	.01	.00	-.15	-.21*	-.21*	.44*	.55*										
10 Configuration. cust. 1	3.87	1.23	.01	.06	.00	.10	-.03	-.05	.08	.08	.01									
11 Configuration. cust. 2	4.11	.96	.05	.10	.12	.20†	.131	.06	-.02	-.15	-.15	.51*								
12 Configuration. cust. 3	4.21	1.01	.10	.13	.10	.18†	.16†	.14	-.07	-.16†	-.13	.41*	.51*							
13 Product configurator	2.62	1.55	.11	-.03	.14	.06	-.02	.16	-.01	-.02	.00	-.24*	-.11	-.09						
14 ATP verification 1	3.49	1.35	.27*	.28*	.19†	.20†	.08	.17†	-.01	-.01	.11	.19†	.21*	.21*	-.19†					
15 ATP verification 2	2.69	1.32	.26*	.31*	.14	.24*	.16	.16	-.03	-.04	.00	-.03	.16	.04	-.15	.51*				
16 ATP verification 3	2.77	1.43	.22*	.35*	.14	.13	.09	.09	.07	.16	.11	.16	.21†	.12	-.12	.61*	.70*			
17 Configuration mgmt 1	3.55	1.26	.49*	.45*	.46*	.15	.07	.18†	.10	.09	-.02	.05	.20†	.15	.20†	.06	.27*	.21†		
18 Configuration mgmt 2	3.20	1.23	.26*	.27*	.30*	.00	.05	.08	.05	.03	.01	-.26*	-.02	-.12	.19†	-.10	.14	.14	.58*	
19 Configuration mgmt 3	3.19	1.30	.35*	.30*	.36*	.04	.01	.09	.08	-.03	-.03	-.20†	-.05	.01	.26*	.07	.21†	.17	.54*	.66*

Component-level customization items are reverse coded (r). † p < .05; * p < .01

5.5 SURVEY RESULTS

5.5.1 Product Customization Gestalts

Figure 5 summarizes the product customization gestalts and gives examples of each. As expected, the quadrant of customized components and standard configurations is empty. Another observation is the imbalance in the distribution of the data points: only 14 percent of the data is located in the quadrant of mass producers. This is actually quite understandable since if the products are made to order anyway, then why not offer some amount of customizability as well. In contrast, there is more variance in the component-level dimension: 87 observational units have a low and 64 a high level of component customization. In sum, the vast majority of the studied processes are involved in either configuration- or component-level customization, or both.

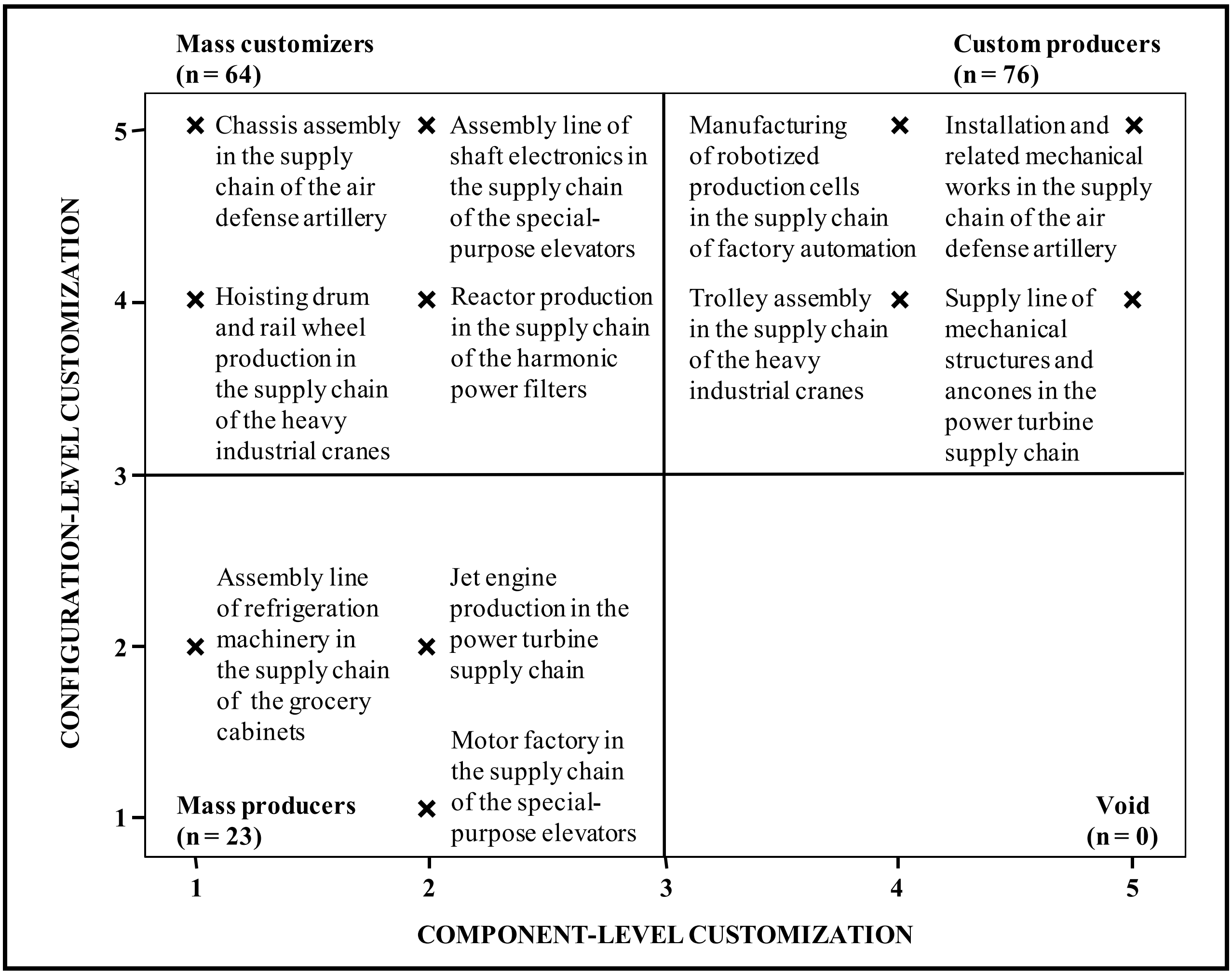


Figure 5: Contents of the product customization gestalts

5.5.2 Hypothesis Testing

Table 19 provides the descriptive statistics of all variables included in the regression analyses. I controlled for the effects of the size of the organization (number of employees) and the supply chains in which the processes were embedded (six dummy variables to control for the seven supply chains). The table also shows the inter-correlation matrix of all continuous variables. Because the use of the PC tools was transformed into a categorical variable, the last three rows display the averages of the continuous variables in each category instead of correlations.

Table 19: Descriptive statistics and inter-correlations of all variables

	Variables for correlations	μ	σ	**1**	**2**	**3**	**4**	**5**
1	Delivery performance	2.99	.78					
2	Product conformance	3.78	.71	.20†				
3	Organization' size [+]	134	178	.00	.26			
4	Available-to-promise verification	3.02	1.21	.32*	.21*	-.16		
5	Configuration management practices	3.29	1.11	.50*	.10	.20†	.20†	
	Grouping variables for t-tests			**1**	**2**	**3**	**4**	**5**
6	Non-use of product configurator			2.88	3.67	80	3.08	2.89
7	Occasional use of product configurator [++]			3.04	3.72	125	3.00	3.40†
8	Systematic use of product configurator [++]			3.02	3.98	199†	2.73	3.66*

[+] Logarithmic transformation of *size* is used in the analyses but μ's and σ's are shown untransformed in order to ease interpretation. † $p < .05$; * $p < .01$

[++] The use of product configurator is operationalized as a categorical variable. Thus, its relationships with the continuous items are illustrated with the averages of each category and the significance levels of the differences.

Hierarchical regression analyses were used to test the hypotheses. Table 20 shows the results of the models with delivery performance as the dependent variable. Both unstandardized and standardized regression coefficients are reported. Although the standardized coefficients are not directly comparable with one another, they provide some basis for assessing the relative effect sizes. In addition the table reports the standard errors of the unstandardized coefficients and the variance inflation factors (VIF).

The regression models on delivery performance provide support for Hypotheses 1b and 1c on the universal positive effects of the ATP verifications and the CM practices. The same applies to the contingency effects of Hypotheses 2b and 2c. That is, the ATP verifications are indeed beneficial when products consist of standard components (*mass producers* and *mass customizers*) and CM practices are beneficial when the products consist of customized configurations (*custom producers* and *mass customizers*).

Table 20: Regression results for delivery performance

	Model 1: Entire sample				Model 2: Mass producers			
Variable	**B**	**(S.E.)**	**β**	**[VIF]**	**B**	**(S.E.)**	**β**	**[VIF]**
Constant	1.48*	(.27)			1.00	(1.49)		
Control variables								
Supply chain dummy variables (omitted)								
Organization's size	.02	(.04)	.03	[1.38]	.15	(.16)	.36	[4.04]
Theoretical regressors								
Product configurator (occasional use)	-.07	(.13)	-.04	[1.50]	-.24	(.54)	-.15	[3.12]
Product configurator (systematic use)	.04	(.16)	.02	[1.62]	-.48	(.50)	-.32	[3.02]
Available-to-promise verifications	.11†	(.05)	.16	[1.36]	.55†	(.17)	.85	[1.92]
Configuration management practices	.32*	(.05)	.46	[1.29]	-.01	(.22)	-.02	[3.05]
Entire model's $\bar{R}^2$				*.50*				*.44*
Theoretical regressors' share from $\bar{R}^2$				*.23*				*.44*
F(ΔR²) for theoretical regressors				*12.89**				*2.62*
	Model 3: Custom producers				**Model 4: Mass customizers**			
Variable	**B**	**(S.E.)**	**β**	**[VIF]**	**B**	**(S.E.)**	**β**	**[VIF]**
Constant	1.65*	(.34)			1.17†	(.51)		
Control variables								
Supply chain dummy variables (omitted)								
Organization's size	.00	(.06)	.00	[1.43]	.03	(.07)	.05	[1.34]
Theoretical regressors								
Product configurator (occasional use)	.21	(.18)	.13	[1.64]	-.33	(.20)	-.21	[1.37]
Product configurator (systematic use)	.31	(.21)	.18	[1.82]	-.17	(.30)	-.08	[1.49]
Available-to-promise verifications	-.02	(.07)	-.03	[1.49]	.20†	(.09)	.31	[1.58]
Configuration management practices	.41*	(.07)	.63	[1.52]	.27*	(.10)	.34	[1.39]
Entire model's $\bar{R}^2$				*.65*				*.40*
Theoretical regressors' share from $\bar{R}^2$				*.32*				*.25*
F(ΔR²) for theoretical regressors				*9.79**				*5.43**

Dependent variable: *delivery performance* † p < .05; * p < .01

Table 21 shows the results of the models with product conformance as the dependent variable. Both the universal effect (Hypothesis 1a) and the contingency effect (Hypothesis 2a) of PC tools are supported. In addition to the expected contingency effect among *mass customizers*, the configurators seem to have a non-hypothesized positive effect in the *custom producer* gestalt. However, the tools appear to be effective only if they are systematically used. CM practices do not seem to have any effects on product conformance (the other half of Hypotheses 1c and 2c). Meanwhile, ATP verifications have a non-hypothesized universal effect as well as a contingency effect in the *mass customizer* gestalt.

Table 21: Regression results for product conformance

Variable	Model 1: Entire sample B	(S.E.)	β	[VIF]	Model 2: Mass producers B	(S.E.)	β	[VIF]
Constant	3.13*	(.32)			.55	(2.42)		
Control variables								
Supply chain dummy variables (omitted)								
Organization's size	.09	(.05)	.19	[1.38]	.37	(.26)	.76	[4.04]
Theoretical regressors								
Product configurator (occasional use)	.04	(.15)	.03	[1.50]	-.20	(.88)	-.11	[3.12]
Product configurator (systematic use)	.43†	(.19)	.26	[1.62]	-1.26	(.82)	-.71	[3.02]
Available-to-promise verifications	.12†	(.06)	.20	[1.36]	.21	(.29)	.28	[1.92]
Configuration management practices	.02	(.06)	.02	[1.29]	.35	(.37)	.45	[3.05]
Entire model's $\bar{R}^2$				*.17*				*.00*
Theoretical regressors' share from $\bar{R}^2$				*.05*				*.00*
F(ΔR²) for theoretical regressors				*2.77†*				*1.14*

Variable	Model 3: Custom producers B	(S.E.)	β	[VIF]	Model 4: Mass customizers B	(S.E.)	β	[VIF]
Constant	3.68*	(.44)			2.44*	(.48)		
Control variables								
Supply chain dummy variables (omitted)								
Organization's size	.05	(.07)	.11	[1.43]	.14†	(.07)	.27	[1.34]
Theoretical regressors								
Product configurator (occasional use)	.15	(.22)	.12	[1.64]	.05	(.19)	.04	[1.37]
Product configurator (systematic use)	.79*	(.26)	.53	[1.82]	.86*	(.28)	.44	[1.49]
Available-to-promise verifications	.09	(.08)	.18	[1.49]	.21†	(.09)	.36	[1.58]
Configuration management practices	-.08	(.09)	-.14	[1.52]	.06	(.10)	.08	[1.39]
Entire model's $\bar{R}^2$				*.23*				*.33*
Theoretical regressors' share from $\bar{R}^2$				*.15*				*.28*
F(ΔR²) for theoretical regressors				*2.94†*				*5.36**

Dependent variable: *product conformance* † $p < .05$; * $p < .01$

5.6 RESULTS FROM THE INTERVIEWS

Next, I discuss and interpret the implications of the statistical results in the light of the qualitative data from the interviews. Table 22 shows all interviewees' positions regarding the product customization gestalts and the use of different order management practices. As for the use of the practices, the table also displays the division between interviewees that were generally satisfied and those that were generally dissatisfied with their current practices.

Table 22: Interviewees' positions regarding the gestalts and order management practices

	Mass producers	Mass customizers	Custom producers	Total
PC tool: non-users	3	3	6	12
PC tool: ERP system	0 | 0 +	3 | 2 +	1 | 3 +	9
PC tool: stand-alone	0 | 0 +	6 | 0 +	2 | 1 +	9
ATP verifications: non-users	0	8	7	15
ATP verifications: users	3 | 0 +	6 | 0 +	0 | 6 +	15
CM practices: non-users	3	0	1	4
CM practices: users	0 | 0 +	4 | 10 +	9 | 3 +	26
Total	3	14	13	

+ Satisfied users | dissatisfied users

5.6.1 Observations about Product Configurators

The survey results provided two important observations on the effects of product configurators. First, as hypothesized, PC tools only influence product conformance. This is an important reminder of the fact that order acquisition includes two separate tasks, verification of configurations and calculation of delivery dates. Although PC tools have recently become increasingly popular, one should remember that they do not replace the systems that are used to manage ATP verifications. The interviewees explained that after the implementation of a PC tool, neglecting ATP verifications was tempting because the tools for that purpose were older, less user-friendly, and had to be accessed separately. This applied also to the cases where the PC tools were featured in the same ERP system where the ATP verifications were conducted.

The other important observation is that PC tools were often used in the *custom producer* gestalt where they also exhibited a non-hypothesized positive effect on product conformance. This intriguing observation was explained by the interviewees: notwithstanding the fact that the components of the one-off products were not standardized and thus the selection of the configurations could not be completely automated, the tools were indeed useful in conducting feasibility checks at a higher level. Instead of using the configurator to ensure the compatibility of individual components, it can be used to check the compatibility of certain "bundles of features." This finding is consistent with the literature on *design rules* (Baldwin and Clark, 2000); even if rules cannot be defined for direct choices between explicit alternatives (i.e., product components), they can be employed as "metaroutines" of sorts, which may prove useful in choices between groups of alternatives (i.e., product features). For example, the specifications of a fully customized industrial crane can be subject to rules by which features like speed, hoisting capacity, and range of operations are restricted by one another. Such rules help prevent sales personnel from accepting infeasible orders even if the component-level compatibility could not be checked at the time of the order's acquisition.

5.6.2 Observations about Available-to-Promise Verifications

The quantitative analyses led to three observations on ATP verifications. First, ATP verifications have a significant effect on delivery performance. This is of course rather intuitive, considering that ensuring the feasibility of the delivery commitments is *the* purpose of these verifications. Second, the survey data showed that ATP verifications were the least-used method among all of the practices examined. This observation is supported by the interviews. Half of the interviewees (15) admitted that they relied on fixed delivery lead time quotes because they considered it the easiest solution. Most interestingly, however, eight of them were *mass customizers*. This is somewhat surprising, given that in the mass customization context in particular, ATP verifications were both hypothesized and found to be effective. Could it be that some practices, while seemingly "old-fashioned," are indeed effective in the contemporary business environments?

The third interesting observation is that many *custom producers* used ATP verifications even though they were neither hypothesized nor found to be effective in that gestalt. The interviewees explained that it is indeed extremely difficult to promise accurate delivery dates in fully customized production. That is because at the time when orders are negotiated with the customers, nobody in the organization has a perfect understanding about the exact amount of work required. The interviewees did maintain, however, that reliable delivery date promises are as crucial in one-off production as in any other MTO environment. Hence, the observed ineffectiveness of ATP verifications in custom production should not be interpreted as evidence that verifications are futile. On a positive note instead, software providers should be encouraged to develop verification methods that help overcome the ambiguities of the one-off production. Perhaps ATP verifications could be based on similar "metaroutines" that worked when PC tools were used by custom producers.

5.6.3 Observations about Configuration Management Practices

One particular observation on the CM practices merits attention: the practices have significant influence on delivery performance both in the *custom producer* and the *mass customizer* gestalts. Extant literature has often considered mass customization to be an extension of mass production of sorts. Consequently, the importance of managing product configurations and delivery schedules systematically during the order fulfillment process has been downplayed. The interviewees, however, specifically emphasized the importance of the systematic maintenance of order documents in both gestalts. Out of the 27 interviewees that belonged either to *mass customizer* or *custom producer* gestalts, one half (14) were satisfied with their CM practices; the other half (13) thought that their practices were not systematic enough. Interestingly, 10 out of the 13 unsatisfied were *mass customizers*.

The importance of CM practices arises from two characteristics that are common to all kinds of customized production: product specifications depend on customer needs and there is always some lead time between order acquisition and product delivery. Their combined effect is that customer needs may change during the order fulfillment phase. If order documents are not well maintained, those who receive change requests will have trouble evaluating how the requested changes will affect both the feasibility of the configuration as well as the promised delivery date. The key is to strike a balance, because automatically declining all change requests will have negative effects on product conformance, but at the same time, accepting all requests will jeopardize delivery performance.

Interviewees argued that change requests were indeed very often accommodated without sufficient understanding of their implications. Accepting changes and additions without appropriate evaluations and approvals was seen especially detrimental for delivery performance. A hastily approved modification that increases order's capacity requirements not only compromises the delivery of that order but it can also mess up the delivery schedules of the entire production process. According to the interviewees, accepting technically infeasible change requests was relatively uncommon and not as much of a problem as accepting requests that are infeasible from a scheduling standpoint. This explains why Hypotheses 2a and 2c were only supported in terms of delivery performance.

The underlying reason for hasty acceptance of change requests was also familiar to the interviewees. Sales and customer service personnel were said to be pressured to exhibit flexibility toward the customers, and in the absence of compelling reasons to decline change requests, they would usually accept them. If in turn they had at their disposal a systematic procedure for managing order amendments and evaluating their consequences, they would be able explicitly to assess the consequences of the requested changes, to make decisions whether to accept them, to revise delivery schedules, and to communicate the new delivery dates to the customers.

5.7 DISCUSSION

5.7.1 Implications for Theory and Research

This study's most important substantive findings are the contingency effects of product customization on the applicability of different order management practices in complex manufacturing environments. The theoretical insight is not, however, limited to context-specific results. At a more formal theoretical level, a detailed look at the two-dimensional nature of product customization has implications for contemporary research on information processing theory (Galbraith, 1973). Specifically, the results demonstrate the implications of product design and architecture on the information processing needs: customizing configurations is not the same as customizing components; the situation where both configurations and components are customized is the most complex and thus it is also the most "information intensive."

I would also argue that taking a more detailed look at product customization contributes to the management research in general because even the most recent organization design literature uses product variety and other crude proxies for complexities that stem from product customization (e.g., Daft, 2004). This tendency could be seen also in the systematic review of Chapter 3 which revealed that crude and ineffective operationalizations are quite prevalent in operations management research as well.

5.7.2 Implications for Practice

The multidimensionality of product customization leads also to interesting practical insights. Understanding the various customization gestalts is essential in developing guidelines on how MTO manufacturers can improve their order management practices. Managers of MTO manufacturing firms should check where they belong in the customization framework and whether they are appropriately utilizing the practices that are effective in their task environments. The results also point to the measures on which each practice can be expected to have its most immediate impact.

On the substantive level, the analysis uncovered one new aspect of mass-customized manufacturing. It is that the CM practices—the systematic ways of documenting and maintaining both product configurations and delivery dates—are as important in mass customization as they are in fully customized production systems. This is a finding that is not discussed in the extant operations management literature. Naturally, the result may reflect the empirical context, which is characterized by relatively long delivery lead times and widely varying customer requirements, and thus it would be interesting to explore how the finding applies to mass customizers that offer lesser customizability and run shorter production processes than the machinery manufacturers of this study.

5.8 RECAPITULATION

This chapter presented an analysis of how the effectiveness of different order management practices depends on how the manufactured products are customized. In addition to the statistical results on the effectiveness, I also presented qualitative data that answered why certain practices were or were not applied by the practitioners. The outcome is an empirically tested theory of order management in complex manufacturing environments, and it is ready to be tested in other empirical contexts than the machinery manufacturing sector of this dissertation.

6 CONTINGENCY THEORY OF CAPACITY PLANNING

This chapter presents the analysis of Research Question 2b on how process complexity influences the effectiveness of different capacity planning methods. The premise of this chapter is the observation that most practitioners use considerably simpler planning methods than what is recommended in the literature. The contingency-theoretical analysis helps to explain the gap between the practice and the academic models of production planning. First, I juxtapose the hypothesis on the superiority of the most advanced planning methods, which is often assumed in operations management literature, with the contingency hypothesis that expects the simpler planning methods to be superior with certain kinds of processes. Then, I test the hypotheses with the survey dataset, which shows that the data support only the contingency hypothesis. Lastly, I use the interview data to explain why organizations end up with their planning methods. The findings have several managerial implications, and they elaborate how classic organization-theoretical concepts can bring practically relevant insights to operations management research and education.

6.1 INTRODUCTION

In manufacturing organizations, many important decisions are made in production planning activities. Production planners decide when and with what resources organizations produce their outputs. The methods that are used to create the plans are crucial to organizational performance (Kanet and Sridharan, 1998; Davis and Mabert, 2000; Zwikael and Sadeh, 2007). Poor methods yield plans that are either too loose and result in excessive lead times or too tight and result in failures to keep promised delivery dates. Consequently, it is not surprising that planning methods have represented a major research area in the operations management literature. Different planning techniques have been studied especially in analytical and simulation-based research (Kouvelis et al., 2005). That stream of research has produced various sophisticated algorithms that enable the leveling and optimization of production plans (e.g., Davis and Mabert, 2000; Yang et al., 2002; Deblaere et al., 2007).

Meanwhile, however, empirical researchers have repeatedly observed that most practitioners use considerably less sophisticated planning methods than what is discussed in the academic literature (Melnyk et al., 1986; Wiers, 1997; McKay et al., 2002). Moreover, empirical evidence indicates that those practitioners using advanced planning methods are on average less satisfied with their plans than those who use simpler and less accurate methods (Jonsson and Mattsson, 2003). This chapter aims to use process complexity as a contingency factor that explains why the practices of production planning often differ from the academic model of production planning.

The analysis of this chapter employs the logic of *strong inference* and the *contingency theory* of organizations to explain the determinants of different planning methods' effectiveness. The strong-inference logic refers to a research design, where theory building is based on tests of competing hypotheses (Platt, 1964). The contingency-theoretical perspectives to process complexity (e.g., Thompson, 1967) are used to propose that sometimes the most sophisticated planning methods may be less effective than the simpler techniques. The contingency hypothesis is tested against a hypothesis about the universal superiority of the most advanced planning methods. The statistical results from the survey dataset are complemented by the interview dataset that sheds light on the reasons why practitioners end up using certain planning methods.

6.2 THEORY DEVELOPMENT

6.2.1 Underlying Assumption: Importance of Planning in Complex Organizations

Planning is necessary in all complex organizations. In the absence of planning, different work units may pursue the possibly conflicting objectives of their own (March and Simon, 1958). However, not all organizations are complex and thus heavy planning efforts are not always necessary. In simple settings, where specialization, action variety, and task interdependence are low, coordination can be achieved through rules and heuristics (Cyert and March, 1963). In manufacturing management, the planning-focused methods have been developed around the concept of *material requirements planning* (MRP, Orlicky, 1975), while the methods that emphasize rule-based control and simplicity are founded on the *just-in-time* (JIT) methodology (Ohno, 1988).

A classic way to pursue simplification in manufacturing is to isolate operations from external uncertainties (Thompson, 1967). The extent of the isolation depends greatly on the *order penetration point* (Olhager, 2003): the earlier the order-specific requirements are taken into account, the higher is the exposure to the environment. That is why planning methods are most important in the MTO manufacturing and the JIT methods are at their best in the make-to-stock environments (Karmarkar, 1989; Vollmann et al., 2005). Usually both approaches coexist in assemble-to-order systems and other intermediate settings. The postponement of the order penetration point enables the use of JIT methods in the upstream operations of customized manufacturing (Olhager and Rudberg, 2002). However, the inherent complexity of producing according to individual orders cannot be eliminated by forcing JIT methods upon the MTO parts of the processes (Hopp and Spearman, 2004). Hence, the time-phased planning has remained as a vital part of manufacturing management despite the important contributions of JIT. Recent literature has described several techniques for integrating the benefits of the two paradigms. The techniques are known by many names (e.g., CONWIP, POLCA, COBACABANA, etc.) and they differ in details but they share the main idea of using the pull logic of JIT for the purposes of shop floor control and time-phased planning methods for the creation of production schedules (Spearman et al., 1990; Suri, 1998; Land, 2009).

Contemporary methods of time-phased production planning are based on the *manufacturing resource planning* (MRPII) framework. It was originally developed to complement MRP with capabilities to check material plans' feasibility against capacity constraints (Landvater and Gray, 1989). Later, more advanced applications of MRPII have been developed so that the feasibility checks could be extended to other factors such as delivery schedules and financial constraints (Yusuf and Little, 1998). However, the practical implementations of such solutions have remained rare (McKay and Wiers, 2004). In fact, it has been observed that even the capacity planning features of MRPII are far less utilized than what could be expected on the bases of the academic literature (Halsall et al., 1994; Kemppainen, 2007). As the material-planning parts of MRPII are well-established (Vollmann et al., 2005), the observation implies that companies' production planning practices can be measured through the methods that they use in *capacity planning*.

Recent developments in enterprise software deliver a promise of easily applicable capacity planning tools. While the conventional ERP systems are well-suited for the simpler capacity checks (Wortmann et al., 1996), the so-called *advanced planning and scheduling* (APS) systems promote the more sophisticated methods (Kreipl and Pinedo, 2004; Stadtler and Kilger, 2005). However, companies' diligence in applying their enterprise systems' features is known to vary considerably (e.g., Bendoly and Cotteleer, 2008). Thus, variance may be found also in the utilization of the capacity planning features. That variance enables testing whether complex organizations that do not put efforts in planning suffer from the lack of coordination (e.g., March and Simon, 1958; Zwikael and Sadeh, 2007). Consequently, the following hypothesis is presented as the underlying assumption of this study:

H3: Efforts in capacity planning are positively associated with performance

6.2.2 Universal Effect: Advantages of Sophisticated Planning Methods

It is reasonable to assume that not only the efforts in planning but also the ways of planning matter. Figure 6 presents the main methods of time-phased production planning according to the framework of Vollmann et al. (2005). The practical relevance of the framework is high because dominant ERP software providers have structured their production planning modules in the same fashion (e.g., SAP, 2009a). In addition, most textbooks either refer to it directly or provide illustrations that closely resemble it (e.g., Hill, 2005; Slack et al., 2007; Stevenson, 2004).

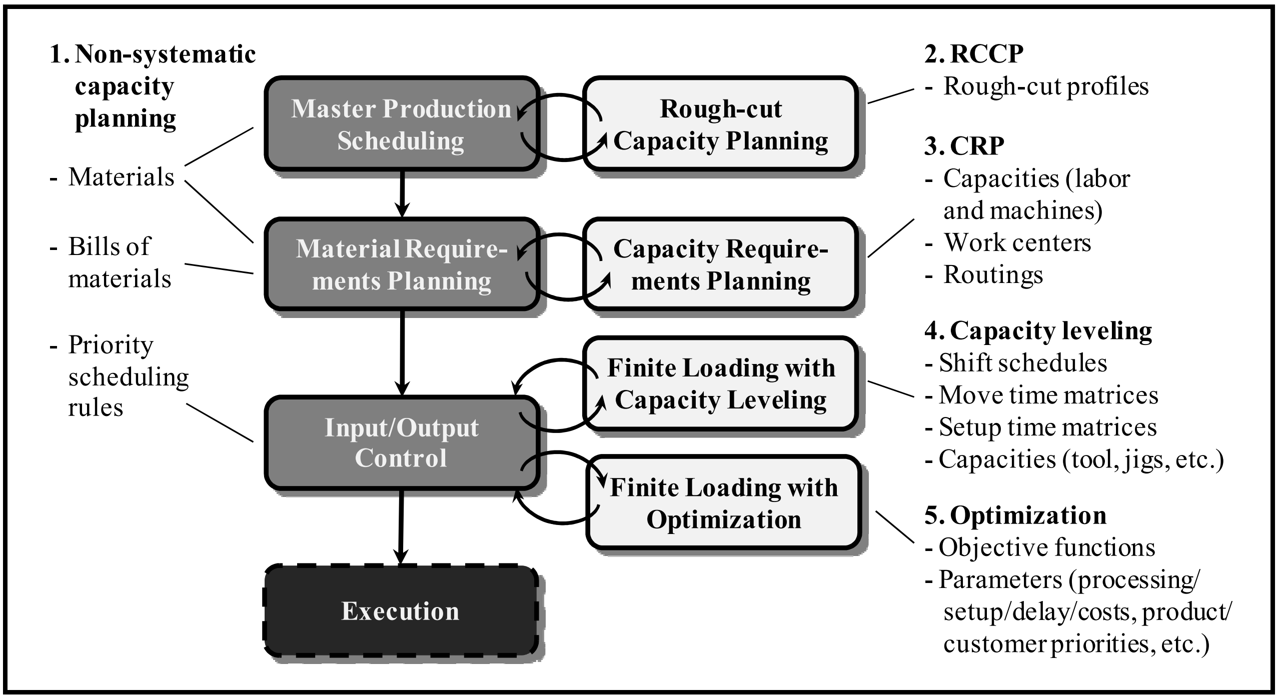


Figure 6: Alternative methods in capacity planning

The backbone of the planning process is in the material planning activities, that is: master production scheduling (MPS), MRP, and the input/output (I/O) control (Vollmann et al., 2005). The optional activities are on the side of capacity planning. In Figure 6, they are numbered in the order of sophistication. The figure shows that the amount of required data records increases as the methods get more sophisticated. The increase is cumulative because the records do not fully substitute each other. Brief descriptions of each method are given in the following:

Non-systematic capacity planning represents inexplicit consideration of capacity constraints. At the level of master schedules, it means that planners use their personal experience to evaluate the feasibility of plans (Proud, 2007). In MRP, the inexplicit capacity considerations are realized through the lead time parameters of bills of materials. The processing lead times represent the averages, while the variances around the averages are taken into account with safety lead times

(Vollmann et al., 2005). In the I/O control, priority scheduling rules can be used to level capacity utilization without formal planning activities (Green and Appel, 1981; Kemppainen, 2007).

Rough-cut capacity planning (RCCP) is the simplest systematic method. It can be done with several techniques but they all share the common characteristic of aggregation (Wortmann et al., 1996). Materials are aggregated to end products or product groups and capacities to production lines or resource groups (Proud, 2007). RCCP simplifies planning by ignoring subassembly inventories, operations' sequences, setups, and batch sizes but still provides the planners with a *systematic* means to supervise how the resource utilization accumulates during the MPS activity (Vollmann et al., 2005). That is an advantage if master schedules are updated frequently, MPS items are numerous, or different MPS items load the same resources. In such situations, the non-systematic methods are prone to human errors and easily result in overloaded schedules.

Capacity requirements planning (CRP) provides a more detailed technique for checking material plans' feasibility. The CRP calculations are done not only for the end products but also for the subassemblies. In addition, the routing data enable calculating loads at individual resources and considering the effects of operations' sequences, setups, and batch sizes. Thus, CRP corrects for the simplifications of RCCP and helps generating more reliable schedules. Iterating the plans to achieve feasibility in terms of resources' capacity limits is done manually by human planners. (Burcher, 1992; McKay and Wiers, 2004)

The next step from CRP is to automate the iterations of the plans. It can be done with *finite loading* methods that are usually featured in APS systems (McKay and Wiers, 2004). The process of using them is typically the following: first, material plans are downloaded from an ERP system. Then, the algorithms of the finite loading software are used to find a solution, where capacity constraints are satisfied with the fewest breaches of due dates. Finally, the revised plans are uploaded back to the ERP system, where they are executed. (Stadtler and Kilger, 2005) The obvious benefit of automating the *capacity leveling* is that it reduces the room for human errors.

In addition to capacity leveling, the finite loading algorithms can be used to solve more complicated scheduling problems. The finite loading tools with *optimization* may be used, for example, to maximize throughput or to minimize setups or downtimes (e.g., Davis and Mabert, 2000). Such techniques require the most planning parameters and their outputs are highly dependent on the accuracy of the parameters. Yet, the data maintenance efforts and the investments in the software may well be justified in some manufacturing environments, for example in capital intensive production systems (Kreipl and Pinedo, 2004; Stadtler and Kilger, 2005).

The planning methods are by no means mutually exclusive. Instead, several methods can be used simultaneously for different purposes (Meal, 1984). For example, plant managers can use RCCP to evaluate sales plans, master schedulers may use CRP to supervise their processes, and production planners can do the finite loading of critical resources. A concept that brings clarity to this plurality is *bottom-up re-planning* (Fransoo and Wiers, 2008; Vollmann et al., 2005). It means that master schedules are updated on the bases of the lower-level planning activities. In a closed-loop planning system, the master schedules are based on the finite loading of critical resources (Kenat and Sridharan, 1998). In an intermediate solution, the master schedules are revised on the bases of CRP. Consequently, the *main method of planning* can be identified. It is the method that determines the output to which the manufacturing function commits itself.

As all of the advanced planning methods aim to reduce errors in planning, it can be proposed that they should have a positive effect on operational performance. Some studies have already implied evidence of such an effect (Sheu and Wacker, 2001; Wacker and Sheu, 2006). Yet, they have not included finite loading techniques, which is a major shortcoming because substantial effort has been put into their development (Kouvelis et al., 2005). The development of progressive algorithms and software would be well justified if there was evidence on the relationship between the accuracy of planning and performance. Hence, the following hypothesis is formulated:

H4a: Sophistication of capacity planning methods is positively associated with performance

6.2.3 Contingency Effect: Fit between Planning Methods and Process Types

Another perspective to different planning methods' effectiveness is to assume that methods' suitability would depend on the context of their usage. Preliminary support for such an argument can be found in the surveys of Jonsson and Mattsson (2002; 2003). They show that practitioners' satisfaction with different planning techniques depends on the type of their production processes: the managers of job shops are content with RCCP, the most satisfied users of CRP work in batch-process plants, and the finite loading methods are most popular in production lines.

The observations are aligned with the systematic review of Chapter 3 and the review of Sousa and Voss (2008), which both indicate that the process type is a typical contingency factor for the effectiveness of various operations management practices. In the context of planning, the influence of the process type can be explained with two classic contingency-theoretical constructs: the *repetitiveness* and the *complexity* of the tasks that constitute the processes (Perrow, 1967; Woodward, 1965):

- RCCP fits with the *job shops* because in low-volume and high-variety environments, the data records of the more detailed methods are difficult to maintain. Moreover, the more detailed resource-specific plans are not necessary because the complexity of the system is limited with general-purpose machinery and widely skilled workforce (Blackstone and Cox, 2005; Hill, 2007).
- CRP fits with the *batch processes* because the more repetitive operations make the maintenance of the data records worthwhile. Furthermore, information about the resource-specific workloads is necessary because the resources are more specialized, and different products utilize them differently (Jonsson and Mattsson, 2003; Wortmann et al., 1996).
- Finite loading methods fit with batch processes, whose complexity is reduced with *bottleneck control* (Goldratt and Cox, 1984; Vollmann, 1986). Finite loading works in a batch process if a stationary bottleneck can be identified and all other resources are subordinated to its schedule. Otherwise, each finite loading of one resource can make another resource a new bottleneck, and consequently the iteration of the plans may become endless.
- In *production lines*, the complexity is low because all resources are subordinated to the flow of the line. Thus, the capacity of the entire line can be planned as a single resource. Detailed planning is desirable because untimely changeovers can be costly in larger assembly lines (Hayes and Wheelwright, 1979a; Kreipl and Pinedo, 2004) or cause congestion in smaller manufacturing cells (Venkatesan, 1990; Vandaele et al., 2008). In addition, the repetitiveness of operations makes it easier to maintain the parameters of the most sophisticated methods (Safizadeh and Ritzman, 1997; Stadtler and Kilger, 2005).

The relationship between the process types and planning methods can also be explained with the interdependence between the resources of the processes. As discussed in Chapter 2, the alternative types of interdependence are pooled, sequential, and reciprocal (Thompson, 1967; Donaldson, 2001). The *pooled* and the *sequential* processes are the simplest to coordinate but they have very different implications for planning (Barki and Pinsonneault, 2005). The processes with pooled resources are inherently flexible, and that is a capability that should not be constrained with too stringent planning. A job shop is an archetype of pooled interdependence (Galbraith, 1973). Meanwhile, the sequential processes are suited for efficiency, which is a capability that can be fostered with detailed planning. In manufacturing environments, sequential relationships exist in production lines and around the bottlenecks of batch processes (Thompson, 1967; Woodward, 1965).

The most difficult processes to coordinate are those where resources are *reciprocally* interdependent. That is because all actions by any resource may affect multiple other resources (Galbraith, 1973; Monahan and Smunt, 1999). Some specificity in planning is necessary to prevent undesirable cascade effects but getting into the details is difficult because the possible interactions are numerous (Tushman and Nadler, 1978). Therefore, a moderately sophisticated planning method such as CRP is the most suitable option for the reciprocal processes of batch shops (Reeves and Turner, 1972).

In summary, classic contingency-theoretical concepts produce a meaningful fit proposition that challenges the hypothesis on the universal superiority of the most sophisticated planning methods. The proposition is illustrated in Figure 7 and it can be formulated as follows:

H4b: Alignment between capacity planning methods and process types is positively associated with performance, that is: RCCP should be used in job shops, CRP in batch processes, and finite loading methods in bottleneck-controlled batch processes and production lines

6.3 THE METHOD OF STRONG INFERENCE

The existence of two competing hypotheses calls for a *strong inference* research design. It is an inductive approach, where theory building is based on tests of mutually excluding hypotheses (Platt, 1964). Strong inference studies must be carefully designed so that the research settings do not favor any of the rival hypotheses (MacKenzie and House, 1978). Multiple data sources are also necessary: quantitative data enable the testing of the hypotheses while qualitative data provide the understanding that is needed in the development of theory (Jick, 1979; Gupta et al., 2006). Although the strong inference research design was originally developed for experimental studies (e.g., Nadler et al., 2003), it has been employed successfully in non-experimental empirical research as well (e.g., Shaw et al., 2005). In overall, the focused sample of this dissertation offers a good setting to utilize the method of strong inference.

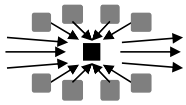
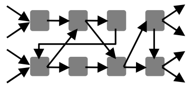
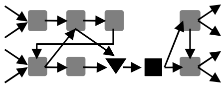
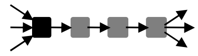
<table>
<tr><th></th><th>Job shop</th><th>Batch process</th><th>Batch process with bottleneck control</th><th>Production line</th></tr>
<tr><td>Process complexity
■ resources
→ different kinds of routings</td><td>
Planning points = 1</td><td>
Planning points > 1</td><td>
Planning points = 1</td><td>
Planning points = 1</td></tr>
<tr><td>Task interdependence</td><td>Pooled</td><td>Reciprocal</td><td>Sequential around the bottleneck</td><td>Sequential</td></tr>
<tr><td>Non-systematic capacity planning</td><td colspan="4">Not recommendable for any environment due to the high exposure to human errors and variance in planners' personal competences</td></tr>
<tr><td>Rough-cut capacity planning (RCCP)</td><td>Fit</td><td colspan="3">Unfit due to the insufficient precision</td></tr>
<tr><td>Capacity requirements planning (CRP)</td><td rowspan="3">Unfit because the high variety of outputs would compromise the maintenance of the planning parameters</td><td>Fit</td><td colspan="2">Unfit because calculating loads for all resources is not necessary and the more precise methods are possible</td></tr>
<tr><td>Finite loading with capacity leveling</td><td rowspan="2">Unfit because the subject of finite loading would not be stationary</td><td colspan="2" rowspan="2">Fit</td></tr>
<tr><td>Finite loading with optimization</td></tr>
</table>

Figure 7: Link between planning methods and process types

6.4 MEASURES

Figure 8 shows the operationalization of the hypotheses. As opposed to the prominent earlier comparisons of planning methods, this study's dependent variable is delivery performance. Earlier analysts, such as Jonsson and Mattsson (2002; 2003), have used planners' satisfaction as the dependent variable. However, *satisfaction* is a problematic variable because it depends not only on solutions' effectiveness but also on respondents' *expectations* about them (e.g., Churchill and Surprenant, 1982). Surveys of planners' satisfaction with their methods probably favor simpler solutions because the more sophisticated methods are likely to carry higher expectations.

The *efforts in capacity planning* were operationalized with two formative indicators. They represent the main aspects of efforts in formal routines: the organizational deployment of the routine (i.e., the structuration aspect), and individuals' efforts to follow the routine in their work (i.e., appropriation, DeSanctis and Poole, 1994). The formative operationalization is suitable because the latter aspect does not always follow from the former and because studies have shown that both aspects are necessary for the routines to be effective (Devaraj and Kohli, 2003). This simple operationalization was used because the more sophisticated measures of planning efforts are typi-

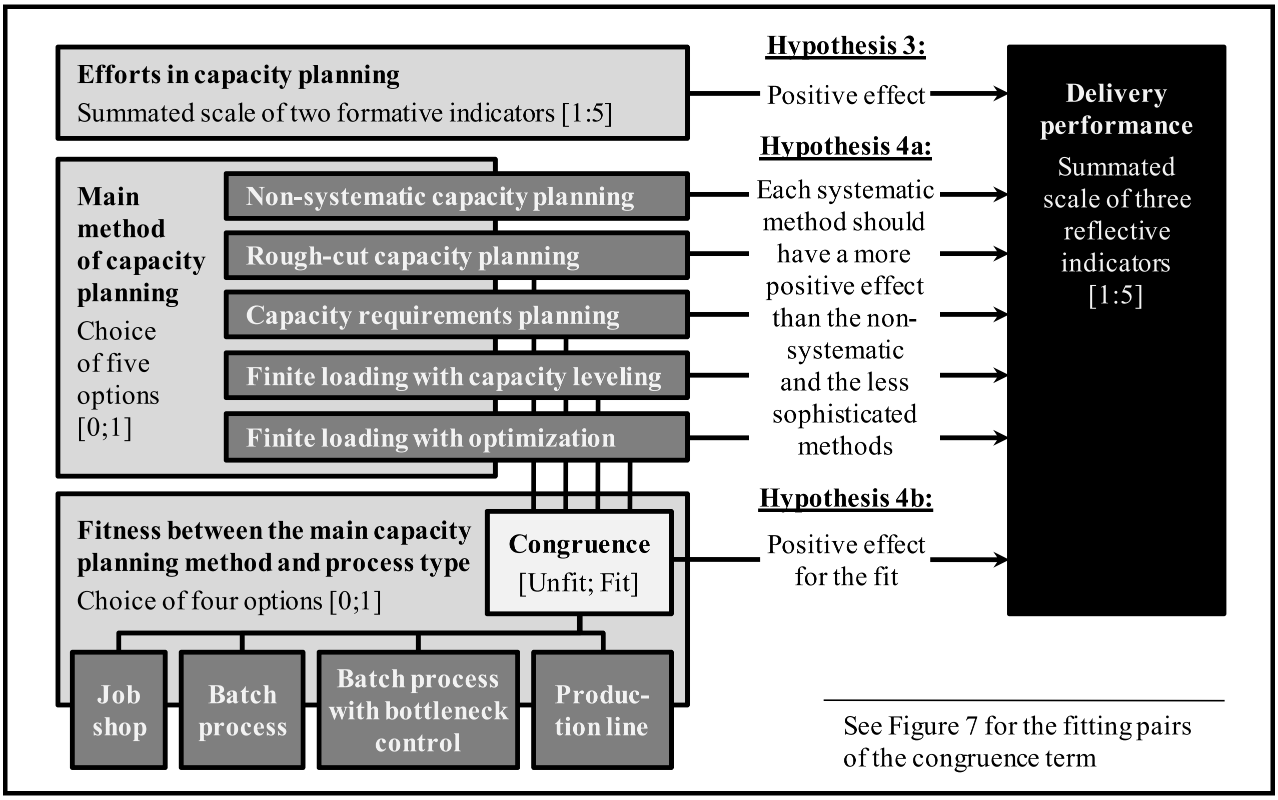


Figure 8: Hypothesized contingency effects of capacity planning methods

cally tied to certain planning methods (e.g., Zwikael and Sadeh, 2007). In this study, the efforts and the methods had to be analyzed separately.

The *planning methods* were operationalized with a *"self-typing paragraph approach"* (James and Hatten, 1995). It means that the respondents were given brief descriptions of each planning method and asked to choose the one that best describes their own method. This kind of an operationalization has been found advantageous for various reasons in many other management studies (e.g., King and Teo, 1997; Slater and Olson, 2001; DeSarbo et al., 2005). In the context of this study, its main benefit is that it does not assume the respondents to be familiar with all alternative planning methods and their textbook labels. In the interviews, the operationalization was also found to be insensitive to plant-specific terminologies. The approach is also suitable because the planning methods constitute a naturally categorical variable due to the bottom-up replanning procedure (Fransoo and Wiers, 2008; Vollmann et al., 2005).

The *process types* were measured according to their *operational definitions* (Ketokivi and Schroeder, 2004a). The respondents were asked to select the process type that best describes the process for which they are responsible (e.g., Das and Narasimhan, 2001; Safizadeh et al., 2000; Swink et al., 2005). The forced choice between the categories was not considered problematic by the interviewees, since the unit of analysis was an individual process and not a plant.

The *fitness* between planning methods and process types was operationalized as a dichotomous *congruence term*. Its values are based on the fitting and the unfitting pairs of Figure 7. The operationalization is called "fit as matching", and its advantage is that the fitness can be determined in isolation of the dependent variable (Venkatraman, 1989). The dichotomic operationalization is also aligned with the theory because there is no reason to expect that some unfit positions would be less disadvantageous than others.

6.5 SURVEY RESULTS

6.5.1 Descriptive Statistics

Table 23 presents the descriptive statistics and inter-correlations of the continuous variables. Table 24 illustrates the bivariate relationships between the dichotomous and the continuous variables. Student's t-tests for independent samples are used for that purpose. All statistics are logical. For example, the users of the finite loading methods seem to put the most efforts in planning. Meanwhile, the least efforts are made by the non-systematic planners.

Table 23: Descriptive statistics and inter-correlations of continuous variables

					Correlations		
Variable	**(scale)**	**Range**	**μ**	**σ**	**1**	**2**	**3**
1 Delivery performance	(Likert)	1-5	3.10	.73			
2 Size of organization [+]	(employees)	8-710	164	170	-.06		
3 Products' complexity	(percentage)	10-100	72	21	.03	.09	
4 Planning effort	(Likert)	1-5	3.49	1.00	.36*	. 07	-.05

[+] Logarithmic transformation of organization's size is used in the analyses but means and standard deviations are shown untransformed to ease interpretation.

* $p < .01$

6.5.2 Hypothesis Testing

The hypotheses were tested with hierarchical regression analysis. The results are shown in Table 25. The first step shows the effect of the supply chain dummy variables. Due to the embedded research design, their explanatory power is quite considerable: as several units of analysis belong to the same supply chains, they share some of the same competitors and performance standards. Hence, controlling for that effect is crucial but the coefficients are not theoretically interesting. The second step adds the other control variables, which turn out to be insignificant although their skewed distributions are corrected with logarithmic transformations. The process types are en-

Table 24: Relationships between dichotomous and continuous variables

			Averages of the continuous variables			
Grouping variable	**Groups**	**n**	**Delivery performance**	**Size of organization**	**Products' complexity**	**Planning effort**
Non-systematic capacity planning	yes no	20 69	2.65* 3.23	177 165	73 71	2.14* 3.91
Rough-cut capacity planning	yes no	26 63	3.14 3.10	151 173	74 70	3.72‡ 3.41
Capacity requirements planning	yes no	18 71	3.20 3.08	179 164	71 71	3.83‡ 3.41
Finite loading with capacity leveling	yes no	15 74	3.49† 3.04	140 173	70 72	4.17* 3.36
Finite loading with optimization	yes no	10 79	3.20 3.10	202 163	62‡ 73	4.15* 3.41
Job shop	yes no	27 62	3.49* 2.93	186 156	72 71	3.65 3.43
Batch process	yes no	24 65	2.87‡ 3.20	214‡ 147	78 70	3.60 3.46
Batch process with bottleneck control	yes no	14 75	3.18 3.09	123 171	71 72	3.61 3.47
Production line	yes no	24 65	2.87‡ 3.19	125 183	65‡ 74	3.17‡ 3.63
Fitting method and process	yes no	38 31	3.59* 2.74	170 166	67‡ 75	4.00* 3.15

Significance of the difference: ‡ p < .10; † p < .05; * p < .01

tered in the third step. There is a significant difference between job shops and batch processes, which highlights the importance of controlling for the process type. The fourth step adds the planning effort into the equation. It has a positive effect as predicted in *Hypothesis 3*. This result is important because it shows that the sample is valid for the comparison of the planning methods. If the sample had included several simple production processes where time-phased planning is unnecessary, then the hypothesis would not have been supported, and the comparison of methods would not have been meaningful.

As for the competing hypotheses, the direct comparison of the different planning methods' effects is conducted first. The fifth step of the analysis shows a lack of direct effects from any of the methods. Thus, *Hypothesis 4a* is not supported by the data. Next, the effect of congruence between planning methods and process types is analyzed. The congruence term is entered into the equation in two ways: when the fitting side of the variable is used in Step 6a, the coefficients of the planning methods represent the negative effects of using the methods in wrong environments.

Table 25: Regression results

Variable	Step 1: Industries	Step 2: Complexity	Step 3: Process	Step 4: Planning effort	Step 5: Methods	Step 6a: Congruence	Step 6b: Congruence	VIF
Constant	2.74* (.16)	2.83* (.44)	2.91* (.48)	2.12* (.51)	2.08* (.56)	2.30* (.39)	2.27* (.39)	
(Supply chain dummy variables)								
Size of organization		.05 (.07)	.06 (.07)	.05 (.07)	.05 (.07)	.01 (.05)	.02 (.05)	[1.52]
Products' complexity		-.07 (.05)	-.06 (.05)	-.04 (.05)	-.04 (.05)	.03 (.04)	.03 (.04)	[1.37]
(Job shop)								
Batch process			-.40‡ (.20)	-.48† (.19)	-.52† (.20)	-.57* (.14)	-.57* (.14)	[1.75]
Batch process & bottleneck control			-.16 (.25)	-.26 (.24)	-.31 (.27)	-.12 (.19)	-.12 (.19)	[1.75]
Production line			-.28 (.22)	-.13 (.21)	-.12 (.25)	-.30‡ (.18)	-.29 (.18)	[3.03]
Planning effort				.28* (.09)	.31† (.13)	.17‡ (.09)	.17‡ (.09)	[3.33]
(Non-systematic planning)								
Rough-cut capacity planning					-.13 (.28)	-.38‡ (.20)	. 47† (.21)	[3.70]
Capacity requirements planning					.09 (.31)	-.32 (.23)	.53† (.23)	[4.35]
Finite loading: capacity leveling					.02 (.37)	-.38 (.27)	.48‡ (.27)	[3.85]
Finite loading: optimization					-.18 (.37)	-.30 (.26)	.56‡ (.28)	[3.85]
Fitting method & process						.86* (.12)		
Unfitting method & process							-.86* (.13)	[1.59]
Adjusted R^2	*.42*	*.42*	*.44*	*.52*	*.49*	*.74*	*.74*	
F for ΔR^2	*8.6**	*1.0*	*1.4*	*9.6**	*.3*	*46.6**	*46.6**	

Dependent variable: *delivery performance*. ‡ $p < .10$; † $p < .05$; * $p < .01$
Regression coefficients are unstandardized. Standard errors are shown in the parentheses.
Coefficients of the supply chain dummy variables are omitted to save space.
VIF statistics are shown only for the last step because they get their highest values at that point.
Job shops serve as the baseline of the process types. The non-systematic planning is the baseline of the planning methods.

When the unfitting side of the congruence term is used in Step 6b, the coefficients show the positive effects of using the methods in the right environments. The congruence term has a significant effect and it explains a considerable portion of variance in performance, so the results give fairly strong support to *Hypothesis 4b*. As all methods' coefficients are significant or at least approach significance in Step 6b, the contingency proposition appears to hold for all of the methods.

Figure 9 provides an illustration of the effect sizes.* In appropriate environments, all systematic planning methods deliver a performance advantage of approximately ten percent from the total variance in delivery performance. As the effects fall within the confidence intervals of each other, it can be concluded that *Hypothesis 4a* does not hold even when the techniques are used in fitting contexts. Similarly, as none of the negative effects is significantly different from zero, it seems that all methods are equally bad if they are applied with wrong kinds of processes.

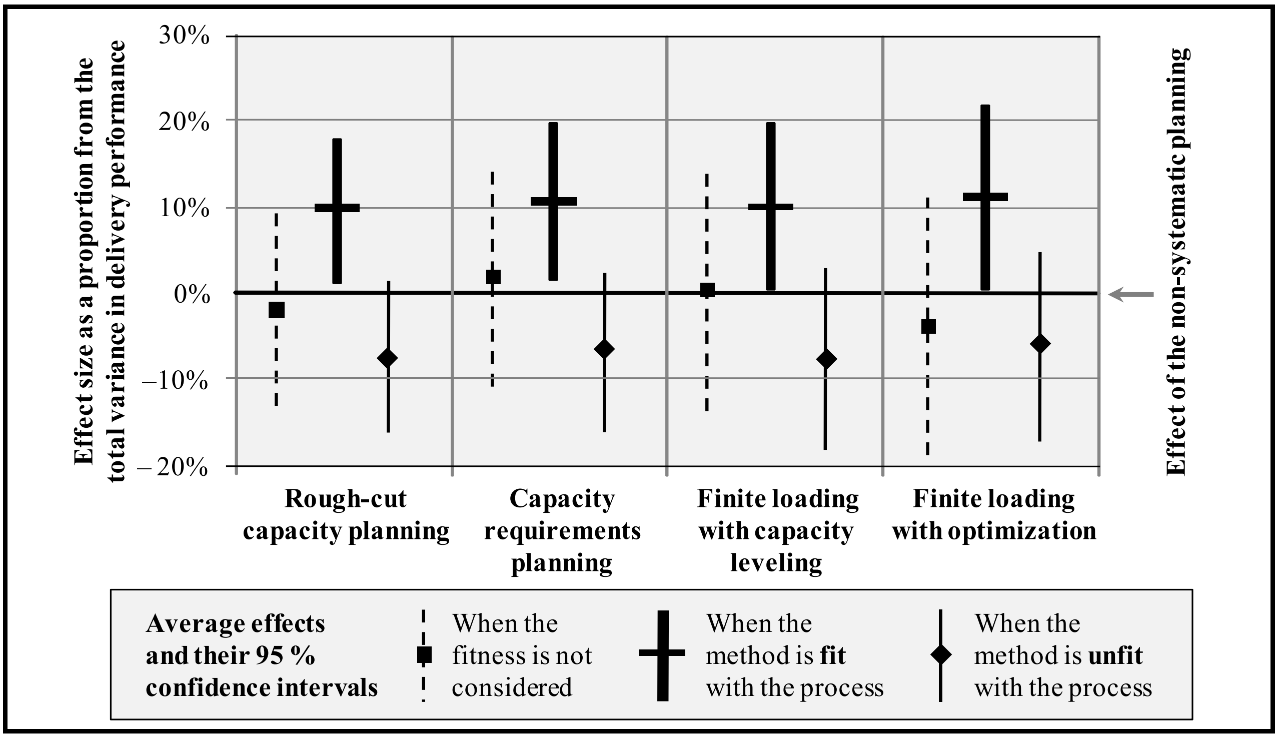


Figure 9: Relative performance effects of the different planning methods

* The effect sizes are estimated as follows: when the method is fit with the process type, the coefficients (and the confidence intervals) of the method and its fitting process type are taken from Step 6b and their sum is proportioned to the explained variance of the model. When the method is unfit with the process type, the coefficient of the method and the average of the "wrong" process types' coefficients are taken from Step 6a and proportioned. When the fitness is not considered, only the method coefficients from Step 5 are used. The coefficient of the congruence term is not used in the estimation of the effect sizes. Its role is only to control for the fitness.

6.6 RESULTS FROM THE INTERVIEWS

One important observation from the statistics is the wide utilization of the non-systematic and unfit planning methods. The question of how practitioners end up with their planning methods was addressed in the interviews. The most illustrative quotations are presented in Table 26. The interviewees' opinions had considerable similarities: for example, those planners, who used non-systematic methods or RCCP in unfit contexts, shared a feeling that the more detailed techniques would be overwhelmingly complicated. Meanwhile, the planners who used RCCP in fitting contexts explained that "fancier" techniques would probably exist but they had not explored them because they were satisfied with the outcomes of their current practices.

Table 26: Rationales for selecting planning methods

	Job shop	**Batch process**	**Bottleneck controlled batch process or production line**
Non-systematic capacity planning	$n_1 = 3$; $n_2 = 1$ "Formal planning methods are not worth the trouble"	$n_1 = 3$; $n_2 = 3$ "We have had bad experiences from systematic techniques" "Our trials with planning tools have failed"	$n_1 = 14$; $n_2 = 2$ "We do not use any planning software because they would only make things complicated"
Rough-cut capacity planning (RCCP)	$n_1 = 12$; $n_2 = 2$ (Fit) "This is sufficiently robust method for our needs" "Fancier solutions probably exist but we do not need them"	$n_1 = 9$; $n_2 = 2$ "More detailed methods could be beneficial but they tend to incur more work and make things difficult"	$n_1 = 5$; $n_2 = 1$ "The advantage of a simple method is that everyone can understand how the plans are derived"
Capacity requirements planning (CRP)	$n_1 = 5$; $n_2 = 2$ "We have done capacity planning in this way since the implementation of our ERP system"	$n_1 = 10$; $n_2 = 2$ (Fit) "This is how capacity planning is done in our ERP system"	$n_1 = 3$; $n_2 = 1$ "This is the only way to do capacity checks in our ERP system"
Finite loading with capacity leveling or optimization	$n_1 = 7$; $n_2 = 1$ "We implemented this software because it was recommended by our consultants"	$n_1 = 2$; $n_2 = 1$ "This software is used for the planning of all processes in our plant"	$n_1 = 16$; $n_2 = 3$ (Fit) "This tool was implemented because the ERP system required too much manual work" "This tool is needed to ensure the feasibility of our plans"

n_1 is the frequency in the survey (total = 89); n_2 is the frequency in the interviews (total = 21)

In both the fitting and unfitting contexts, the rationale for using CRP was that it was part of the companies' ERP systems. None of the interviewees knew whether their ERP systems featured any alternative methods. In the cases, where CRP should not have been used, the planners blamed the unreliability of their plans on the poor usability of their ERP systems. However, even those planners who used CRP in the right contexts told that capacity planning was a particularly challenging part of their work. This notion is aligned with the earlier discussions about the batch shop being the most complex process type when it comes to capacity planning.

The most typical reason to adopt finite loading methods seemed to be that someone in the organization had come across a convincing software tool. In the situations where the method was too detailed for the process, the users admitted the existence of problems but attributed them to the incorrect use of the software. The method's contextual unsuitability was not considered.

6.7 DISCUSSION

6.7.1 Organization-Theoretical Perspectives to Capacity Planning

The results indicate that there is time and place for such "imprecise" planning methods as RCCP and CRP whose widespread utilization has been wondered in the academia (Halsall et al., 1994; Jonsson and Mattsson, 2003). It seems that if the finite loading techniques are used in job shops, they encourage making tight schedules for processes that are not sufficiently stable for them. The job-shop process design is based on preferring flexibility to efficiency (Hayes and Wheelwright, 1979a; Safizadeh et al., 1996). Hence computerized capacity leveling or optimization, which specifically aims for efficiency, is out of place in those environments. In the terminology of contingency theory, the resources of job shops are said to be *pooled* (Thompson, 1967). If the resources are by definition *aggregated*, then it is not surprising that the planners, who use *detailed* techniques, complain that their plans are not robust enough, as observed by Wiers (1997).

In the batch processes, the challenge of the detailed planning is the "shifting bottlenecks" (Monahan and Smunt, 1999). The finite loading techniques do not seem to work despite that researchers and software providers have developed algorithms to tackle the problem (e.g., Kouvelis et al., 2005; SAP, 2009d). Yet, instead of blaming the tools or their users, it can be asked whether the failures could have more fundamental causes. A contingency-theoretical explanation is that the planning itself becomes a less effective coordination mechanism in the reciprocal processes of batch shops (Galbraith, 1973; Tushman and Nadler, 1978; Barki and Pinsonneault, 2005). Thus, instead of striving for more detailed *planning*, the managers of batch shops would be better off by investing in capabilities to solve exceptions in the *execution* of the plans (Perrow, 1967; Reeves and Turner, 1972). These exception processing capabilities will be the subject of the next chapter.

The finite loading techniques work in bottleneck-controlled batch shops and production lines because the complexity of those processes is reduced by the fact that the tasks to be planned are *sequentially* interdependent (Thompson, 1967). The iteration of plans is simple because changes in the schedule of one resource only influence the resources in the downstream of the process.

In addition to contingency theory, the limited applicability of the advanced planning methods is also aligned with the concept of *bounded rationality* (March and Simon, 1958). It holds that in the complex reality of organizations, it is usually sufficient to satisfy some level of performance instead of trying to optimize the outcomes, which is only possible in special occasions (Simon, 1978). In capacity planning, the special occasions take place when scheduling problems can be narrowed down to fairly static formulae, status information from the processes is complete, and the processes can be isolated from external uncertainties. Such conditions hold badly in typical job shops and batch processes (Reeves and Turner, 1972). In most cases, the scheduling problems depend on what products are loaded onto the processes, the real-time collection of precise status information is not economically viable, and the processes cannot be completely sealed from their environments.

In summary, several classic organization-theoretical concepts give reasons to suspect the universal applicability, let alone superiority, of the most sophisticated capacity planning methods. Yet, practitioners appear to be uninformed about the importance of matching planning methods with their processes. In addition, it seems that the issue is not discussed in the existing literature either. Therefore, the results of this analysis elaborate the benefits of taking theoretical perspectives to operations management topics, which have been traditionally viewed from a problem-solving perspective (see, Schroeder, 2008). Specifically, the findings demonstrate the practical utility of contingency theory (see, Sousa and Voss, 2008).

6.7.2 Practical Implications

The findings have several practical implications: first, most practitioners seemed to be unaware of the various alternative methods in capacity planning and the limitations of their applicability. As the unsuitable methods turned out to be very common, it can be proposed that exploring the options would be beneficial for many organizations. Second, if a planning tool does not appear to work, then the culprit is not necessarily the software or its users. Instead, the entire method may be unfit for the process. Third, although ERP systems provide fine tools for CRP (e.g., McKay and Wiers, 2004), it does not mean that CRP would be the "best practice" for everyone. The users of ERP systems should consider whether to use CRP or not. In job shops, it is sufficient to use rough-cut methods, which are usually also featured in ERP systems (e.g., SAP, 2009a). However, users may not be aware of them because they may be less promoted due to their rudimentary image. On the other hand, if the production process is sequential, then the finite loading techniques are more suitable and the organization should consider an investment in some add-on software.

Also it should be noticed that in those plants where different kinds of production processes coexist, it is detrimental to try and use the same capacity planning method for all processes. Instead, each process should use its own method. Fortunately, contemporary enterprise systems typically enable simultaneous use of different methods so that job-shop processes can be run with rough-cut methods, the use of CRP can be limited to batch-shop processes, and production lines can use separate add-on finite loading software.

Overall, the findings indicate that there is still work to be done with such seemingly mature topics as capacity planning. An important lesson lies in the fact that the users of non-systematic techniques presumed successful capacity planning to be something very difficult. Such presumptions imply that if the most sophisticated planning methods are overly emphasized in management education, then some practitioners may be alienated from making a serious attempt with any method. Such an outcome is not acceptable even if the most sophisticated methods were beneficial in some environments. Hence, the outcome of this analysis joins the calls for more pragmatic research in operations management (Guide and Van Wassenhove, 2007; Hopp et al., 2007). A pragmatic approach to the research on production planning would acknowledge that a single method or practice can seldom prevail in all environments. It would also acknowledge that optimization is not always desirable in the real-world planning situations. Wider adoption of organization-theoretical concepts, such as contingency effects and bounded rationality, on the technical level of everyday operations management could be helpful in developing the more pragmatic discipline.

6.7.3 Further Research

One important limitation in the presented analysis is the reliance on delivery performance. It may have understated the contributions of *optimization* tools because they can be used to minimize costs instead of maximizing schedule adherence (Stadtler and Kilger, 2005). Hence, the job shops and the batch processes, whose delivery performance had suffered from the finite loading, may have benefited in terms of reduced costs. That possibility is left as a topic of further research because it would necessitate a different research design. It is unlikely that the possible advantages in cost efficiency could be measured in a typical cross-sectional survey, where respondents are asked to evaluate their material and labor costs relative to their competitors (e.g., Swink and Nair, 2007). The possible benefits occur more likely as increased productivity, which is an internal measure and therefore difficult to evaluate in comparison to competitors. Hence, a more appropriate research design would be based on a longitudinal study on an implementation of a finite loading tool.

6.8 RECAPITULATION

This chapter presented a *contingency theory of capacity planning* which proposes that the complexity of process types determines the applicability of different capacity planning methods. As illustrated in Figure 7, the theory proposes that there are two possible ways to misalign planning methods with process types: the methods can be either too simple or too sophisticated. The theory is offered as a new answer to the question of why so many practitioners use less sophisticated planning methods than what is discussed in the literature (Jonsson and Mattsson, 2003; McKay et al., 2002). As the results indicate that the less sophisticated methods are more effective in some processes, it is not appropriate to attribute the gap to practitioners' lack of mathematical skills or insufficient training (Hopp et al., 2007).

7 CONTINGENCY THEORY OF EXCEPTION PROCESSING

This chapter presents the analysis of Research Question 2c on how the sources and nature of uncertainty influences the effectiveness of different exception processing routines. The first premise of this chapter is that exceptions, that is, changes in production plans, occur because of glitches that can originate from suppliers, internal operations, or customers. The second premise is that the exceptions are processed in communication channels that can be informal, formal-interpersonal, or formal-automated. I first explain how the equivocality and urgency of the exceptions depend on the sources of the uncertainty. Then, I develop contingency-theoretical hypotheses on how the effectiveness of different communication channels—and thus exception processing routines—depend on whether the exceptions are equivocal or urgent. Lastly, I test the hypotheses with the survey dataset and discuss the results in light of the interviews and different theoretical frameworks.

7.1 INTRODUCTION

Research on supply chain glitches has demonstrated how deviations from the planned flow of materials, such as material and capacity shortages, can cause problematic cascading effects in manufacturing processes and firm performance. For example, suppliers' failures to deliver raw materials can prevent the planned execution of the buying firm's operations (e.g., Craighead et al., 2007; Sheffi and Rice, 2005) and eventually impact its reliability and financial performance (Hendricks and Singhal, 2003; 2005a). Glitches originating from the internal operations of a manufacturing organization can create external failures that tarnish the firm's reputation and brand equity (Dawar and Pillutla, 2000). Also, customers can generate glitches that disrupt the reliability of manufacturing firms—as highlighted, for example, by the literature on the bullwhip effect (Lee et al., 1997; Cachon et al., 2007).

The literature on supply chain glitches has mostly focused on how to remove or alleviate the root causes of glitches. For example, manufacturers can reduce supplier-originated glitches by initiating collaborative just-in-time delivery agreements with their suppliers (Krajewski et al., 2005). Manufacturers' internal glitches can be reduced with investments in quality improvement programs (e.g., Deming, 1986; Yeung et al., 2006; Zu et al., 2008). Glitches generated by customers, such as unexpected changes in requested delivery dates or quantities of ordered items

(Hendricks and Singhal, 2003; 2005a) can be reduced by investing in the effective gathering and sharing of demand information (Frohlich and Westbrook, 2002; Småros, 2007).

Although the reduction of glitches and the elimination of their sources are certainly desirable objectives, they are not sufficient. Much as preventive maintenance cannot fully replace reactive maintenance, the adverse effects of glitches cannot be totally eliminated by addressing their typical causes (Zsidisin et al., 2005). There are so many sources of variability within organizations that there will always be something that does not happen according to plan. Moreover, the pressure to cut slack in operations and the vertical disintegration of supply chains make business organizations increasingly vulnerable to glitches, as they effectively reduce the chances to buffer and control the sources of uncertainty (Sheffi and Rice, 2005; Jacobides, 2005). Therefore, glitches have to be considered as a sort of *routine non-conformity* (Vaughan, 1999) that requires organizations to develop adequate mitigation capabilities (Craighead et al., 2007).

Despite the general agreement on the fact that glitch mitigation capabilities require significant amounts of coordination across the different functions of business organizations (Zsidisin et al., 2005; Craighead et al., 2007), the literature is silent relative to which coordination mechanisms a company should adopt to facilitate appropriate cross-functional coordination and decision-making when supply chain glitches occur. For example, how much centralization or improvisation is needed for the coordination mechanism to be effective? How much formality or informality is needed when the glitches are communicated within an organization? What is the role of information systems in the mitigation of glitches? Thus far, all of these questions have remained largely unanswered.

Starting from these premises, this chapter presents a theoretical and empirical investigation of how different cross-functional coordination mechanisms and communication channels influence organizations' glitch mitigation capabilities. More specifically, I develop a theoretical framework for how different coordination mechanisms (i.e., mutual adjustment and centralized decision-making) are related to different communication channels (i.e., telephone calls, emails, formal review meetings, and enterprise systems). I theorize how the appropriateness of these coordination mechanisms and communication channels depend on the nature and the source of the glitch. I will propose that the alignment between communication channels and the sources of glitches has a significant impact on organizations' capability to overcome glitches. I will justify the propositions by combining capacity management reasoning, which is typical of operations management literature, with contingency theory and especially Daft and Lengel's (1986) media richness theory and Argote's (1982) input uncertainty theory.

7.2 THEORY DEVELOPMENT

Supply chain *glitches* are defined as events that disturb the planned flow of materials within a supply chain (Craighead et al., 2007; Hendricks and Singhal, 2003; Kleindorfer and Saad, 2005). According to the quality management literature and socio-technical systems theory, supply chain glitches should be tentatively addressed as near as possible to their point of origin, that is, locally and at the lowest possible level of the organizational hierarchy (Cherns, 1976; Manz and Stewart, 1997; Waldman, 1994). However, a local solution may not be always possible—for example, if the disruption has immediate implications for other business functions or if the expertise that is required to address it is not available locally. In order to prevent an interruption in the flow of materials, these disruptions, or glitches, have to be communicated as *exception messages* to the decision-makers who operate in other functions and/or at the higher hierarchical levels (Carroll et al., 2006; Vollmann et al., 2005).

The exception messages trigger an *exception processing routine* in which the decision-makers from different functions search for a solution that will mitigate the effects of the glitch. The successful execution of the exception processing routine necessitates effective cross-functional communication channels, because different decision-makers may have to recognize mutual constraints and available courses of action in order to arrive to the best possible solution. These communication channels may take various different forms: the decision-makers may communicate informally over telephone or via email, or communication may take place during regular cross-functional meetings. The communication channels can also be highly automated. For example, the constraints and the preferred courses of action can be codified in an information system that can then be used to revise plans and transmit the new plans to all relevant functions (e.g., production, purchasing, logistics, and sales).

Ideally, the exception processing routines should result in revised plans that do not imply any changes in the timing of the organization's deliveries to its customers, thus constraining the changes within the process in which the glitch originally occurred. Therefore, the goal of the exception processing routines is to protect *organizational reliability*. One measurable aspect of organizational reliability is the ability of the organization to comply with its delivery commitments to customers, that is, to maintain high delivery performance.

The goal of maintaining high delivery performance regardless of glitches can be pursued by utilizing all available sources of flexibility, including slack resources, extra shifts, overtime work, rush orders to subcontractors, and so forth. However, exception processing routines are necessary to inform decision makers when and where the flexibilities must be utilized.

My central argument is that a key aspect of the design of effective exception processing routines exists in the selection of the communication channels that are used to transmit information about glitch occurrences and the solutions to them. Without appropriate communication channels, structural flexibility cannot be used effectively because the decision-makers do not receive sufficiently timely and precise information about the glitches, nor are they able to pass their solutions and revised plans back to where the processes are executed. The theoretical endeavor is therefore to explain how organizational reliability can be supported by different communication channels under different contingencies.

7.2.1 Formal versus Informal Communication Channels

Decision-makers have different alternatives when it comes to communicating and coordinating their responses to supply chain glitches. The simplest approach is not to invest in any formal communication channels and let the decision-makers coordinate their responses over the telephone or via email. It is known that innovative solutions may often emerge from the use of such informal communication channels (Majchrzak et al., 2007). Alternatively, the task of addressing supply chain glitches can be executed by means of formal cross-functional review meetings, in which teams of decision-makers periodically meet to examine the glitches encountered in organization's processes and agree upon the responses according to a proceduralized approach. Examples of such procedures are the configuration management meetings that are discussed in the project management literature (Guess, 2002; PMI, 2006).

The formalization of communications can also be pushed further by putting the management of the exception processing routines into enterprise information systems such as the ERP software (Davenport, 2000; Vollmann et al., 2005). In this case, the production planner would be first notified of the glitch through a standard exception message (e.g., incomplete receipt of a purchase order, delayed confirmation of a shop order, or a requested change to customer's order). Then, based on this information, the planner would produce a new delivery plan and the ERP system would generate new exception messages for the appropriate decision-makers in other business functions (e.g., logistics, sales, purchasing, etc.), promptly signaling the new plans and the needed adjustments.

It is reasonable to expect that any company would rely to some extent on informal communication channels: people naturally send emails or call other people when they encounter unexpected events in their work. Such informal channels have the great benefit of being very easy to implement and maintain (Kraut et al., 1999; Majchrzak et al., 2007). Another important benefit of informal channels is that they enable communication on a wide variety of issues (Hage et al., 1971; Tushman, 1979).

Yet, contingency theory informs us that informal means of communication and coordination are particularly appropriate in events that happen very rarely and unpredictably (Argote, 1982; Gittell, 2002). This is not the case with supply chain glitches, which can be characterized as recurring facts of the day-to-day operations of manufacturing enterprises (e.g., Hendricks and Singhal, 2003; 2005a). The recurrence of supply chain glitches means that they are best communicated through formalized channels for at least three reasons. First, repetition gives organizations an opportunity to learn how to address the glitches and to codify the learning into programmed, systematic and therefore *formalized* coordination and communication mechanisms (Argote, 1982). Second, standard communication protocols and syntaxes, which are central to formalized communication and coordination, reduce any room for misunderstandings and prevent messages from being corrupted during the communication processes (Galbraith, 1973; Tushman and Nadler, 1978). Third, formal communication protocols make people unambiguously responsible for communicating certain predefined issues whenever they occur, thus ensuring that glitch-related information is always relayed in a timely manner (Bigley and Roberts, 2001; Roberts et al., 1994). Consequently, the following hypothesis can be proposed:

> *H5: Exception processing routines that are based on formal communication channels mitigate supply chain glitches' effects on delivery performance more effectively than do exception processing routines that are solely based on informal communication channels.*

7.2.2 Automated versus Interpersonal Formal Communication Channels

Once it is postulated that formal communication channels should be more effective in dealing with supply chain glitches, the next question is whether organizations should adopt formal channels that personally connect the various functional decision-makers (e.g., cross-functional review meetings) or whether they should pursue automation and manage the communications within their ERP systems. These two kinds of communication channels enable different cross-functional coordination mechanisms. The cross-functional review meetings support *coordination by mutual adjustment* (Thompson, 1967; Van de Ven et al., 1976), which is the kind of coordination that relies heavily on feedback and consensus building among the decision-makers. On the other hand, when the communication channel is managed within an ERP system and the exchange of information is manifested as unidirectional exception messages, then *coordination through centralized decision making* (Galbraith, 1973; Thompson, 1967) takes place.

According to sociological theory, coordination by means of centralized decision-making is appropriate when the speed of decision-making is critical and the threat is "known or repeated in nature […so that…] a well-learned response is likely to be correct" (Staw et al., 1981, p. 517). In fact, the pressure for speed is known to create a mechanistic shift towards the centralization of decision-making. That is because centralization helps in economizing information processing functions (Scott, 2003), reducing the slowness that can be caused by political activity (Bourgeois and Eisenhardt, 1988; Baum and Wally, 2003) and recalling well-learned or salient behavioral responses in a timely fashion (Staw et al., 1981).

On the other hand, contingency theory, and specifically *media richness theory* (Daft and Lengel, 1986; Daft et al., 1987), postulate that cross-functional coordination should take place by means of communication channels that enable rich, face-to-face interaction between decision-makers when the organizational task is affected by *equivocality*. Equivocality refers to "the existence of multiple and conflicting interpretations of an organizational situation," and addressing it mandates "the exchange of existing views among managers to define problems and resolve conflicts" by means of mutual feedback (Daft and Lengel, 1986, p. 556-557). Naturally, both formal and informal communication can be rich and therefore adequate for situations with high task equivocality, but because of Hypothesis 5, I will hereafter consider only formal communication channels.

Consequently, it can be argued that urgency and equivocality of the supply chain glitch determine the appropriate cross-functional coordination mechanism and therefore the appropriate communication channel. Urgent exception messages are best transmitted through automated communication channels (e.g., within an ERP system), while equivocal exception messages call for formal interpersonal communication channels (e.g., cross-functional review meetings). I argue that supply chain glitches originating from different sources vary in their degree of urgency and equivocality, and thus the sources determine the most effective communication channels.

7.2.3 Supplier Glitches

Supplier-generated glitches refer to situations where a manufacturer does not receive necessary raw materials when they have been promised by its suppliers. The nature of these glitches is *unequivocal*; the materials are evidently unavailable and there is no doubt that the operational plans cannot be executed as originally intended. The task of the production planners is *urgent*: the lack of materials creates idle capacity, which generates costs unless it is put to use by bringing forward some shop orders for materials that are available. Besides efficiency, the urgent reallocation of capacity also benefits reliability. That is because the orders that have been brought forward free up capacity for the execution of the delayed orders at a later point in time, when the supplier has finally completed its delivery. Further delays are therefore less likely to happen if the capacity swapping is executed swiftly. High urgency and low equivocality call for centralized decision-making, which is best supported by the formal automated communication channels that are embedded in the ERP systems. I therefore hypothesize as follows:

> *H6: The impact of supplier glitches on delivery performance is best mitigated by exception processing routines that rely on formal automated communication channels.*

There are limits to the capacity of internal exception processing routines to mitigate supply glitches, for example, when a supplier glitch involves materials that are required by all shop orders. However, manufacturers tend to protect themselves from such large-scale glitches by holding inventory buffers of most common materials. Should the buffers be insufficient, no intra-organizational exception processing routines can help. Instead, the manufacturer must take inter-organizational actions that fall outside the scope of this dissertation. Such actions include the activation of an emergency supply source (Tomlin, 2006) or the exertion of market power vis-à-vis the supplier to contain the magnitude of the glitch.

7.2.4 Customer Glitches

Customer glitches occur when customers request changes to their orders (e.g., delivery dates, items, accessories, configurations, etc.). Customer glitches are different from supplier glitches, because they are not similarly unavoidable. Instead, the manufacturer may turn down the change request or suggest a compromise that is not exactly what the customer originally asked but that still satisfies the changed needs of the customer. In other words, customer glitches are subject to *equivocality*. The essence of the equivocality originates from the fact that the customers are seldom aware of their requests' exact implications for the prices or delivery dates of their orders. Sometimes, requests may be outright impossible to fulfill due to some technical or economic constraints. In some other cases, requests may be very costly or difficult to execute as such but much cheaper or easier with minor modifications. In order to find out the constraints and come up with the most feasible solutions, the sales staff needs to iterate customers' requests to various internal functions (e.g., manufacturing, engineering, purchasing, etc.). This interactive, cross-functional exception processing routine typifies coordination by mutual adjustment—which, as argued before, is best supported by formal channels that ensure face-to-face communication (Argote, 1982; Daft and Lengel, 1986), such as cross-functional review meetings (Guess, 2002; PMI, 2006).

Customer glitches also differ from supplier glitches in the sense that they are less *urgent*. It is the customer, not the manufacturer, who deviates from a contractual agreement, and thus, the manufacturer has the right to make the necessary feasibility checks before committing to the requested changes. Customers typically accept the fact that the process may take some time because it would not be in their interests, either, if manufacturers approved their requests as such but then failed to deliver. In summary, the high equivocality and moderate urgency of customer glitches call for exception processing routines that rely on formal interpersonal communication channels. Therefore, I formulate the following hypothesis:

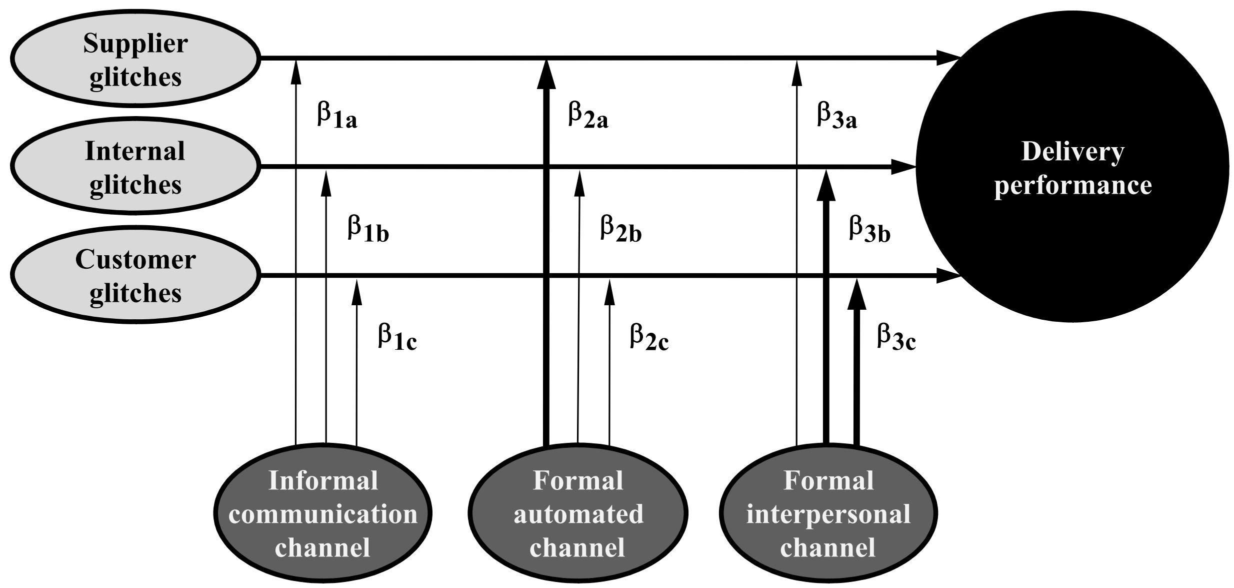
H7: The impact of customer glitches on delivery performance is best mitigated by exception processing routines that rely on formal interpersonal communication channels.

7.2.5 Internal Glitches

Internal glitches refer to situations where the manufacturer's internal operations are not executed as planned. Regardless of the glitch's cause (e.g., scrap, poor quality, machine breakdowns, etc.), its outcome constitutes an unexpected capacity requirement. At first, addressing internal glitches appears to be an *urgent* task in the same way, as it is with supplier glitches; any time wasted on deciding how to address the glitch reduces the degrees of freedom in how the plans can be revised. Yet, unlike the supplier glitches, which translate quite unavoidably into delays, the internal glitches can be addressed in many different ways. The propagation of the glitch can be stopped by allocating slack capacity to the affected order or by arranging extra shifts or allocating overtime workers to solve the problem. The availability of multiple solutions makes the task of addressing internal glitches less urgent but also more equivocal. That is because the availability and the costs of utilizing different buffers and flexibilities may vary case by case. Furthermore, the buffers and flexibilities are likely located in several different functions, and thus their availability and costs must be verified by different sources. The process of identifying, comparing, and deciding upon the most suitable solutions in a given situation therefore takes an iterative form similar to that used in the processing of customers' change requests. Lesser urgency and the higher equivocality make the centralized decision-making and automated communication channels less suitable for the task. I therefore offer the following proposition:

> *H8: The impact of internal glitches on delivery performance is best mitigated by exception processing routines that rely on formal interpersonal communication channels.*

Figure 10 illustrates the proposed contingency theory on the effectiveness of different communication channels in the mitigation of supply chain glitches.



Hypothesis 5: $\beta_{1a} < (\beta_{2a} \vee \beta_{3a}) \wedge \beta_{1b} < (\beta_{2b} \vee \beta_{3b}) \wedge \beta_{1c} < (\beta_{2c} \vee \beta_{3c})$

Hypothesis 6: $\beta_{2a} > \beta_{3a}$

Hypothesis 7: $\beta_{2c} < \beta_{3c}$

Hypothesis 8: $\beta_{2b} < \beta_{3b}$

Figure 10: Hypothesized contingency effects of different communication channels

7.3 MEASURES

7.3.1 Supply Chain Glitches

The sources of supply chain glitches were operationalized with three composite variables, each computed by averaging three reflective indicators. The operationalization and the results of its confirmatory factor analysis are presented in Table 27. First, the convergent validity is satisfactory because all items load significantly to their hypothesized latent variables and because their standardized loadings are relatively high. Second, the composite reliability indices indicate no problems with the reliability of the measurement. Third, the discriminant validity between the studied constructs is supported because each variable's AVE index is considerably greater than the highest squared correlation between the variables (Fornell and Larcker, 1981). Fourth, the overall fitness of the hypothesized structures is supported in the sense that the fit indices pass the most commonly used threshold values (Hair et al., 2006).

Table 27: Confirmatory factor analysis of supply chain glitch measures

"How often orders' execution needs to be changed due to…" ***1: very seldom, 2: quite seldom, 3: sometimes, 4: quite often, 5: very often***	***Standardized item loading***
Supplier glitches (composite reliability = .82, average variance extracted = .61)	
"…delayed raw material shipments"	.80**
"…incomplete raw material shipments"	.80**
"…poor quality of raw materials"	.74**
Internal glitches (composite reliability = .84, average variance extracted = .64)	
"…unexpected lack of capacity (e.g., machine breakdowns or employee absence)"	.79**
"…uneven utilization of resources (e.g., work centers or employee competences)"	.83**
"…quality problems of own operations (e.g., scrap and rework)"	.77**
Customer glitches (composite reliability = .90, average variance extracted = .75)	
"…change orders for the required products (e.g., end-product types or required quantities)"	.98**
"…changes orders for the required delivery dates"	.82**
"…change orders for the detailed contents of requirements (e.g., specifications or designs)"	.79**
χ^2 = 41.09, degrees of freedom = 25, χ^2/d.f. = 1.64, CFI = .973, NFI = .935, RMSEA = .063 Cov(supplier glitches—internal glitches) = .19†; Cov(customer glitches—internal glitches) = .13	** $p < .001$ † $p < .05$

7.3.2 Moderating Variables

The variables for the different cross-functional communication channels are conceptually different from the variables for the sources of the glitches. The latter can be considered as latent variables that can only be measured through their reflections: that is, the frequencies of their occurrences. Meanwhile, the use of any communication channel can be considered as a directly observable attribute and thus it can be operationalized as a formative index (Bollen and Lennox, 1991). The indices that were selected to represent the variables are presented in Table 28. Each index consisted of five dichotomous items that are shown in the columns of the table. The indices were measured as the sums of the columns, and thus, they all had a range from zero to five. The descriptive statistics and inter-correlations of all questionnaire items are shown in Table 29.

Table 28: Questions and constructs for the communication channels

"How do you communicate changes in delivery plans with regard to..." [Check the closest alternative. Multiple choices are allowed.]	***in telephone***	***via email***	***in cross-functional review meetings***	***within ERP system***
"…items (e.g., product types or quantities)?"	☐	☐	☐	☐
"…delivery dates?"	☐	☐	☐	☐
"…configurations (e.g., accessories, colors, etc.)?"	☐	☐	☐	☐
"…designs (e.g., technical details or drawings)?"	☐	☐	☐	☐
"…costs or invoice values?"	☐	☐	☐	☐
Column sums constitute formative indicators of:	Informal communication channels		Formal interpersonal	Formal automated

7.3.3 Control Variables

Similarly as in the earlier chapter, the average performance levels of the seven different supply chains were controlled with six dichotomous dummy variables. Also similarly as before, I controlled for the organization's size and products' complexity. In addition, I controlled for the management's emphasis on the flexibility of operations (as a five-point Likert scale from very little to very high), which served as a proxy for the capability of the production process to contain the effects of the supply chain glitches. Table 30 shows the descriptive statistics and the inter-correlation matrix of all continuous variables.

7.4 SURVEY RESULTS

The hypotheses were tested with a hierarchical regression analysis. The control variables, the main effects of the theoretical variables, and the interaction terms were entered in separate steps as shown in Table 31.[*] The variables of the interaction terms were mean-centered to avoid multi-

[*] The table shows the use of emails as the variable for the informal channel because the variable for the use of the telephone loaded so poorly. However, the results would not have been any different even if I had used the telephone variable, both variables separately, or a composite of the two.

Table 29: Descriptive statistics and inter-correlations of all questionnaire items

Variable	μ	σ	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 Delivery performance 1	3.01	.86															
2 Delivery performance 2	3.08	.92	.71*														
3 Delivery performance 3	2.87	.88	.65*	.61*													
4 Supplier glitches 1	3.37	.92	-.09	-.20†	-.09												
5 Supplier glitches 2	3.16	.97	-.04	-.11	-.17†	.65*											
6 Supplier glitches 3	2.57	1.04	-.13	-.15	-.20†	.61*	.61*										
7 Internal glitches 1	3.01	1.11	-.16	-.12	-.21†	-.10	.09	-.01									
8 Internal glitches 2	3.22	1.20	-.10	-.04	-.23†	-.04	.16	.08	.62*								
9 Internal glitches 3	3.21	1.07	-.23*	-.25*	-.28*	.15	.22†	.24*	.58*	.59*							
10 Customer glitches 1	3.13	1.02	-.13	-.14	-.15	.00	.09	-.09	.18†	.06	.16						
11 Customer glitches 2	3.24	1.08	-.13	-.17†	-.18†	.09	.09	-.03	.22†	.16	.25*	.80*					
12 Customer glitches 3	3.22	1.05	-.09	-.08	-.08	.03	.05	-.04	.21†	.08	.08	.77*	.65*				
13 Telephone	1.71	1.79	-.10	-.08	-.02	.23*	.10	.03	.12	.20†	.08	.16†	.06	.07			
14 Emails	3.34	1.51	.00	.04	-.02	.13	.06	.06	.11	.08	.01	.01	.04	.00	.42*		
15 Review meetings	2.03	1.90	-.09	.07	.00	.13	.08	.18†	-.01	-.01	-.01	.08	.04	.14	.04	.12	
16 ERP system	1.49	1.39	.22*	.14	.22*	.03	-.02	-.02	-.12	-.09	-.12	.05	.04	.07	.02	-.09	-.01

† p < .05; * p < .01

Table 30: Descriptive statistics and inter-correlations of all variables

Variable	μ	σ	1	2	3	4	5	6	7	8	9
1 Organization's size +	134	178									
2 Proportion of non-MTO sales +	.31	.16	-.02								
3 Structural flexibility +	3.91	1.01	-.12	-.08							
4 Supplier glitches	3.05	.87	-.19†	-.24*	.03						
5 Internal glitches	3.26	1.03	-.15	-.11	-.10	.20†					
6 Customer glitches	3.20	.95	.13	-.19†	.07	.03	.14				
7 Informal channel	3.34	1.51	-.01	.06	-.04	.07	.09	.03			
8 Formal interpersonal channel	2.03	1.90	.23†	.00	-.08	.16†	.00	.10	.12		
9 Formal automated channel	1.49	1.39	-.03	.08	-.05	.01	-.11	.06	.09	-.01	
10 Delivery performance	2.99	.78	-.01	.12	-.09	-.13	-.22*	-.17†	.00	.02	.21*

+ Logarithmic transformations of the control variables are used in analyses but μ's and σ's are shown untransformed in order to ease interpretation. (Flexibility was reversed before transformation and then reversed back after the transformation.)

† p < .05; * p < .01

collinearity (Aiken and West, 1991). The results show the independent variables' unstandardized regression coefficients with their standard errors and the summary statistics of each step. VIF statistics are only shown for the last step, because that is where they get their highest values.

The first step shows that as in Chapters 5 and 6 the dummy variables for the average performance levels of the studied supply chains have considerable explanatory power. The second step of the analysis reveals that glitches have a significant main effect only when they are caused by suppliers. This supports the view that missing materials have a more immediate relationship with reliability than do internal glitches or customer glitches. Another finding is that both the formal interpersonal and the formal automated communication channels have non-hypothesized main effects on reliability.

The results of the third step are presented as three parallel models because that enables showing the explained variances separately for Hypotheses 6, 7, and 8.[*] Overall, the results indicate that the communication channels have a substantial impact on delivery performance. One of the moderating effects is significant with respect to every type of glitch, and the interaction terms explain the significant proportions of the variance in the dependent variable. Thus, the results lend support to the general statement of exception processing routines (and the associated commu-

[*] The regression coefficients would not have been substantially different even if the interaction terms had been entered in the equation together.

Table 31: Regression results

Variable	Step 1: Controls	Step 2: Main effects	Step 3a: Supplier glitches	Step 3b: Internal glitches	Step 3c: Customer glitches
Constant	2.36** (.35)	3.38** (.58)	3.09** (.52)	3.05** (.55)	3.39** (.55)
Control variables					
(Supply chain dummy variables)					
Organization's size	.06 (.06)	-.01 (.06)	.00 (.05) [1.49]	.06 (.05) [1.64]	-.01 (.05) [1.49]
Proportion of non-MTO sales	.24 (.15)	.18 (.14)	.11 (.13) [1.37]	.17 (.13) [1.35]	.20 (.13) [1.41]
Structural flexibility	-.01 (.15)	.07 (.14)	.04 (.13) [1.23]	.06 (.14) [1.25]	-.12 (.14) [1.37]
Main effects					
Supplier glitches		-.29** (.08)	-.17† (.08) [1.72]	-.26** (.08) [1.52]	-.20* (.08) [1.59]
Internal glitches		-.02 (.08)	-.07 (.07) [1.39]	-.02 (.07) [1.43]	-.07 (.07) [1.39]
Customer glitches		-.04 (.08)	.01 (.07) [1.43]	-.05 (.07) [1.37]	.02 (.07) [1.43]
Informal channel		.02 (.05)	.00 (.04) [1.19]	.04 (.05) [1.33]	.00 (.04) [1.20]
Formal interpersonal channel		.09† (.04)	.09* (.03) [1.25]	.07† (.04) [1.30]	.07† (.04) [1.30]
Formal automated channel		.12† (.05)	.12† (.05) [1.28]	.10† (.05) [1.28]	.12† (.05) [1.28]
Moderation effects					
Informal channel			-.02 (.05) [1.19]	.00 (.05) [1.41]	-.04 (.04) [1.35]
Formal interpersonal channel			.01 (.03) [1.18]	.13** (.04) [1.28]	.17** (.05) [1.45]
Formal automated channel			.25** (.05) [1.27]	.03 (.05) [1.23]	.06 (.05) [1.18]
$R^2 \mid \bar{R}^2$	$.34 \mid .27$	$.47 \mid .38$	$.59 \mid .50$	$.56 \mid .46$	$.56 \mid .47$
ΔR^2		*.13*	*.12*	*.09*	*.09*
F for ΔR^2		*3.72**	*8.26***	*5.48**	*5.81**

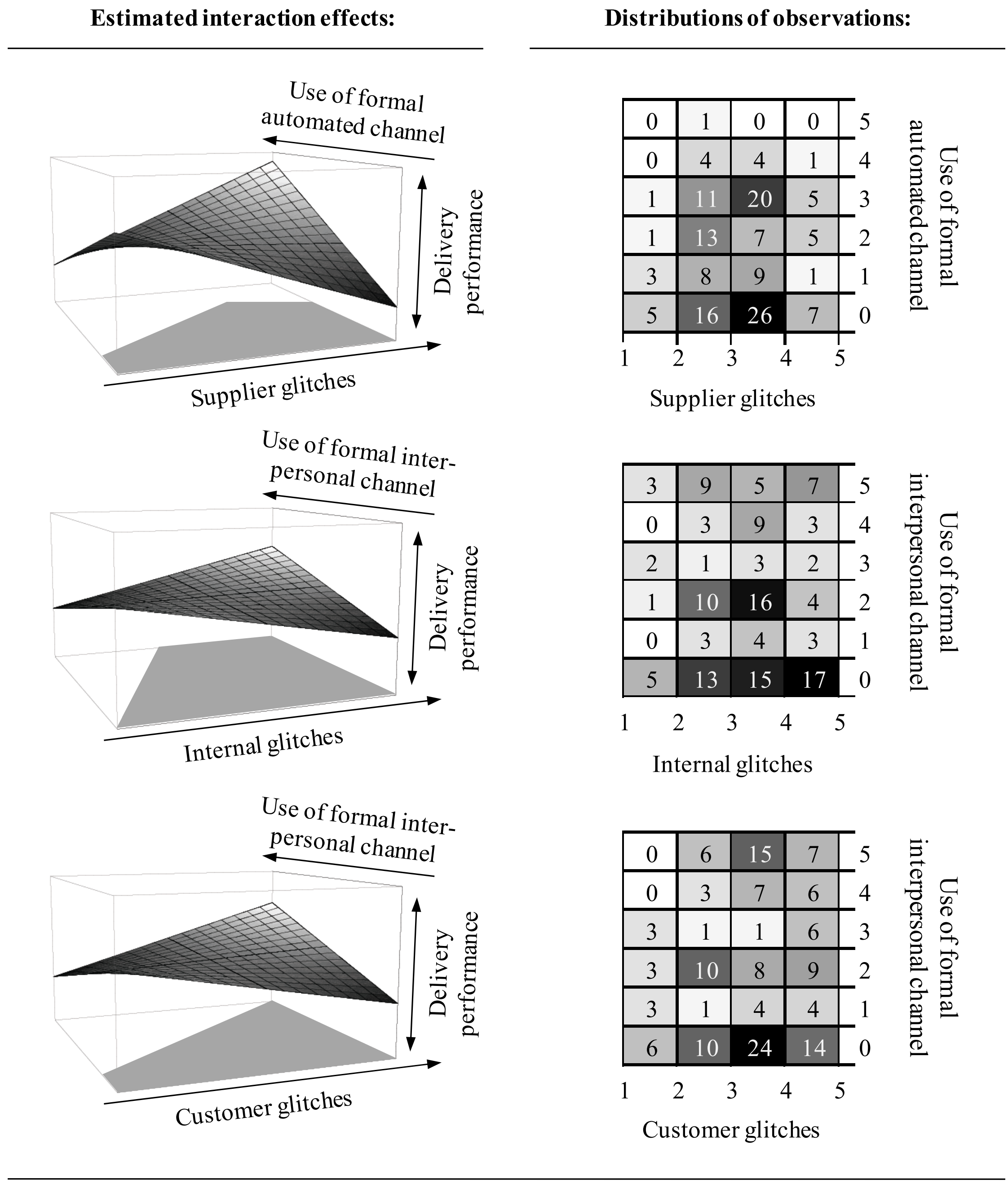
Dependent variable: *delivery performance* † p < .05; * p < .01; ** p < .001
Supply chain dummy variables' coefficients are omitted in order to save space.
Regression coefficients are unstandardized. Standard errors are shown in parentheses and VIF statistics in square brackets.

nication channels) being an important element of organizational glitch mitigation capabilities.

The results provide strong support for Hypothesis 5. Tentative evidence is the fact that either the formal automated channel or the formal interpersonal channel has a significant moderating effect on every type of glitch ($p < .001$), while none of the informal channels' interaction terms is significant. Moreover, the coefficients of the latter are negative. Nevertheless, this evidence is not conclusive, since the upper boundaries in the confidence intervals of the informal channel's interaction terms are above zero. Therefore, they may overlap with the confidence intervals of the formal channels' significant interaction terms, and thus, the statistical significance of the regression coefficients' differences must be estimated separately. It can be done in various ways, but calculating the differences' z-test statistics from the unstandardized coefficients and standard errors provides the most conservative estimates (Clogg et al., 1995; Paternoster et al., 1998). The calculations show that all differences are significant ($z = 3.87$, $p < .001$; $z = 2.30$, $p < .05$; $z = 3.31$, $p < .001$, for supplier, internal, and customer glitches, respectively).

The tests of the null hypotheses also support Hypotheses 6, 7, and 8, since only the proposed channels have significant moderating effects. The formal automated channel is a significant moderator of supplier glitches, while the formal interpersonal channel mitigates internal glitches and customer glitches. The comparison of regression coefficients provides strong support for Hypothesis 6, since the difference in favor of the formal automated channel is very large ($z = 3.82$, $p < .001$). When it comes to the internal and customer glitches, the differences are much smaller, and their z-test statistics are only approaching significance ($z = 1.65$, $p < .10$ for the interactions with internal glitches and $z = 1.68$, $p < .10$ for the interactions with the customer glitches).

In summary, it can be stated that the data provide good support for Hypotheses 5 and 6 and tentative support for Hypotheses 7 and 8. Figure 11 illustrates the interaction terms' effects on delivery performance. They show that the lack of main effects does not mean that the internal and customer glitches would not be detrimental if appropriate communication channels are not in place. The contour plots beside the graphs illustrate the boundaries in the empirical validity of the estimated effects. They indicate that inferences should only be made about the diagonals and the lower right-hand corners of the graphs. Situations where extensive glitch-related communications take place in the absence of glitches (i.e., the upper left-hand corners) are nearly or completely void of empirical observations. The fact that the analyses provide estimates for such situations is merely a result of the mathematical symmetry of the multiplicative interaction terms (e.g., Schoonhoven, 1981).



The shadows of the graphs illustrate the interaction effects' domains of empirical validity. The exact distributions of observations are shown in the contour plots on the right.

Figure 11: Illustrations of the significant interaction effects

Post-hoc analyses with a model where Steps 3a, 3b, and 3c are carried out simultaneously reveal that the combined direct and moderating effects of the formal automated channel explain eight percent of the total variance in delivery performance. Meanwhile, the combined effects of the formal interpersonal channel explain nine percent of the total variance.

7.5 RESULTS FROM THE INTERVIEWS

One interesting observation from the statistics is that the effective formal channels are much less used than the ineffective informal communication channels. To get a better understanding why individual production planners rely on different kinds of channels, I asked the interviewees about the reasons why they use the channels that they do and why they have not implemented any of the other alternatives. Table 32 summarizes the results of that inquiry. The table only includes arguments that were mentioned by at least two interviewees. However, the perceptions were generally so well shared that on average each argument was mentioned by at least six interviewees.

Table 32: Perceived advantages and disadvantages of different communication channels

Communication channel	Advantages	Disadvantages
Informal channel	**Costless:** infrastructures for email and phone calls exist in every firm	**Variable in timeliness:** people are not necessary available when needed
	Flexible: one can always contact the person who has the best expertise in the problem at hand	**Variable in clarity:** people express problems differently (one might exaggerate or belittle the encountered problems)
	Timely: emails and phone calls are not tied to any review schedules	**Unclear in accountability:** the transfer of responsibility is often implicit
	Flexible: one can discuss anything from routine exceptions to the most complex problems possible	**Unreliable:** the threshold of reporting exceptions may vary between individuals
Formal interpersonal channel	**Preserves accountability:** the delegation of responsibilities is typically very clear	**Costly:** people have other things to do than to sit in meetings
	Flexible: people can discuss a wide variety of issues and ask clarifying questions	**Not in real time:** the communication is tied to scheduled meetings
	Timely: although not a real-time channel, there is a cap on the lead time of reaching people (e.g., weekly meetings)	
Formal automated channel	**Costless:** the exception reporting features are included in most ERP systems	**Costly:** people need to be trained to use the exception reporting features of the ERP system
	Swift: the exception report shows immediately in all plans across the organization once it has been created	**Costly:** the parameters of ERP system's exception reporting features must be configured and maintained correctly
	Unambiguous: all exception reports have clear meanings and reactions to them should be uniform across the organization	**Limited reach:** ERP system is not necessarily used by all relevant people
		Lacks feedback: one does not know whether or when the message has reached its recipients
		Lacks reciprocity: one does not know if the exception report has triggered any actions
		Inflexible: one can only communicate exceptions that have been configured to the system

7.5.1 Perceptions of the Informal Communication Channels

Interviewees' opinions about the advantages of the informal channels explain their wide utilization (see Table 29). Most interviewees considered them as timely, virtually costless, and extremely flexible. However, many of those interviewees who relied primarily on the formal channels pointed to the exactly same weaknesses that were attached to the informal channels in the theory development. Although the interviewees did not use theoretical terms like "syntaxes" and "protocols," they explained the same crucial differences by describing how formal channels are superior in their reliability, clarity in the transfers of responsibilities, and independence from individual ways of expressing and interpreting information. In their opinion, informal channels worked as auxiliary media but as the sole communication channels, they would be too prone to errors and messages being corrupted when information is passed on to different decision makers. One interviewee actually explained the problem of informal channels with the metaphor of the childhood game of Chinese Whispers (also known as Broken Telephone), where the outcome is always that a message that is passed along a line from one player to another gets sooner or later completely distorted.

When the interviewees were comparing the informal and formal channels to each other, they incidentally explained the non-hypothesized main effects of the formal channels. Namely, the statistical results showed the formal channels not only mitigate the effects of uncertainty but they are also related to higher delivery performance regardless of the glitches' frequencies. The explanation for this statistical observation was that the informal channels are used to communicate so many things with varying levels of severity and urgency that people may misinterpret messages as exception reports when the sender of the message is actually only giving a warning or speculating about a possible glitch. Thus, the recipient of such information may self-inflict glitches by engaging in unnecessary corrective actions.

7.5.2 Perceptions of the Formal Interpersonal Channel

The main argument against the formal interpersonal channel appeared to be the reluctance to implement any new meeting procedures. The production planners who did not use formal review meetings shared the sentiment that the meetings would be a waste of their time. Daily meetings would be out of the question for them while weekly meetings were considered as a hopelessly tardy procedure. At the same time, the proponents of the formal interpersonal channel argued that even weekly review meetings are relatively timely procedure, since at least they put a cap on the lead time of reaching all relevant decision makers. According to the interviewees, the same does not necessarily apply to the informal channels that supposedly constitute "real-time" media. In other words, when people are busy with other things, they are not necessarily always available by phone or emails. Emails may end up unanswered or even unread, and when people are reached by phone, they are usually in "difficult situations" and promise to call back, which may or may not occur within a reasonable time frame.

7.5.3 Perceptions of the Formal Automated Channel

The most striking observation about the formal automated channel is its very low overall utilization. The low average usage is quite remarkable considering the fact that all studied organizations ran ERP systems. The interviewees gave reasons for this finding as well. First, the existence of an ERP system does not necessarily mean that all relevant decision makers are using it. Based on the interviews, it appeared to be quite ordinary for many salespersons, purchasers, and shop floor supervisors to manage their plans with other tools than the ERP system (e.g., in their personal spreadsheet solutions). Obviously, these people could not get the exception messages through the software but had to rely on some other communication channels. Many of the interviewees explained that switching to the sole use of the formal automated channel would require considerable training efforts and changes in organizational culture. On the other hand, they pointed out that if one wanted to benefit from the formal automated channel, it would be absolutely necessary to get everyone on board since if someone was left out of the loop, it would compromise the value of the entire effort.

Another challenge in the use of the formal automated channel was seen in ERP systems' modular architecture that enables leaving some functions out of their influence. Based on the interviews and the site visits, it appeared to be relatively common for the production functions to run their own software products (known as manufacturing execution systems). Such a solution causes a problematic discontinuity in exception processing routines, because the production function is critically situated in the middle of the cross-functional communication channels.

Lastly, many interviewees expressed concerns about the general dependability of their ERP systems. Most production planners had experienced all kinds of struggles with their systems and shared the view that putting the exception reporting into the system would take a considerable amount of time and the problems that would be unavoidable in the process would become extremely costly. In addition, some of the interviewees, who regularly used the formal automated channel, mentioned that constant efforts are required to keep the parameters of the exception processing features up to date so that messages are guaranteed to go to the right people and comprise the correct information.

7.6 DISCUSSION

I believe that the results of this chapter make at least three contributions, each one with multiple implications for research and practice. First, the results support the view that intra-organizational exception processing routines play an important role in manufacturers' resiliency against supply chain glitches. Second, the results indicate that the formalization of communication channels is generally beneficial, which is a finding that contributes to the debate between the proponents and opponents of formal procedures in organizations. Third, the results add to the literature on organizational flexibility by demonstrating that glitches originating from different sources (customers, suppliers, and the internal operations) call for exception processing routines and communication channels that are formalized in different ways.

7.6.1 Implications for Supply Chain Resiliency

This study contributes to filling a specific gap that exists both in the contemporary organization-theoretical research as well as in the research on supply chain resiliency. Current research in both disciplines is focused either on major crises, such as natural disasters and terrorist attacks (Majchrzak et al., 2007; Craft et al., 2005; Kleindorfer and Saad, 2005; Knemeyer et al., 2009), or on supply chain disruptions that are sufficiently severe to gain the attention of the business press (Hendricks and Singhal, 2003; 2005a). Yet, the day-to-day life of any organization is characterized by the continuous occurrence of unplanned events that require managerial attention and ad-hoc decisions. So far, no theory has explained how the reaction to these "routine non-conformities" should be organized (Vaughan, 1999). Nor has any theory guided the design of such ad-hoc coordination mechanisms and communication channels that would enhance organizations' glitch mitigation capabilities (Craighead et al., 2007). Evidently, the creation of task forces (Bigley and Roberts, 2001) or reliance on enacted sensemaking (Weick, 1988), or other solutions that have been devised through the study of severe organizational crises, do not apply to ordinary supply chain glitches. Likewise, normal accident theory's prescription that the organization should be decoupled in order to avoid failures (Perrow, 1984) does not apply in the case of everyday supply chain glitches. That is because the glitches are rather unavoidable, and because the possibilities for complete decoupling of manufacturing processes are often limited (Thompson, 1967).

The results of this analysis begin to close the gap in the literature by showing how concepts from the literatures of organization design and operations management can be integrated to provide a theoretically grounded and empirically substantiated answer to the question of how organizations can develop effective mitigation capabilities for supply chain glitches. Future research opportunities in this subject area are numerous and, as often happens, stem from the necessary limitations of the study at hand. Besides the more in-depth examinations of different communication alternatives, future research could explore the factors that prevent glitches from being reported in the first place, eventually integrating findings from error-reporting (Zhao and Olivera, 2006) and whistle-blowing (Gundlach et al., 2003) literatures.

Likewise, consistent with the current substantial research interest on inter-organizational relations, it would be important to examine how inter-organizational exception processing routines are structured, perhaps under the theoretical lens of the relational view of the firm (Dyer and Singh, 1998). It would be interesting to see whether the coordination mechanisms, communication channels, or relevant contingency factors would be any different from the intra-organizational exception processing routines that were the foci of this chapter. In inter-organizational contexts, it could be proposed that effective exception processing may even improve some performance dimensions such as customer satisfaction (Hart et al., 1990; Craighead et al., 2004). Finally, it would be worthwhile to examine how organizations learn from supply chain glitches that they have addressed in the past. That would establish a link between the day-to-day fixing of glitches and the creation of long-term solutions to the causes of the glitches.

7.6.2 Implications for Organizational Communications

A few important points can be made from the differences among the three kinds of communication channels. First, it can be argued that the positive main effects of both formal channels, and the explanations that the interviewees gave to them, make sense from a theoretical point of view. The occasional misinterpreted messages represent a kind of "noise" in the informal channels, which reduces organizations' information processing capacity when a glitch has to be addressed (Galbraith, 1973). Likewise, pure noise can be sometimes confused with real and purposeful messages (Shannon, 1984), thus increasing the risk that decision-makers react to glitches that do not exist in reality. In other words, in the long-linked and tightly coupled manufacturing processes (Thompson, 1967), the lack of formal information channels may cause decision-makers to take corrective actions and revise their plans unnecessarily on the bases of beliefs, misunderstandings, or presumptions.

This finding may shed light on the debate concerning whether formalization under uncertainty is beneficial or not. As the systematic review showed, this question has received mixed evidence in recent operations management studies. Some researchers have found out that formal procedures mitigate the effect of uncertainty (e.g., Shenhar, 2001), others have found them ineffective under uncertainty (e.g., Germain et al., 2008), and yet another stream of studies have suggested that they only have the positive main effect on performance (e.g., Naveh, 2007). The solution to this puzzle may lie in the domain where the formal procedures are applied. In this study, they had positive effects as they were applied to the processing for routine non-conformities but they could have even negative effects if applied to more innovation-oriented processes, as discussed in the theory development.

Another noteworthy issue regarding the domain of this inquiry is that the studied exception processing routines are used to mitigate the immediate effects of glitches. The processing of an exception message may well be followed by another process where the root causes of the glitch are analyzed and remedied in an effort to reduce the future occurrences of the same glitch (e.g., Deming, 1986). This procedure is obviously different from coping with glitch's immediate effects on delivery performance. Thus, it may involve completely different routines than what were studied in this chapter. In fact, expanding the contingency-theoretical analysis into that domain could prove a fruitful area of future research.

Yet another point about organizational information processes lies in the interviewees' comments about decision makers' reluctance to use ERP systems for communications. Also that observation is related to recent research literature (Boudreau and Robey, 2005; Bendoly and Cotteleer, 2008). The findings of this chapter complement the existing research because they show the detrimental effects of the circumvention practices while the earlier studies have mainly explored the behavioral mechanisms that lead to them. From this perspective, the managerial efforts to reduce circumventions seem recommendable, unlike what some critics of ERP systems have suggested (e.g., Kallinikos, 2004). Consequently, it can be suggested that more research efforts should be aimed at answering the question of how to avoid and curtail detrimental circumvention practices.

The lack of effects from the informal communication channels is another intriguing finding that deserves future inquiry. As the utilization of email for exception processing appeared to be quite high, it cannot be said with certainty that the informal channels do not have any role in the mitigation of glitches. Some existing studies have been aligned with the interviewees' suggestion that the informal channels may constitute a support medium, which can be used to ensure that the formally reported messages have gotten across and triggered the desired actions (Kraut et al., 1999; Maznevski and Chudoba, 2000). Therefore, it would be interesting to conduct a more in-depth study on the interplay of informal and formal communication channels.

7.6.3 Implications for Organizational Flexibility

The finding that supplier, customer, and internal glitches call for different communication channels corroborates the view that matching an organization's design with its task-environmental characteristics is important for organizational effectiveness. This analysis adds its own contribution to the contingency-theoretical literature by demonstrating that there is a time and place for interpersonal formalization and the automation of communication channels.

Failures to match exception processing routines and communication channels with organizations' most typical glitches result in a reduced capacity to utilize structural flexibilities. The finding may shed light on the surprising empirical results of Pagell and Krause (1999; 2004), who found no relationship between structural flexibility and performance under the conditions of high environmental uncertainty. It may have been that in their samples, sufficient proportions of seemingly flexible organizations may have employed contextually unfitting exception processing routines and communication channels. Simply put, flexibility can be used to absorb external disruptions only if the appropriate decision-makers get and exchange timely and accurate information about the glitches that are occurring in their processes.

More generally, the findings suggest that exception processing routines represent a form of flexibility that complements structural flexibility. Flexibility therefore can be seen as a synthesis of at least two major components: resources and routines. Resource flexibility refers to the ability of a physical or intangible asset to yield multiple outputs (e.g., flexible workers, machines, suppliers, etc.). Routine flexibility, instead, refers to the existence of organizational routines that facilitate the recombination of available assets in response to uncertainties. The results point to the importance of routine flexibility. The dual view of flexibility may be useful in future research as it may provide a better understanding of how organizations can cope with unplanned events.

7.7 RECAPITULATION

This study began to answer the call for research on the mechanisms that enable organizations to cope with supply chain glitches (e.g., Craighead et al., 2007). This investigation integrated concepts from organization theory with the capacity-management logic of the operations management literature. The resulting insights can be labeled broadly as the *contingency theory of exception processing routines*. Its propositions suggest that, when it comes to recurring glitches in organizations' everyday operations, the exception processing routines that rely on formal, rather than informal, communication channels mitigate the negative effects on organizational reliability most effectively. Additionally, the type of the formal communication channel needs to be matched with the type of glitches that the organization needs to deal with. If the task of resolving the glitch is predominantly urgent, then formal automated channels are more effective, and if the task is relatively more equivocal, then formal interpersonal channels are more effective. If an organization operates in an environment where both urgent and equivocal glitches are frequent, then it needs both kinds of formal channels to be effective.

In general, the results demonstrated that perhaps the basic tenets of contingency theory have been too hastily dismissed from organization-theoretical literature in favor of perspectives that emphasize the virtues of informality and decentralization, and that view the organization structure as an emerging nexus rather than a designed artifact (e.g., Majchrzak et al., 2007; Tsai, 2002). Contrary to those views, the results indicated that there is a time and place for formal routines. In the studied context, where uncertainty was high but not too unpredictable or life threatening, the more resilient organizations had carefully designed the protocols that were used to address glitches. The less resilient organizations expected the best solutions to emerge from informal interactions. My intention is not to devalue the benefits of informality and decentralization, but the results indicate that their applicability is contingent upon organizations' task environments just as the classic contingency theory has proposed (e.g., Burns and Stalker, 1961; Thompson, 1967).

8 DISCUSSION

The purpose of this chapter is to synthesize the results of the empirical chapters and to reflect their implications back to the theories from which the hypotheses were originally derived. The implications unfold on three levels: at the level of the studied contexts, at the level of middle-range theories on operations management in complex task environments, and at the level of formal organizational theory. These three levels also constitute the main parts of this chapter. After the synthesis of the implications, the methodological limitations of this dissertation will be discussed.

8.1 THREE LEVELS OF IMPLICATIONS

In the introduction chapter, I used the holistic construal of Bagozzi and Phillips (1982) to explain the logic and the structure of this dissertation (Figure 1, on page 12). That framework may also help to understand the implications of the results. Similarly as the deductive part of the holistic construal is composed of three layers: theoretical concepts, derived concepts, and empirical concepts, also the inductive part can be divided in three levels. At the lowest level, there are the context-specific implications that are generalizable to production processes that are similar to the studied ones. That level of implications corresponds to the level of empirical concepts in the deductive part of the construal. In addition, the results can be reflected back against the theories from which the empirical concepts were derived. That induction takes place first at the level middle-range operations management theory, which corresponds to the derived concepts of the holistic construal. Then, the induction can be taken further by discussing how the results relate to the existing organization-theoretical literature, which corresponds to the level of the theoretical constructs in the holistic construal. Figure 12 illustrates this multi-leveled nature of the implications. Following the terminology of Glaser and Strauss (1967), I label the middle-range operations management theory as *substantive theory* and the more general organization theory as *formal theory*.

8.2 IMPLICATIONS FOR THE STUDIED TASK ENVIRONMENTS

8.2.1 Product Complexity and Order Management Practices

Chapter 5 addressed Research Question 2a on how the applicability of different order management practices depends on the complexity of the manufactured products. The results showed that

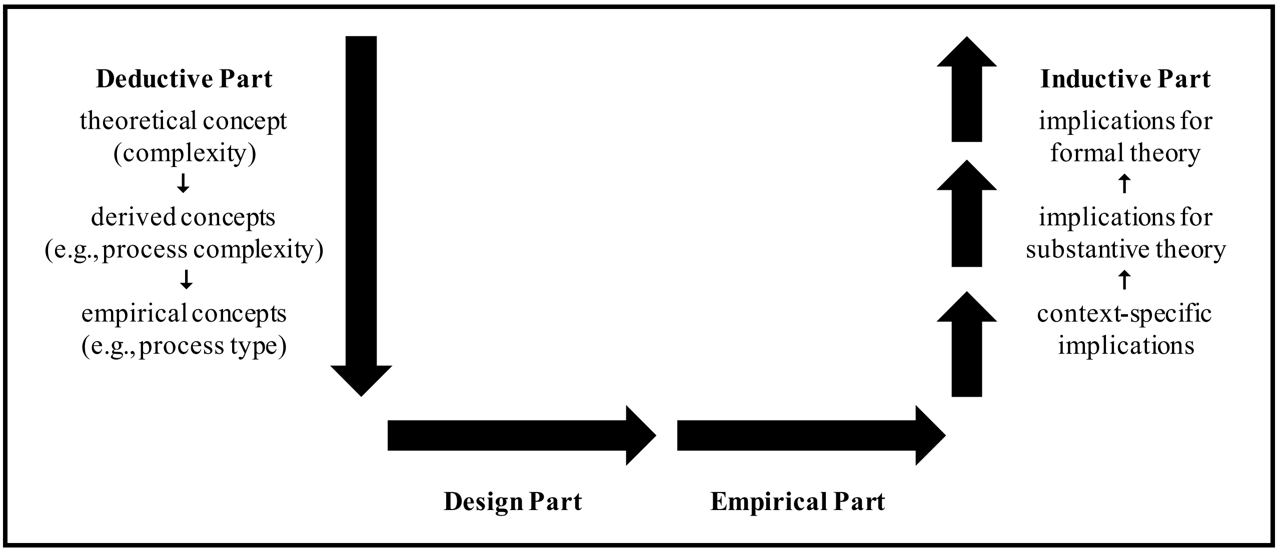


Figure 12: This dissertation's holistic construal revisited

if the complexity is operationalized as a two-dimensional framework that comprises component-level and configuration-level customization, then one can identify three complexity gestalts, which determine the effectiveness of three studied practices: the use of product configurators, the use of ATP verifications, and the use of configuration management practices. The resulting contingency propositions are as follows:

- The use of product configurator software is associated with higher product conformance in those MTO production processes where product configurations are customized.
- The use of ATP verifications is associated with higher delivery performance in those MTO production processes where products' components are not customized. In addition, this order management practice has a positive relationship with the product conformance of mass customizers (i.e., in those processes where configurations are customized but components are not).
- The use of configuration management practices is associated with higher delivery performance in those MTO production processes where both the components and the configurations of products are customized.

These propositions have immediate practical implications because first, the results showed that despite its effectiveness, the ATP verification procedure is widely neglected among mass customizing manufacturers. It seems that the product configurator software as a much newer solution has occupied the attention of the practitioners. The results remind us that the configurators do not replace the more traditional ATP verifications in the order acquisition. Both practices are needed to guarantee performance in terms of both product conformance and delivery performance.

The second managerial implication is the reminder about the value of the systematic configuration management practices. Again, it seemed that many mass customizers overlook these practices (i.e., the systematic documentation of product specifications and the formalized processes of making changes to them). This result demonstrates that mass customization as a manufacturing paradigm has elements from both mass production and customized production. Thus, it is not sufficient just to emulate the practices of mass production but one needs to master the practices of customized production as well.

The third practical implication is that the applicability of product configurator tools is not limited to mass customized manufacturing as suggested by the contemporary literature. Instead, also manufacturers whose products are purely customized can benefit from them. They just need to use the tools a bit differently. Instead of using the tools to automate the configuring of products, they must use the tools to verify the compatibility of the features and specifications that the customers desire for their purely customized products.

The third practical implication has a corollary that should be of interest for software developers. If the product configurators can benefit manufacturers even when component-level master data cannot be maintained, then why is it that ATP verifications do not work the same way? The contemporary software tools for ATP verifications (i.e., ERP systems) necessitate that detailed processing times, routings, and capacity requirements are recorded in the system. We have seen, however, that the product configurators, which should also require component-level master data, can be used to perform higher-level compatibility checks. It would sound reasonable that the software for the ATP verifications could be programmed in the same way, so that they would enable a kind of higher level rough-cut verification. The results of this study indicated that demand for such software definitely exists.

Lastly, the first study has an important implication for future research on product customization. The systematic review showed that statistical operations management studies have generally operationalized product customization as a single continuum from standardized to customized products. This study showed that it may be beneficial to operationalize the customization in two dimensions: the component level and the configuration level. Implementing this operationalization in the future studies can improve the validity of the product customization construct.

8.2.2 Process Complexity and Capacity Planning Methods

Chapter 6 addressed Research Question 2b on how the applicability of different capacity planning methods depends on the complexity of the manufacturing processes. By juxtaposing two competing hypotheses, I tested whether advanced planning methods are universally advantageous as suggested by the contemporary operations management literature or whether the complexity of processes sets constraints on their applicability. The results were strongly in favor of the latter view, and thus the study led to the following contingency propositions:

- The capacity planning of job-shop processes is best done with *rough-cut capacity planning* methods.
- The capacity planning of batch-shop processes is best done with *capacity requirements planning* methods.
- The capacity planning of assembly lines and bottleneck-controlled batch shops is best done with *finite loading* methods.

Although these contingency propositions may sound intuitive, the study showed that they are not appreciated in contemporary literature, nor they are known by the practitioners in the field. The results indicated that the selection of a capacity planning method for an MTO production process is not a rational procedure where the fit between the method and the process is considered. Instead, production planners seem to end up with methods that are implemented by the consultants that have configured their ERP systems or with the finite loading methods of an advanced planning tool whose vendors had managed to convince someone in the organization about their tool's superiority.

Similarly as in the case of the ATP verifications, it again seemed that some methods were overlooked due to the rudimentary or old-fashioned connotations that are attached to them. This time, the unjustly treated methods were the rough-cut capacity planning and capacity requirements planning. Despite not being the most recent inventions, the results showed that these methods are the only effective planning techniques for job-shop and batch-shop processes.

Lastly, the results also revealed an alarming population of production planners who do not use any systematic capacity planning methods because they perceive the techniques as overwhelmingly complicated. The finding is concerning because only the systematic methods—when applied with fitting process types—turned out to be effective. This has implications for the educators of operations management. It may be that the capacity planning examples and exercises in typical operations management courses are so simplistic that they delude the students to favor non-systematic methods. Alternatively, it may be that the examples and exercises of typical industrial engineering courses parallel the contemporary literature and give extensive attention to the optimization methods at the cost of the more basic methods. These speculations could explain why a large part of production planners appear to be alienated from the systematic planning methods. If the conjectures are correct, then the educators could do a favor to their students by making the planning exercises more realistic and taking the more traditional planning methods back in the syllabi of their courses.

8.2.3 Sources of Uncertainty and Exception Processing Routines

Chapter 7 addressed Research Question 2c on how the applicability of different cross-functional exception processing routines depends on the sources of uncertainty in MTO production. The chapter viewed the exception processing routines from the perspective of the cross-functional channels that are used to communicate intra-organizational exception reports about the glitches that have occurred in a manufacturing process. The results can be summarized in the following contingency propositions:

- Supplier-originated glitches, such as delayed raw material shipments, are best communicated (within a production process) through a formal automated channel like the exception reporting features of ERP systems.
- Glitches that originate from the internal operations, such as machine breakdowns, are best communicated (within a production process) through a formal interpersonal channel like periodic review meetings.
- Customer-originated glitches, such as changes to orders' specifications, are best communicated (within a production process) through a formal interpersonal channel like periodic review meetings.

As for the immediate implications for practicing operations managers, the results make several points. First, although the informal communication channels like email and telephone are immediately available, very cheap, and extremely flexible, they are not at all recommendable for the primary exception reporting channel within any MTO production process. They appear to be so prone to misinterpretations and other communication failures that they do not mitigate glitches negative effects at all.

Second, the results show that if an MTO process faces uncertainty from the suppliers and from either the internal operations or the customers, then a single intra-organizational exception reporting channel is not sufficient. The glitches from the two sources are so different that the process needs to use both an automated formal channel and an interpersonal formal channel.

Lastly, the study showed that resource flexibility, which is manifested as flexible labor and machines, is not sufficient for MTO processes that are run in uncertain task environments. In addition to the resource flexibility, the processes need routine flexibility that facilitates the harnessing of the available resources to respond to the encountered uncertainties. Effective exception processing routines contribute to this routine flexibility. In other words, it does not help if the labor and machines are flexible if the appropriate decision makers do not get the information about the glitches that have occurred or if they fail to communicate the revised plans to the resources. Therefore, both resource flexibility and routine flexibility are needed in uncertain task environments.

8.3 IMPLICATIONS FOR SUBSTANTIVE THEORY

The previous section summarized the main implications of the results to the operations managers who are responsible for the studied production processes. However, the generality of the implications does not have to be limited to the studied sample. Instead, by identifying the critical *boundary conditions* (Dubin, 1978), within which the results can be expected to hold, one can propose *theoretical generalization* to other contexts (Yin, 2003). That will be done in this section. With regard to each study, I make a suggestion about the boundary conditions and give examples that describe contexts where I would expect the results to hold and contexts where I would not expect them to hold. This demarcation of the boundaries results in propositions at the level of *substantive theory*. In this dissertation the substantive theory can be labeled the middle-range theory of operations management in complex task environments.

8.3.1 Middle-Range Implications for Order Management

The most important boundary conditions in the study on the order management practices are that products are made to individual orders, that they are customized, and that they have relatively long order-to-delivery lead times. The *MTO production logic* is obviously necessary to justify any of the systematic order management practices. For example, the ATP verifications would not be needed at all if the customers were served from stocks of finished products. In such a case, the outcome of the verification would be trivial: either the product is available or not, and if it is not, then one can check the master schedule of the production process for the finishing time of the next batch. Yet, there is a provision to this clear-cut demarcation. Namely, many traditional make-to-stock manufacturers nowadays allow their customers to make reservations for the planned future production. Such a practice naturally makes the boundary ambiguous. However, one can say that whenever reservations are made to the future production, it essentially makes the process an MTO process and thus a potential application area for the results.

The other boundary condition is the presence of *product customization*. For obvious reasons, it is necessary for the findings that are related to the use of product configurators and configuration management practices. If there is nothing to be customized in customers' orders, then there is no need to define and maintain the configurations individually for each order.

The third boundary condition is the *relatively long order-to-delivery lead times*. It is relevant to the results on the use of configuration management practices. Many of the studied mass customizers failed to manage changes to orders' specifications (e.g., product configurations and delivery times) in a sufficiently systematic manner and consequently suffered from poorer performance than their competitors. The lead times relate to this finding because the shorter the lead times are, the less there is time for changes to occur during the order fulfillment processes.

These boundary conditions help understanding where the results should and should not hold. Obviously many mass customizers pursue to postpone customization of their products so that the order-to-delivery lead times would be minimal. One way to do it is to customize products with software. In that approach the hardware of each product is identical but the features of the product depend on the software that is uploaded at the point of sales. A good example of such practice can be found in the mobile telecommunications infrastructure industry. The base stations of the mobile telecommunication networks almost fulfill the boundary conditions because the products are customized to individual orders and they take a relatively long time to produce. However, the order-to-delivery lead time constitutes only a fraction of the entire production lead time because the contents of the base station (so-called transceiver modules) are customized to fit hundreds of parameters solely on the basis of software, which is programmed remotely after the installation.

The software-based customization is not the only way to minimize the order-to-delivery lead times in customized MTO production. Another popular approach is to use accessories. For example, many consumer electronics products like cell phones are tailored to customers' likings with exchangeable covers, holsters, and other comparatively low-cost accessories that can be produced to stock. The same approach is, in fact, included also to the earlier example on the telecommunication base stations because also their installation requires varying amounts of power cables, antenna coils, fittings, and other relatively simple and low-cost accessories.

While the above paragraphs give examples on contexts where the results are not likely to hold, one can also imagine environments that are completely different from the studied machinery manufacturing industry but where the results are still likely to hold. One such example could be the production of professional services like consultancy or engineering projects. Such projects are also made to order, customized, and take a relatively long time to deliver. Thus, there are individual specifications for each order, which require systematic order acquisition practices so that one can determine a reliable delivery date (i.e., completion time in a service context) and a feasible configuration (i.e., a project plan) for each order. Furthermore, the specifications may well change—and are probably even more likely to change than in the studied context—during the order fulfillment process (i.e., the execution of the project). Thus, the implications of the order management study should inform also practitioners and researchers working on the field of professional service production.

8.3.2 Middle-Range Implications for Capacity Planning

The study on the capacity planning methods likewise has three boundary conditions. First, there must be *variance in the capacity requirements* of different products. That is not always the case. For example, one does not need any capacity planning methods to manage flow-line production processes, where all products have approximately the same capacity requirements (or processing times). They can be planned reliably on the bases of rate-based material planning methods (Vollmann et al., 2005). The amounts and types of output from those processes are determined by the amounts and types of the raw materials that are fed to the processes (e.g., in a chemical production lines) or by the amounts and types of the kanban cards that are released to the processes (e.g., in repetitive discrete manufacturing processes).

The second boundary condition is that *capacity constraints must be relevant*. That is not a self-evident condition either. If the processes are extremely flexible, then proactive planning is not that important. For example, labor-intensive production plants operating in the countries of low labor costs may well be in a situation that implementing an effective planning system is much more costly than adjusting the amount of resources on a weekly or even daily basis. The sustainability and the ethical aspects of such practices are, of course, another issue but from purely technical and economic perspectives that option exists and is evidently in relatively wide use (Jiang et al., 2009).

The third boundary condition is that *planning parameters must be known*, or in other words, the planning must be based on MRPII logic. Proactive planning of any operations is simply impossible if one does not know what needs to be produced or what it takes to produce it. Producers of extremely customized goods may operate in environments where products are completely unique. For example, as discussed in Chapter 4, many of the downstream processes in the sample of this dissertation had to be excluded from the capacity planning study because they were involved in assembling, installing, or integrating products to customers' applications or to other systems delivered by different manufacturers. Often the end products of such processes are unique entities that have not been done before and may not be done ever again. The exact capacity requirements unravel as the process unfolds and thus systematic planning methods are not usable. These processes do not fit into the job-shop-assembly-line continuum that was used as the contingency variable of this study. Instead, they can be labeled as project processes where the planning methods are no longer based on the MRPII logic but on the methods of the project management discipline. Of course, capacity planning exists in that context as well. It is done by creating work breakdown structures, Gantt charts, and critical chains, for instance. However, those methods are markedly different from the systematic planning techniques that are used in discrete manufacturing processes. For example, work breakdown structures are manually created case by case, whereas the capacity plans of manufacturing processes are automatically produced from rough-cut planning profiles, routings, and other master data, which is maintained in planning software. The interest in this study was in the latter type of capacity planning.

The description of the boundary conditions already gave several examples of environments where the results of the capacity planning study are not expected to hold. In summary, they include flow-line production processes, labor-intensive production processes with flexible labor, and project processes.

However, there are also environments other than the studied contexts where the results may well apply. Once again, I take an example from service production. Let us consider the production of medical services. In that context, surgical operations constitute job-shop processes, advanced diagnostics represent batch-shop processes (i.e., the patient is routed through different specialized resources, which all produce inputs to one another), and basic diagnostics, like the processing of blood samples, constitute assembly lines or bottleneck-controlled batch shops.

Those who are familiar with hospital operations management can probably see how the capacity planning methods used in the above-mentioned processes resemble the rough-cut capacity planning, the capacity requirements planning, and the finite loading methods of MRPII. It may even be that contextually unfitting planning methods are less often used in the service environments because the “best practices” are not as well established as in the manufacturing environments. Thus, service providers must often develop the methods internally. Achieving contextual fitness is more likely when solutions are developed to certain needs than when solutions are implemented directly out of standard software products like ERP or APS systems. Naturally, however, it is not very efficient if all service producers develop their planning methods from scratch. Hence I hope that the analogy between the process types and planning methods of the service and manufacturing sectors could lead to research on the proposed contingency theory of capacity planning methods in the service operations context. Eventually the results of such research could prove helpful for the people who develop planning techniques of service operations.

8.3.3 Middle-Range Implications for Exception Reporting

There are four boundary conditions for the results of the exception reporting study. First, the glitches that trigger the processing must be what Vaughan (1999) discusses as *routine nonconformities*; that is, they need to recur in approximately same ways over and over again. Otherwise, it would be impossible to develop formal response procedures. The delayed raw material shipments, machine breakdowns, and changes in customers’ requirements represent the recurring type of glitches in many complex production processes. The question of what is not a recurring glitch is, however, highly context specific. For example, product recalls may constitute recurring glitches, rare glitches, or even organizational crises. If in a given task environment, they are considered as recurring glitches, then the results of this study should hold, and the recommendation would be to develop a formal exception processing routine to deal with them. However, if they are not recurring glitches, then it is probably not recommendable to rely on formal communication channels but instead on the informal channels due to their flexibility and information richness (Daft and Lengel, 1986).

The second boundary condition is related to my definition of glitches. They were defined as disruptions in the planned flow of materials within a supply chain (Craighead et al., 2007; Hendricks and Singhal, 2003). The word “disruption” refers to an occurrence with *limited impact*. While a delayed raw material shipment can be considered as a glitch, a permanent end or a several months’ break in the supply of some raw materials cannot be considered as a glitch. In situations where organizations are facing challenges of great impact, the formal channels are not likely to be as effective as the informal channels. That is because the organizations must come up with something innovative in order to save the future of the process. There is no reason to believe that the standardized protocols and syntaxes of the formal communication channels would be helpful in an innovative process, as discussed in the theory development of this study.

The third and fourth boundary conditions are related. They are the *availability of sufficient flexibility* and the *prioritization of delivery performance*. The contextually fitting communication channels are not helpful if the physical process cannot adapt to the changed conditions or if the adaptation is not considered worthwhile. The studied machinery manufacturing processes are typically quite flexible and willing to use their flexibilities because their batch sizes are generally small, they utilize multipurpose machinery, they have multi-skilled labor, and the high value of their products makes it comparatively cheap to use over-time work. Meanwhile, in a capital-intensive production process, where batch sizes are large and setup times considerable, the effectiveness of the communication channels may play little role as in most situations, not much can be done for the glitches even if the decision makers are well informed about them. On the other hand, if the end products are very cheap, then the decision makers may choose to take the dent in the delivery performance instead of absorbing the costs of flexing. Also in that case, the match between the glitches and the communication channels would not explain the variance in delivery performance.

In summary, the results of the exception processing study are not likely to hold in environments where uncertainties occur in unique and unprecedented forms or their impacts are life-threatening for the organization, or the organization is not able or willing to adopt the changes in the plans. Several examples of such situations are depicted above. Yet once again, one can also imagine environments other than the studied one where the results would hold. One such example is the development of software products. In that context a glitch in supply is manifested as a bug that is automatically flagged and communicated to the entire organization through a debugging software tool. An internal glitch would be a change in resources. For example, the managers of the software company may suddenly assign some personnel to other tasks, and then the responsible manager of the project, from which the resources were taken, may have to summon a meeting to reallocate the remaining work. Customer-originated glitches in that context would be exactly similar changes in specifications as they are in the manufacturing context. Also in those situations, a formal meeting is probably the most effective way to find a solution that accommodates the changes in the least disruptive manner.

8.4 IMPLICATIONS FOR FORMAL THEORY

The last step in the inductive process of theoretical generalization is the abstraction of the findings back to the language of the formal theory. In this dissertation, the focal theoretical construct is complexity in organizations, and thus the formal theory is the organization theory on complexity. Next, I discuss how this dissertation elaborates two important issues in theorizing about complexity in organizations.

8.4.1 Need for Contingency Theories

As described in the theoretical review of Chapter 2, the organization theorists have proposed that complexity is detrimental for organizational performance when it is accompanied with uncertainty. To minimize the detrimental effects, the theorists have proposed different ways of decreasing complexity, reducing uncertainty, and coordinating organizational activities in situations where complexity and uncertainty cannot be avoided. The propositions were drawn from multiple different theories, including information processing theory (Galbraith, 1973), media richness theory (Daft and Lengel, 1986), input uncertainty theory (Argote, 1982), normal accidents theory (Perrow, 1984), and high reliability theory (Weick, 1987).

However, already the literature review of Chapter 3 showed that coping with complexity is a relatively complex issue in itself. Namely, the studies showed that many of the activities that can be used to reduce either uncertainty or complexity tend to increase the other. These include vertical integration (vs. outsourcing), buffering of processes (vs. reduction of lead times), and the reduction of supplier base (vs. multiple-vendor sourcing). Furthermore, the systematic review showed that in some studies, researchers have found that complexity (or uncertainty) has negative influence on the effectiveness of certain practices, while in other studies, the exactly same practices have been found to be positively influenced by complexity. Similarly, complexity was observed to have both negative and positive main effects on performance.

From these findings, I would conclude that it may not be possible to theorize anything universally applicable about how organizations should cope with complex task environments. Instead, the theories should depend upon what kinds of complexities and uncertainties are present and what are the relevant dimensions of organizational performance. Such theorizing falls into the domain of contingency theory of organizations (Thompson, 1967; Donaldson, 2001). That was why I designed the studies of this dissertation so that they would develop contingency theories, and on the bases of the encouraging results, I would propose that the first implication for the formal theory is that complexity is a fundamentally contingency-theoretical concept, whose effects depend always on the other constructs that are analyzed in conjunction with it.

8.4.2 Need for Middle-Range Theories

My other general proposition for the formal theory is related to the above. Since I argue that the effects of complexity are necessarily dependent upon contextual variables, I must also argue that theorizing about the effects of complexity has to occur at the level of middle-range theories. The boundary conditions that were discussed in the previous section demonstrate the specificity of the domains in which the propositions can be generalized. For example, formal communication channels can only be recommended for processes where routine non-conformities are being resolved, and it cannot be recommended for processes where solutions are sought for unprecedented challenges.

The need for middle-range theorizing is good news for operations management researchers because this is a field that naturally contributes to substantive theory. So far, studies published in operations management journals have typically had little impact in terms of citations in general management journals. If the importance of middle-range theorizing can be justified, and operations management researchers are able to present their results in the framework of organization-theoretical constructs, then there is a possibility that the impact of operations management studies will increase in the future.

8.5 LIMITATIONS AND DIRECTIONS FOR FURTHER RESEARCH

8.5.1 Selected Theoretical Lenses

In the beginning of Chapter 2, I set the theoretical domain of this dissertation by making three important choices. I decided to study *intra-organizational* aspects of complexity, to focus on the *management* of organizational processes instead of the behavior of individuals, and to view *complexity as an objective characteristic* of an organizational system rather than a product of cognitive processes. On the one hand, each of these choices influences the implications and the generality of the results. On the other hand, they also open numerous opportunities for further research within the topics of this dissertation.

Let us consider, for example, the result on the formal interpersonal communication channels being most effective in processing equivocal exceptions. Here, one could expect that the result would not necessarily hold in inter-organizational communications, especially if the formal interpersonal channel was operationalized as periodic review meetings. It is obviously more feasible to arrange periodic meetings within an organization than between organizations. That is because manufacturing firms often have hundreds or thousands of customers and suppliers. Thus, the general proposition of formal interpersonal channels being the most effective may hold but it should be operationalized in another way if this result was to be tested in an inter-organizational context.

Furthermore, my focus on the management of organizations instead of organizational behavior means that the periodic review meetings—albeit on average effective—may not work in every organization. As discussed in the qualitative results of Chapter 7, people tend to consider formal meeting procedures as a waste of their time, and thus implementing such a procedure may require certain individual qualities (e.g., patience and diligence) from the people who are expected to participate in the meeting. Similarly, good leadership skills are probably required from the manager who is put in charge of the procedure. Consequently, an interesting and a relatively straightforward extension of this research would be to measure the organizational culture (in terms of diligence and patience, for instance) or the leadership skills and hypothesize them to moderate the effectiveness of the periodic review meetings.

Lastly, the choice to consider complexity as an objective characteristic of an organizational system has its own effects on the example at hand. According to my theory, the factor that necessitates the use of formal interpersonal channels is equivocality. While my proposition is based on the logic that some exceptions are on average more equivocal than others, one could also argue that equivocality depends on the cognitive capacity of the people who are faced with the exceptions. Thus, an exception that is perceived as equivocal by one group of decision makers may be considered pretty clear by another group of decision makers. Consequently, one could study my results further by measuring decision makers' cognitive capabilities and hypothesizing them to have a negative effect on the utility of periodic review meetings.

There is no simple way to enumerate all limitations and future research opportunities that result from the selected theoretical lenses. However, the above examples should help understanding how they can be taken into account when considering the implications and the generality of the results.

8.5.2 Focused Sample

As discussed in the data collection section of Chapter 4, the empirical studies of this dissertation were conducted in a focused sample within seven machinery manufacturing supply chains. The fact that the dataset is not collected from a random sample means that the coefficients and the effect sizes found in the quantitative analyses are not statistically generalizable to any population of production processes. As discussed earlier, the objective of this dissertation was more of an exploratory kind and thus the interest was more in seeing the directions of the effects than in trying to establish accurate effect sizes. In my personal opinion, this is not a major shortcoming because whenever the dependent variables are measured with a survey instrument, the coefficients lack clear quantifiable meanings—even when they would be statistically generalizable. Also, I believe that the benefits of the focused sampling (i.e., the possibility to take control of contextual variables, the ability to collect auxiliary data, and the high response rate) overweigh the lack of statistical generalizability.

Due to the exploratory nature of the empirical studies, the next step in advancing the proposed contingency theories should be to test them in random samples of manufacturers. The sampling should be guided by the boundary conditions of the theoretical generalizations that were discussed earlier in this chapter. To make a larger contribution, the tests could be done in significantly different industries. For example, the theoretical generalizations included examples from professional service production, healthcare operations, and software development. Randomly sampled replications in any of those environments would provide an interesting opportunity for further contributions.

8.5.3 Operationalizations

As discussed in the measure development section of Chapter 4, the process-level units of analysis made it difficult to take an advantage of existing measurement scales. For example, at the process level, dynamism can be measured as the frequency of specific exceptions instead of the overall rate of change, which in turn, is a more aggregate measure and commonly used at the levels of plants and firms. Moreover, as the systematic review encouraged the usage of more accurate measures (especially in case of dynamism), I took the opportunity to develop scales of my own. The obvious shortcoming of this approach is the variable quality of the measures. For the reflective indicators, that can be seen in the results of the confirmatory factor analyses, which are by no means stellar. Consequently, when moving forward in the development of the proposed contingency theories, further work must also be dedicated to the development of measures.

8.5.4 Dependent Variables

In this dissertation, I focused on analyzing the effects of order management practices, capacity planning methods, and exception processing routines on two dimensions of organizational reliability: delivery performance and product conformance. As discussed earlier, it turned out for quite understandable reasons that only the order management practices are related to the product conformance dimension. Thus, a majority of the results are about the effects on delivery performance. Naturally, there are many other dimensions of organizational performance that are of interest to operations managers. Most notably, the effects of the studied practices on cost efficiency and quality would be interesting.

During the development of the survey instrument, my original quality construct transformed into the form of product conformance, which is admittedly not exactly the same issue as what is traditionally meant by quality. As for the cost efficiency dimension, the pilot tests of the survey instrument showed that its traditional measures such as unit costs, overhead costs, and material costs (e.g., Ward et al., 1995; Swink et al., 2005; Krause et al., 2007) have absolutely nothing to do with the independent variables of interest. The respondents of the pilot survey rightly pointed out that whatever they do at the process level has only a minimal impact on those measures. However, only part of the inadequacy can be attributed to the unit of analysis. The cost efficiency is a problematic dimension also because of the difficulties related to measuring it in a cross-sectional study. The comparison to competitors' performance works for the reliability dimensions but cost efficiency is such an internal matter that the respondents of the pilot survey could not give any answers for the questions.

Nevertheless, I believe that future studies could address the cost effects of the studied practices as well. It would only necessitate research designs where the measures are not as rough as in typical plant-level surveys and where the comparison is not made to competitors. An example of such research design would be a longitudinal analysis of an organization implementing some of the studied practices. In such a setting, one could use process data to measure changes in rework or overtime, for instance. These measures of cost efficiency could well be influenced by effective order management practices, capacity planning methods, and exception processing routines.

8.5.5 Respondent Reliability and Common Method Bias

As the hypotheses were tested in a single-respondent survey, a potential concern arises from respondent reliability. As discussed in Chapter 4, I was able to collect data and test the inter-rater reliability in seven different processes. Naturally, these seven processes cannot fully represent the entire sample. Thus, it must be acknowledged that there is a possibility of unreliable responses, which may have increased random errors in the measurement or caused systematic biases like common method bias. While the presence of the former can only be revealed in replications of the studies, the effect of the latter can be analytically evaluated.

Common method bias refers to common variance in all variables, which results from underlying unmeasured factors that may bias the measurement. In surveys, such factors include at least positive or negative affectivity, social desirability, halo effects, acquiescence, and position biases. Although some of the factors can be measured (e.g., affectivity), the complete controlling of common method variance is typically impossible (Podsakoff et al., 2003). One test that can be conducted to check that the common method bias is at least within reason is Harman's single factor test (Podsakoff and Organ, 1986). All measurement models used in the studies of this dissertation passed that test as the items always loaded onto different components in unrotated primary component analyses.

However, Harman's test is so rudimentary that passing it is a necessary condition to every study but never sufficient to conclude that common method variance is not present. Thus, it is important to understand how the potential biases may have affected the results. The results from the study on Research Question 2a are in most jeopardy because common method variance may inflate main-effect regression coefficients between continuous variables. To evaluate this risk, I used the heuristic of Siemsen et al. (forthcoming). It reveals the point in which the inflating effect turns into a deflating effect when the correlations among the independent variables and the dependent variable increase. The required correlation depends on the number of independent variables that are affected by the same common method bias. In this study, that number is three (i.e., the use of ATP verifications, PC tools, and CM practices), for which the heuristic gives the required correlation of .33. The heuristic assumes that the independent variables are uncorrelated but according to the numerical experiments of Siemsen et al. (forthcoming), the heuristic is reliable if the correlations among the independent variables are less than .30.

If the two conditions regarding the correlations hold, then the coefficients of the first study cannot be inflated by common method variance but instead they are deflated and thus constitute conservative estimates of the true effects. To examine this, I calculated the correlations in the three gestalts (i.e., mass producers, mass customizers, and custom producers).[*] The assumption

[*] In Chapter 5, I used a categorical variable for PC tools to remedy its U-shaped distribution. To apply the heuristic

regarding the correlations among the independent variables holds in each gestalt (i.e., they are below .30). The assumption regarding the correlations among the independent and the dependent variables holds for three of the supported hypothesized effects (i.e., they are above .33). Those effects are ATP verifications' effect on delivery performance in mass production, ATP verifications' effect on delivery performance in mass customization, and CM practices' effect on delivery performance in mass customization. For three other effects, the correlations come very close to meeting the assumption (i.e., they are .30 instead of .33). Those effects are PC tools' effect on product conformance in mass customization, ATP verifications' non-hypothesized effect on product conformance in mass customization, and CM practices' effect on delivery performance in custom production. The only effect that falls far from meeting the assumption (i.e., it is .15 instead of .33) is PC tools' effect on product conformance among the custom producers, which was the second non-hypothesized effect.

In conclusion, three of the hypothesized results regarding Research Question 2a must have been deflated instead of inflated if they were affected by common method variance. The other two hypothesized and two non-hypothesized effects may have been inflated and if so, then the most inflated is one of the non-hypothesized effects.

The results regarding the other two research questions are safer with regard to the possible effects of common method variance. In the study on Research Question 2b, the variables of interest are categorical, and thus the most typical sources of common method variance (e.g., affectivity and halo effects) are not applicable or at least it is difficult to fathom how they would work. At least, similar systematic inflation as in the regression analyses of continuous variables cannot occur. In the case of the study on Research Question 2c, the situation is the best. The hypotheses were operationalized as multiplicative interaction terms, which means that the common method variance can never inflate but only deflate the coefficients (Evans, 1985). In other words, it can only increase the chance of Type II error (i.e., failure to identify a significant effect) but never lead to Type I error (i.e., false identification of a significant effect). Thus, the results from that study are, in fact, conservative estimates of the true effects. Furthermore, the fact that some statis-

of Siemsen et al. (forthcoming), all variables must be continuous. Thus, I checked that the results hold when the continuous version of the variable is used. They do and the bias from the distorted distribution is likely small because the results correspond to the results from the models where the more reliable categorical variable was used.

tically significant effects could be found in that analysis must essentially mean that the common method variance was not substantial. Also this mitigates the concern regarding the possible inflation of the four susceptible coefficients in the first study.

8.6 RECAPITULATION

This chapter summarized the implications of the empirical results to the studied contexts, to the middle-range theories of operations management, and to the formal theory of organizational effects of complexity. After the three-leveled synthesis of implications, the methodological limitations of the analyses and the directions for future studies were discussed.

9 CONCLUSIONS

This chapter briefly summarizes the findings and the theses of this dissertation.

The purpose of this dissertation is to contribute to the body of knowledge on operations management in complex task environments. The first set of research questions asked what is already known about the subject and where are the best opportunities for contribution. Those questions were answered with a review of organization-theoretical literature and a systematic review of recent articles in the leading operations management journals. The sample of the systematic review consisted of 1645 articles from which 277 turned out to be relevant to the topic. Among other things, the review revealed contribution opportunities in combining certain operationalizations of complexity (i.e., product variety and customization, resource interdependence and process types, and dynamism, equivocality, and urgency aspects of uncertainty). Other main contribution opportunities were found in studying the mitigation—rather than the reduction—of complexity as well as the effects of complexity on the applicability of different operations management practices.

On the bases of the contribution opportunities identified in the systematic review, I focused the second set of research questions to ask how the applicability of different order management practices depends on product complexity, how the applicability of different capacity planning methods depends on process complexity, and how the applicability of different exception processing routines depends on the sources of uncertainty. To address these questions, I conducted an empirical multi-method study in a focused sample of 163 machinery manufacturing processes. Based on statistical analyses of quantified survey data and qualitative analyses of interview data, I came up with the following contingency-theoretical theses:

- The two-dimensional construct of product complexity determines the applicability of different order management practices in make-to-order production processes so that:
  - Product configurator tools and configuration management practices are beneficial when products are customized at the configuration level
  - Available-to-promise verifications are beneficial when products are not customized at the component level
- The complexity of production processes determines the minimum and maximum levels of precision to which their capacity utilization can be planned. The fitting pairs of process types and planning methods are as follows:

  - In job shops, where process complexity is manifested as pooled interdependences between resources, the only effective capacity planning method is rough-cut capacity planning
  - In batch shops, where process complexity is manifested as reciprocal interdependences between resources, the only effective capacity planning method is capacity requirements planning
  - In bottleneck-controlled batch shops and assembly lines, where process complexity is manifested as sequential interdependences between resources, the only effective planning method is finite loading
- When communicating glitches within a production process, the communication channel must fit the equivocality and the urgency of the glitch. The fitting combinations are:
  - When communicating primarily urgent glitches such as delayed raw material shipments, the most effective communication channel is a formal automated channel such as the exception processing feature of an ERP system
  - When communicating primarily equivocal glitches such as changes in customers' orders, the most effective communication channel is a formal interpersonal channel such as a periodic review meeting among functional decision makers
  - When communicating glitches that are both urgent and equivocal the requirements of the equivocality prevails and the most effective communication channel is the formal interpersonal channel

In addition to the contingency-theoretical propositions, the results also support the following general theses:

- In complex task environments, practitioners have a tendency to overlook the value of traditional operations management practices if more modern practices are available. For example, mass-customizing manufacturers make better use of product configurator tools, which are more recent inventions than the available-to-promise verifications, which are equally effective but more seldom used
- The use of non-systematic capacity planning methods is always detrimental to the performance of a production process regardless of its complexity
- When communicating glitches within a production process, informal communication channels are always ineffective in mitigating the negative performance effects regardless of the

glitches' nature

I propose that the theses together constitute a middle-range contingency theory on everyday operations management in complex task environments. In the synthesizing discussion of this dissertation, I explore the boundaries of the findings' generality. I believe that the propositions may well hold in other environments than the studied machinery manufacturing industry. Examples of other potential domains of application include service production, healthcare operations, and software development. Future studies can be directed to test the propositions in these operating environments.

APPENDIX

This appendix presents the detailed results and references of the systematic literature review of Chapter 3.

Table A-1: Operationalizations of complexity

	Definition	Studies	Total	Used in a statistical test	Significant effect found
1	Complexity as the number of parts and possible interactions between them	(Anderson and Dekker, 2005; Burton et al., 2002; Chao and Kavadias, 2008; Choi and Hong, 2002; Choi and Krause, 2006; Closs et al., 2008; Fixson, 2005; Guide et al., 2003; Hegde et al., 2005; Jensen and Szulanski, 2007; MacCormack et al., 2006; Macher, 2006; Matos and Hall, 2007; Mitchell and Nault, 2007; Mullens et al., 2005; Oh and Jeon, 2007; Oke et al., 2008; Scavarda et al., 2006; Shenhar, 2001; Sosa et al., 2004; Stock and Tatikonda, 2000; Wolf, 2001)	22	9	9
9	Organizational complexity as tight coupling	(Bajaj et al., 2004; Bendoly et al., 2008; Carlile and Rebentisch, 2003; Choi and Krause, 2006; Gray and Meister, 2004; Haas, 2006; Hui et al., 2008; Krause et al., 2007; Lejeune and Yakova, 2005; Pagell and LePine, 2002; Sobrero and Roberts, 2001; Sosa et al., 2004; Simons and Russell, 2002; Tatikonda and Montoya-Weiss, 2001; Tucker et al., 2007; Vickery et al., 2004; Wolf, 2001)	17	9	8
10	Process complexity as (a) pooled, (b) sequential, (c) reciprocal, (d) team interdependence	(Crook and Combs, 2007; Monahan and Smunt, 1999; Stock and Tatikonda, 2000; Stringfellow et al., 2008)	4[a]	1	1
11	Task complexity as action variety	(Cummings, 2004; Fransoo and Wiers, 2006; Haunschild and Rhee, 2004; Schilling et al., 2003)	4	4	4
12	Task complexity as component variety	(Choi and Hong, 2002; Closs et al., 2008; da Silveira, 2006; Dennis and Meredith, 2000; Droge et al., 2004; Fixson, 2005; Flynn and Flynn, 1999; Fong Boh et al., 2007; Gatignon et al., 2002; Hoetker et al., 2007; Koufteros et al., 2002; Krajewski et al., 2005; Lieberman et al., 1999; Mukherjee et al., 2000; Nambisan, 2002; Novak and Stern, 2008; Rungtusanatham and Salvador, 2008; Salvador et al., 2002; Schoenherr and Mabert, 2008; Singhal and Singhal, 2002; Sousa and Voss, 2001; Trovinger and Bohn, 2005; Tu et al., 2004; Verma and Sinha, 2002; Williams et al., 2002)	25	15	13
13	Task complexity as product variety	(Ahmad and Schroeder, 2001; Berry and Cooper, 1999; Bohlmann et al., 2002; Childerhouse et al., 2002; Corbett and Campbell-Hunt, 2002; DeHoratius and Raman, 2008; Dennis and Meredith, 2000; Flynn and Flynn, 1999; Fisher and Ittner, 1999; Fung, 2008; Guide et al., 2003; Haunschild and Rhee, 2004; Ketokivi, 2006; Ketokivi and Jokinen, 2006; Kocabasoglu et al., 2007; Narasimhan and Kim, 2002; O'Leary-Kelly and Flores, 2002; Randall et al., 2006; Randall and Ulrich, 2001; Safizadeh et al., 2003; Schoenherr and Mabert, 2008; Sousa and Voss, 2001; Swamidass et al., 1999; Trovinger and Bohn, 2005; Voss et al., 2008)	25	15	13

(to be continued on the next page)

[a] Only the work of Stock and Tatikonda (2000) include (d) team interdependence. The others use only a-c.

Table A-1 (continued)

14	Task complexity as rate of new product introductions	(Chen and Paulraj, 2004; da Silveira, 2006; Dehning et al., 2007; Gerwin and Barrowman, 2002; Holcomb and Hitt, 2007; Krause, 1999; Mendelson, 2000; Sousa, 2003; Sousa and Voss, 2001; Zhou and Benton, 2007)	10	6	5
15	Task complexity as customization	(Ahmad and Schroeder, 2001; Campa and Guillen, 1999; Dehning et al., 2007; Dennis and Meredith, 2000; Devaraj et al., 2001; 2004; Hegde et al., 2005; Ketokivi, 2006; Klein, 2007; Mayer et al., 2004; Rungtusanatham and Salvador, 2008; Saeed et al., 2005; Safizadeh et al., 2003; Salvador et al., 2002; Sousa, 2003; Sousa and Voss, 2001; Squire et al., 2006; Stewart, 2003)	18	12	11
	Just "complexity"	(Atuahene-Gima and Evangelista, 2000; Dilts and Pence, 2006; Größler et al., 2008; Harter et al., 2000; Hayward et al., 2006; Kaufmann and Carter, 2006; Koufteros et al., 2005; Lewis, 2004; Lieberman et al., 1999; Linderman et al., 2003; Mayer et al., 2004; Mehring, 2000; Novak and Eppinger, 2001; Novak and Stern, 2008; Parker and Anderson, 2002; Sousa, 2003; St. John et al., 2001; Stewart and Grout, 2001; Stratman, 2007; Stuart et al., 2002; Tsikriktsis et al., 2004; Youngdahl and Ramaswamy, 2008)	22	12	7
	Organization's size	(Ahmad and Schroeder, 2001; Ang et al., 2002; Atuahene-Gima and Evangelista, 2000; Burton et al., 2002; Cummings, 2004; Denrell et al., 2004; Dröge et al., 2003; Forman, 2005; Haas, 2006; Im and Rai, 2008; Jansen et al., 2006; Ketokivi and Schroeder, 2004b; Lin et al., 2007; Pisano et al., 2001; Ravichandran, 2000; Ren et al., 2006; Shah and Ward, 2003; Sorenson, 2003; Stratman, 2007; Swink, 1999; Swink et al., 2006; Tatikonda and Montoya-Weiss, 2001; Terwiesch and Loch, 1999; Wolf, 2001; Zhu et al., 2006)	25	25	16
	Distance between different parts of a system	(Choi and Hong, 2002; Cummings, 2004; Dehning et al., 2007; Forman, 2005; Kaufmann and Carter, 2006; King, 1999; Mayer et al., 2004; Salvador et al., 2002; Stock et al., 2000)	9	7	5
	Diversification (e.g., business sectors, countries, technologies, etc.)	(Benner and Veloso, 2008; Chari et al., 2008; Flynn and Flynn, 1999; Hendricks and Singhal, 2001; Narasimhan and Kim, 2002; Sabherwal and Sabherwal, 2005; Sorenson, 2003; Zeynep Aksin and Masini, 2008)	8	8	8
	Process type	(Cua et al., 2001; Das and Narasimhan, 2001; Dennis and Meredith, 2000; Devaraj et al., 2001; 2004; Dröge et al., 2003; Kathuria et al., 1999; Ketokivi and Schroeder, 2004b)	8	6	5
	Number of parts in a system	(Barry et al., 2006; Chen et al., 2004; Chen-Ritzo et al., 2005; Fong Boh et al., 2007; Gattiker et al., 2007; Mukhopadhyay and Kekre, 2002; Williams et al., 2002)	7	6	4
	Lack of routines or process standardization	(Droge et al., 2004; Gray and Meister, 2004; Kalnins and Mayer, 2004; Stewart and Grout, 2001; Stringfellow et al., 2008; Tu et al., 2004)	6	4	4

(to be continued on the next page)

Table A-1 (continued)

Difficulty of a task	(Murthy et al., 2008; Primo and Amundson, 2002; Salomon and Martin, 2008; Sobrero and Roberts, 2001; Vickery et al., 2004)	5	4	4
Number of information cues	(Bolt et al., 2001; Speier et al., 1999; Speier et al., 2003)	3	3	3
Cognitive complexity	(Speier et al., 2003; Swink and Speier, 1999)	2	2	2
Number of suppliers	(Flynn and Flynn, 1999; Hui et al., 2008)	2	2	2
Constraints on communications	(Bolton et al., 2003)	1	1	1
Inspection costs per process costs	(Aron et al., 2008)	1	1	1
Number of process steps	(Ahire and Dreyfus, 2000)	1	1	1
Out-of-stock policy	(Prasad et al., 2005)	1	1	1
Social distance	(Singh, 2005)	1	1	1
Volume of operations	(DeHoratius and Raman, 2008)	1	1	1
“Boundedness”	(Haas, 2006)	1	1	0
Computational complexity	(Ho and Zhang, 2008)	1	1	0
Cultural distance	(Denrell et al., 2004)	1	1	0
Demographic diversity	(Cummings, 2004)	1	1	0
Industry concentration	(Pagell and Krause, 2004)	1	1	0
Inventory management model	(Prasad et al., 2005)	1	1	0
Labor diversity	(Flynn and Flynn, 1999)	1	1	0
Number of customers	(Flynn and Flynn, 1999)	1	1	0
Use of matrix organization structure	(Ravichandran, 2000)	1	1	0
Number of different routings	(Dennis and Meredith, 2000; Hopp et al., 2007)	2	0	
Number of constraints in scheduling	(Sampson, 2004)	1	0	
Outcome interdependence	(Pagell and LePine, 2002)	1	0	
Separation of causes and effects	(Lapre et al., 2000)	1	0	

Table A-2: Operationalizations of uncertainty

Definition	Studies	Total	Used in a statistical test	Significant effect found
2 Uncertainty as lack of information	(Abramson et al., 2005; Agrawal et al., 2002; Amaldoss and Jain, 2008; Astebro and Elhedhli, 2006; Atuahene-Gima and Evangelista, 2000; Bhardwaj et al., 2006; Bhuiyan et al., 2004; Burton et al., 2002; Carlile and Rebentisch, 2003; Cooper and Giuffrida, 2000; Das and Van de Ven, 2000; Dasu and Rao, 1999; de Treville et al., 2004; Faraj and Xiao, 2006; Ferrer and Whybark, 2001; Gans et al., 2008; Goldenberg et al., 2001; Gopal et al., 2003; Herroelen, 2005; Holcomb and Hitt, 2007; Jedidi and Zhang, 2002; Lee, 2003; Lee et al., 2003; Makadok and Barney, 2001; Matos and Hall, 2007; Mitchell and Nault, 2007; Mithas and Jones, 2007; Montgomery et al., 2004; Naveh, 2007; Ofek et al., 2007; Shenhar, 2001; Spann and Skiera, 2003; Sroufe and Curkovic, 2008; Steckel et al., 2004; Stock and Tatikonda, 2000; 2008; Swink, 1999; Tatikonda and Montoya-Weiss, 2001; Tatikonda and Rosenthal, 2000; Taylor and Bunn, 1999; Van Landeghem and Vanmaele, 2002; Warren and Nicholls, 1999; Ziedonis, 2007)	43	21	16
3 Dynamism	(Amoako-Gyampah and Boye, 2001; Anderson and Joglekar, 2005; Bhardwaj et al., 2006; Burton et al., 2002; Calantone et al., 2002; Chao and Kavadias, 2008; Chen and Paulraj, 2004; Choi et al., 2001; Choi and Krause, 2006; Corbett and Campbell-Hunt, 2002; Cummings, 2004; Dilts and Pence, 2006; Dröge et al., 2003; Ellram et al., 2008; Faraj and Xiao, 2006; Ferdows, 2006; Field et al., 2006; Germain et al., 2008; Germain et al., 2001; Goldenberg et al., 2001; Hayward et al., 2006; Holcomb and Hitt, 2007; Im and Rai, 2008; Jack and Powers, 2004; Jansen et al., 2006; Kaufmann and Carter, 2006; Ketokivi, 2006; Ketokivi and Jokinen, 2006; Kim et al., 2008; Kocabasoglu et al., 2007; Koufteros et al., 2002; Krause et al., 2007; Lapre et al., 2000; Maxwell et al., 1999; McCutcheon and Stuart, 2000; Mukhopadhyay et al., 2007; Oh and Jeon, 2007; Pagell and Krause, 2004; Rabinovich et al., 2007; Ravichandran, 2000; Ren et al., 2006; Sabherwal and Sabherwal, 2005; Shepherd, 1999; Sorenson, 2003; Speier et al., 1999; St. John et al., 2001; Terwiesch et al., 2005; Tucker, 2004; Van Landeghem and Vanmaele, 2002; Van Wezel et al., 2006; Ward and Duray, 2000; Vickery et al., 1999; Vickery et al., 2004; Zeynep Aksin and Masini, 2008; Zhou and Benton, 2007)	55	33	17
4 Equivocality	(Anderson and Dekker, 2005; Anderson and Joglekar, 2005; Bhardwaj et al., 2006; Burton et al., 2002; Du and Budescu, 2005; Ellram et al., 2008; Faraj and Xiao, 2006; Finch, 2007; Gattiker et al., 2007; Harter et al., 2000; Koufteros et al., 2002; Lapre et al., 2000; Lin et al., 2005; Macher, 2006; Parker and Anderson, 2002; Stock and Tatikonda, 2000; Warren and Nicholls, 1999; Vickery et al., 2004)	18	8	6
5 Urgency	(Faraj and Xiao, 2006)	1	0	
6 (a) State, (b) effect, (c) response uncertainty	(Bhardwaj et al., 2006; Ellram et al., 2008; Kocabasoglu et al., 2007; Melnyk et al., 2003; Mitchell and Zmud, 2006; O'Leary-Kelly and Flores, 2002; Rabinovich et al., 2007; Sroufe and Curkovic, 2008)	8[a]	4	4
7 (a) Primary, (b) secondary uncertainty	(Beugré and Acar, 2008; Grover and Malhotra, 2003)	2	0	

(to be continued on the next page)

[a] Only one instance of the full scale.

Table A-2 (continued)

8	Input uncertainty	(Chen and Paulraj, 2004; Faraj and Xiao, 2006; Germain et al., 2008; Gittell, 2002; Guide et al., 2003)	5	2	2
	Just “uncertainty”	(Anderson and Joglekar, 2005; Barratt and Choi, 2007; Faraj and Sproull, 2000; Gerwin and Barrowman, 2002; Gruber et al., 2008; Keizers et al., 2003; MacCormack et al., 2001; McDermott, 1999; Mehring, 2000; Noori and Chen, 2003; Sawhney, 2006; Srinivasan et al., 2007; Terwiesch and Loch, 1999; Zwikael and Sadeh, 2007)	14	6	6
	Variability	(Ahmad and Schroeder, 2001; Akkermans and Vos, 2003; Anand and Ward, 2004; Avramidis et al., 2004; Blocher et al., 1999; Chari et al., 2008; Childerhouse et al., 2002; Croson and Donohue, 2006; Fleming, 2001; Hyer et al., 1999; Jack and Raturi, 2003; Kanyamibwa and Ord, 2000; Ketokivi, 2006; Klassen and Menor, 2007; Krajewski et al., 2005; Lin et al., 2007; Monahan and Smunt, 1999; Randall et al., 2006; Rhee et al., 2006; Schweitzer and Cachon, 2000; Stewart and Grout, 2001; Vickery et al., 2004)	22	11	10
	Unpredictability	(Anand and Ward, 2004; Barry et al., 2006; Childerhouse et al., 2002; Dröge et al., 2003; Germain et al., 2001; Germain et al., 2008; Jambulingam et al., 2005; Ketokivi and Jokinen, 2006; Pagell and Krause, 1999; 2004; Zhao et al., 2004)	11	9	7
	Individual exceptions	(Craighead et al., 2007; Hendricks and Singhal, 2003; 2005a; 2005b; Kleindorfer and Saad, 2005; Raz and Gloor, 2007; Regnier, 2008; Speier et al., 1999; Speier et al., 2003; Tatikonda and Montoya-Weiss, 2001; Tucker, 2004; Waller et al., 2004; Wu and Knott, 2006)	13	12	12
	Hostility	(Amoako-Gyampah and Boye, 2001; Barnett and Pontikes, 2008; Hoetker et al., 2007; Jambulingam et al., 2005; Jansen et al., 2006; Kocabasoglu et al., 2007; Saeed et al., 2005; Salomon and Martin, 2008; Shepherd, 1999; Sorenson, 2003; Zhu et al., 2006)	11	11	8
	Risk	(Baesens et al., 2003; Finch, 2007; Lewis, 2003; Mantel et al., 2006; Verter and Kara, 2008)	5	2	2
	Errors	(Naveh et al., 2005; Stern et al., 2008; Stewart and Chase, 1999)	3	2	2
	Risk-taking behavior	(Dillon and Tinsley, 2008)	1	1	1
	Distribution method	(Prasad et al., 2005)	1	1	0
	Goal divergence	(Ketokivi and Schroeder, 2004b)	1	1	0
	Rate of technological improvement	(Koufteros et al., 2005)	1	1	0

Table A-3: Performance effects of uncertainties from different sources

	Proposition	Studies	Total	Studied statistically	Significant effect found
1a	Internal uncertainty reduces performance	(Anderson and Joglekar, 2005; Blocher et al., 1999; Dilts and Pence, 2006; Germain et al., 2008; Germain et al., 2001; Hendricks and Singhal, 2003; 2005a; 2005b; Hyer et al., 1999; Kanyamibwa and Ord, 2000; Keizers et al., 2003; McKay et al., 2002; Maxwell et al., 1999; Mitchell and Zmud, 2006; Monahan and Smunt, 1999; Naveh et al., 2005; Ren et al., 2006; Stern et al., 2008; Stewart and Chase, 1999; Stewart and Grout, 2001; Tucker, 2004; Van Landeghem and Vanmaele, 2002; Wolf, 2001; Vollmann et al., 2000)	24	12	12
1b	Supplier uncertainty reduces performance	(Amaldoss and Jain, 2008; Anderson and Dekker, 2005; Beugré and Acar, 2008; Bhuiyan et al., 2004; Ferrer and Whybark, 2001; Gittell, 2002; Grover and Malhotra, 2003; Hendricks and Singhal, 2003; 2005a; 2005b; Montgomery et al., 2004; Rungtusanatham and Salvador, 2008; Tucker, 2004; Van Landeghem and Vanmaele, 2002)	14	6	6
1c	Customer uncertainty reduces performance	(Agrawal et al., 2002; Ahmad and Schroeder, 2001; Akkermans and Vos, 2003; Amaldoss and Jain, 2008; Anderson and Joglekar, 2005; Avramidis et al., 2004; Beugré and Acar, 2008; Bhuiyan et al., 2004; Chari et al., 2008; Dasu and Rao, 1999; Dilts and Pence, 2006; Dröge et al., 2003; Ferrer and Whybark, 2001; Field et al., 2006; Germain et al., 2001; Harter et al., 2000; Hendricks and Singhal, 2003; 2005a; 2005b; Jack and Powers, 2004; Jack and Raturi, 2003; Keizers et al., 2003; McKay et al., 2002; Lin et al., 2007; Noori and Chen, 2003; O'Leary-Kelly and Flores, 2002; Rungtusanatham and Salvador, 2008; Schweitzer and Cachon, 2000; Terwiesch et al., 2005; Vollmann et al., 2000)	30	16	14
1d	Uncertainty caused by competitors reduces performance	(Abramson et al., 2005; Barnett and Pontikes, 2008; Hoetker et al., 2007; Mithas and Jones, 2007; Sorenson, 2003)	5	5	3
		(Salomon and Martin, 2008)	+1	+1	+1
1e	Uncertainty caused by the natural environment reduces performance	(Hendricks and Singhal, 2005b; Regnier, 2008)	2	1	1
1f	Uncertainty caused by regulatory agencies reduces performance	(Dilts and Pence, 2006; Gans et al., 2008; Hendricks and Singhal, 2005b; Noori and Chen, 2003)	4	2	1
	Technological uncertainty reduces performance	(Anderson and Joglekar, 2005; Atuahene-Gima and Evangelista, 2000; Dilts and Pence, 2006; Gerwin and Barrowman, 2002; Goldenberg et al., 2001; Koufteros et al., 2005; Koufteros et al., 2002; Macher, 2006; Mitchell and Nault, 2007; Naveh, 2007; Noori and Chen, 2003; Oh and Jeon, 2007; Ren et al., 2006; Swink, 1999; Tatikonda and Montoya-Weiss, 2001; Tatikonda and Rosenthal, 2000)	16	13	6
		(Dröge et al., 2003)	+1	+1	+1

(to be continued on the next page)

Plus signs indicate studies on the positive performance effects of uncertainty.

Table A-3 (continued)

Overall environmental uncertainty reduces performance	(Anand and Ward, 2004; Craighead et al., 2007; Krause et al., 2007; Oh and Jeon, 2007; Pagell and Krause, 1999; 2004; Ravichandran, 2000; Sabherwal and Sabherwal, 2005; Speier et al., 1999; Speier et al., 2003; Tatikonda and Montoya-Weiss, 2001; Zwikael and Sadeh, 2007)	12	10	4
	(Im and Rai, 2008; Jansen et al., 2006)	+2	+2	+2
Recessions reduce performance	(Raz and Gloor, 2007)	1	1	1
Market entry uncertainty reduces performance	(Gruber et al., 2008)	1	0	
Traffic accidents reduce performance	(Verter and Kara, 2008)	1	0	

Plus signs indicate studies on the positive performance effects of uncertainty.

Table A-4: Reduction of complexity

Proposition		Studies	Total	Studied statistically	Significant effect found
2	Reduction of tight coupling	(Craighead et al., 2007; Flynn and Flynn, 1999; Haas, 2006; Jack and Powers, 2004; Parker and Anderson, 2002; Tucker, 2004)	6	3	3
3a	Reduction of specialization	(Flynn and Flynn, 1999)	1	1	0
3b	Reduction of reciprocal interdependences	(Monahan and Smunt, 1999; Stringfellow et al., 2008)	2	1	1
3c	Reduction of team interdependences		0		
4a	Focusing on specific market segments	(Vollmann et al., 2000)	1	0	
4b	Redundant resources		0		
4c	Standardization	(Droge et al., 2004; Stringfellow et al., 2008; Tu et al., 2004; Tucker, 2004)	4	2	2
4d	Outsourcing	(DeHoratius and Raman, 2008; Jack and Powers, 2004; Novak and Eppinger, 2001; Shenhar, 2001; Vollmann et al., 2000) (Parker and Anderson, 2002)	5 +1	3 +0	3
4e	Component commonality	(Choi and Hong, 2002; Flynn and Flynn, 1999; Fixson, 2005; Rungtusanatham and Salvador, 2008; Salvador et al., 2002; Squire et al., 2006; Williams et al., 2002)	7	2	2
4f	Reduction of product variety	(DeHoratius and Raman, 2008; Fisher and Ittner, 1999; Flynn and Flynn, 1999; Ketokivi, 2006; Safizadeh et al., 2003; Sousa, 2003)	6	4	4
4g	Reduction of new product introductions		0		
4h	Reduction of customization	(Ketokivi, 2006; Rungtusanatham and Salvador, 2008; Sousa, 2003; Squire et al., 2006)	4	1	1
4i	Use of modularity	(Barry et al., 2006; Choi et al., 2001; Fixson, 2005; Fleming, 2001; Flynn and Flynn, 1999; Hoetker et al., 2007; Ketokivi, 2006; Koufteros et al., 2002; MacCormack et al., 2006; MacCormack et al., 2001; Nambisan, 2002; Novak and Stern, 2008; Parker and Anderson, 2002; Rungtusanatham and Salvador, 2008; Salvador et al., 2002; Singhal and Singhal, 2002; Sosa et al., 2004; Squire et al., 2006; Tu et al., 2004; Verma and Sinha, 2002; Williams et al., 2002; von Hippel and Katz, 2002)	22	12	12
	Reduction of supplier base	(Chen et al., 2004; Choi and Krause, 2006; Flynn and Flynn, 1999; Hui et al., 2008; Vollmann et al., 2000)	5	3	2
	Formalization and centralization	(Choi and Hong, 2002; Shenhar, 2001)	2	0	
	Use of a “causal mapping tool”	(Mullens et al., 2005; Scavarda et al., 2006)	2	0	

(to be continued on the next page) The plus sign indicates a study suggesting that outsourcing increases complexity.

Table A-4 (continued)

Use of consultants	(Shenhar, 2001)	1	0
Scheduling algorithm	(Sampson, 2004)	1	0
Use of a "service design model"	(Stewart, 2003)	1	0
Appropriate strategy, governance, and information systems decrease complexity	(Closs et al., 2008)	1	0
Toolkits for customers to customize products on their own	(von Hippel and Katz, 2002)	1	0

Table A-5: Reduction of uncertainty

	Proposition	Studies	Total	Studied statistically	Significant effect found
5a	Collection of information	(Abramson et al., 2005; Akkermans and Vos, 2003; Bhardwaj et al., 2006; Craighead et al., 2007; Croson and Donohue, 2006; Dasu and Rao, 1999; de Treville et al., 2004; Field et al., 2006; Grover and Malhotra, 2003; Hyer et al., 1999; Jack and Powers, 2004; Jedidi and Zhang, 2002; Ketokivi, 2006; Klassen and Menor, 2007; Lewis, 2003; Mantel et al., 2006; Montgomery et al., 2004; Naveh et al., 2005; Spann and Skiera, 2003; Steckel et al., 2004; Terwiesch et al., 2005; Tucker, 2004; Zhou and Benton, 2007; Waller et al., 2004)	24	12	12
5b	Strategic aversion of uncertainty	(Lewis, 2003; McDermott, 1999; Ward and Duray, 2000)	3	1	1
5c	Culture of reliability	(Hyer et al., 1999; Naveh et al., 2005; Stewart and Grout, 2001; Tucker, 2004; Wolf, 2001)	5	2	1
5d	Vertical integration	(Mantel et al., 2006)	1	1	1
5e	Contracts and alliances	(Anderson and Dekker, 2005; Grover and Malhotra, 2003; Jack and Powers, 2004; Ketokivi, 2006; Krajewski et al., 2005; McDermott, 1999; Rungtusanatham and Salvador, 2008; Vollmann et al., 2000)	8	1	1
5f	Reduction of throughput times	(Akkermans and Vos, 2003; Corbett and Campbell-Hunt, 2002; de Treville et al., 2004; Regnier, 2008; Steckel et al., 2004)	5	1	1
	Forecasting	(Astebro and Elhedhli, 2006; Avramidis et al., 2004; Lee et al., 2003; Taylor and Bunn, 1999)	4	1	1
	Increasing supplier base	(Field et al., 2006; Mantel et al., 2006; Rungtusanatham and Salvador, 2008)	3	1	1
	Planning	(Mitchell and Zmud, 2006; Ofek et al., 2007)	2	1	1
	Freezing of plans	(Shenhar, 2001)	1	1	1
	Advanced manufacturing technologies	(Pagell and Krause, 1999)	1	1	1
	Process improvement programs	(Field et al., 2006)	1	1	1
	High perceptions of risk, pessimism, and not showing near-miss information to decision makers	(Dillon and Tinsley, 2008)	1	1	1
	Use of non-hazardous materials, small size, low debt/equity ratio, high sales, and high socio-economic environment	(Kleindorfer and Saad, 2005)	1	1	1

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Table A-5 (continued)

Employees' situational learning orientation, autonomy, and voice	(Stern et al., 2008)	1	1	1
"Frontloading" (e.g., rapid prototyping, automated design tools, & early reviews)	(Terwiesch and Loch, 1999)	1	1	1
Decision support system	(Baesens et al., 2003; Verter and Kara, 2008)	2	0	
Quality control	(Akkermans and Vos, 2003; Kanyamibwa and Ord, 2000)	2	0	
Datamining	(Cooper and Giuffrida, 2000)	1	0	
Use of everyday low prices policy	(Akkermans and Vos, 2003)	1	0	
Patenting	(Gans et al., 2008)	1	0	

Table A-6: Mitigation of uncertainty

	Proposition	Studies	Total	Studied statistically	Significant effect found
6a	Coordination by rules (for lowly complex organizations)	(Faraj and Sproull, 2000; Faraj and Xiao, 2006; Gittell, 2002; Mehring, 2000; Stewart and Grout, 2001; Tatikonda and Montoya-Weiss, 2001)	6	3	3
6b	Coordination by hierarchical referral (for moderately complex organizations)	(Bajaj et al., 2004; Corbett and Campbell-Hunt, 2002; Faraj and Xiao, 2006; Mehring, 2000; Oh and Jeon, 2007; Shenhar, 2001)	6	2	2
6c	Coordination by goals (for highly complex organizations)	(Gittell, 2002; Hyer et al., 1999; Mehring, 2000)	3	1	1
7a	Coordination via formal information processes	(Craighead et al., 2007; Dehning et al., 2007; Faraj and Sproull, 2000; Faraj and Xiao, 2006; Gittell, 2002; Stock and Tatikonda, 2000; Tatikonda and Montoya-Weiss, 2001; Zhou and Benton, 2007)	8	5	5
7b	Coordination by human coordinators (with equivocal uncertainty)	(Bhuiyan et al., 2004; Faraj and Xiao, 2006; Flynn and Flynn, 1999; Field et al., 2006; Gattiker et al., 2007; Gittell, 2002; Mehring, 2000; Mitchell and Nault, 2007; Parker and Anderson, 2002; Stock and Tatikonda, 2000; 2008; Tucker, 2004; Waller et al., 2004; Vickery et al., 2004)	14	8	7
7c	Coordination via information systems (with urgent uncertainty)	(Field et al., 2006; Flynn and Flynn, 1999; Gittell, 2002; Mehring, 2000; Parker and Anderson, 2002; Vickery et al., 2004)	6	3	2
	Planning	(Agrawal et al., 2002; Anderson and Joglekar, 2005; Craighead et al., 2007; Ferrer and Whybark, 2001; Gruber et al., 2008; Harter et al., 2000; Herroelen, 2005; McKay et al., 2002; Mitchell and Nault, 2007; Noori and Chen, 2003; Shenhar, 2001; Van Landeghem and Vanmaele, 2002; Van Wezel et al., 2006; Zwikael and Sadeh, 2007)	14	3	3
	Flexibility	(Anand and Ward, 2004; Choi et al., 2001; Field et al., 2006; Flynn and Flynn, 1999; Jack and Powers, 2004; Jack and Raturi, 2003; Ketokivi, 2006; Klassen and Menor, 2007; Sawhney, 2006; Shenhar, 2001)	10	5	4
	Feedback	(Keizers et al., 2003; MacCormack et al., 2001; Mukhopadhyay et al., 2007; Schweitzer and Cachon, 2000)	4	3	2
	Configuration management practices (formal documentation & reviews)	(Faraj and Sproull, 2000; Harter et al., 2000; Shenhar, 2001; Tatikonda and Montoya-Weiss, 2001)	4	4	4
	Quality control	(Field et al., 2006; Harter et al., 2000; Mayer et al., 2004; Shenhar, 2001)	4	4	4
	Experience	(Barnett and Pontikes, 2008; Fong Boh et al., 2007; Kalnins and Mayer, 2004)	3	3	3
	Knowledge management	(Dröge et al., 2003; Lapre et al., 2000; Ren et al., 2006)	3	2	2
	Cross-training of employees	(Field et al., 2006; Flynn and Flynn, 1999)	2	2	2

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Table A-6 (continued)

Design templates	(Goldenberg et al., 2001)	1	1	1
Ambidexterity	(Lin et al., 2007)	1	1	1
Wide social networks	(Raz and Gloor, 2007)	1	1	1
Alignment between product's and organization's structures	(Sosa et al., 2004)	1	1	1
Appropriate representation of tasks	(Speier et al., 2003)	1	1	1
Employee discretion and empowerment	(Tatikonda and Montoya-Weiss, 2001)	1	1	1
Strong customer relationships, blanket purchase orders, and just-in-time production control	(Flynn and Flynn, 1999)	1	1	1
Shared mental models and not paying attention to time	(Waller et al., 2004)	1	1	1
Task distribution and prioritization	(Waller et al., 2004)	1	1	0
Optimization algorithm	(Amaldoss and Jain, 2008; Lin et al., 2005)	2	0	
Relational commitment	(Beugré and Acar, 2008)	1	0	
Organization's size	(Oh and Jeon, 2007)	1	0	
Poka-yoke practices	(Stewart and Grout, 2001)	1	0	
Team rotation and automated design tools	(Barry et al., 2006)	+1	+1	+1

The plus sign indicates a study where team rotation and automated design tools were found to amplify the negative effect of uncertainty.

Table A-7: Other effects of complexity

	Proposition	Studies	Total	Studied statistically	Significant effect found
8	Leads to isomorphism	(Barratt and Choi, 2007; Ketokivi and Schroeder, 2004b; Rhee et al., 2006; St. John et al., 2001)	4	2	2
	Reduces performance	(Ahmad and Schroeder, 2001; Anderson and Dekker, 2005; Bajaj et al., 2004; Chen et al., 2004; Choi et al., 2001; Crook and Combs, 2007; Droge et al., 2004; Dröge et al., 2003; Fisher and Ittner, 1999; Flynn and Flynn, 1999; Gerwin and Barrowman, 2002; Harter et al., 2000; Haunschild and Rhee, 2004; Hegde et al., 2005; Ho and Zhang, 2008; Lewis, 2004; Lieberman et al., 1999; Macher, 2006; Mukherjee et al., 2000; Oke et al., 2008; Ren et al., 2006; Ritzman and Safizadeh, 1999; Rungtusanatham and Salvador, 2008; Saeed et al., 2005; Salomon and Martin, 2008; Singhal and Singhal, 2002; Sobrero and Roberts, 2001; Speier et al., 1999; Speier et al., 2003; Squire et al., 2006; Stewart and Grout, 2001; Stringfellow et al., 2008; Swamidass et al., 1999; Swink and Speier, 1999; Swink et al., 2006; Terwiesch and Loch, 1999; Verma and Sinha, 2002; Wolf, 2001)	38	32	22
	Increases performance	(Chen-Ritzo et al., 2005; Fung, 2008; Gatignon et al., 2002; Kaufmann and Carter, 2006; Klein, 2007; Schoenherr and Mabert, 2008; Swamidass et al., 1999; Voss et al., 2008)	8	7	7
	Influences strategic decisions	(Berry and Cooper, 1999; Campa and Guillen, 1999; Childerhouse et al., 2002; Closs et al., 2008; Devaraj et al., 2001; Hayward et al., 2006; Kathuria et al., 1999; Ketokivi, 2006; Krajewski et al., 2005; Randall et al., 2006; Randall and Ulrich, 2001; Safizadeh et al., 2003)	12	5	5
	Influences the effects of strategic decisions	(Bohlmann et al., 2002; Burton et al., 2002; Devaraj et al., 2004; Zeynep Aksin and Masini, 2008)	4	4	4
	Leads to the use of certain practices	Proposed/supported: inventory and pricing policies (Berry and Cooper, 1999), process governance practices (Closs et al., 2008), “innovative manufacturing practices” (Ketokivi and Schroeder, 2004b), lean management practices (Shah and Goldstein, 2006), batching of orders (Simons and Russell, 2002), knowledge management practices (Carlile and Rebentisch, 2003; Gray and Meister, 2004), “ambidextrous alliance formation” (Lin et al., 2007), quality inspections (Mayer et al., 2004), project management practices (Shenhar, 2001) Not supported: preventive maintenance (Ritzman and Safizadeh, 1999), total quality management (Ravichandran, 2000), contracting (Anderson and Dekker, 2005)	13	9	6

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Table A-7 (continued)

Influences the effects of certain practices	Advanced manufacturing technologies: configurations (Das and Narasimhan, 2001); ISO 9000: curvilinear (∩) effect (Benner and Veloso, 2008); life cycle assessment: negative effect (Matos and Hall, 2007); quality management: negative effect (Cua et al., 2001; Hendricks and Singhal, 2001), configurations (Sousa and Voss, 2001); supplier involvement in R&D: negative effect (Primo and Amundson, 2002); teamwork: positive effect (Pagell and LePine, 2002); optimization: negative effect (Größler et al., 2008); close governance of contractors: positive effect (Hui et al., 2008); radical new product development: positive (Chao and Kavadias, 2008); simulation-based training: positive (Murthy et al., 2008); behavior-modeling-based training: positive (Bolt et al., 2001)	13	8	8
Increases the benefits from knowledge management efforts	(Cummings, 2004; Denrell et al., 2004; Gray and Meister, 2004; Jensen and Szulanski, 2007; Ren et al., 2006)	5	5	3
Decreases the benefits from knowledge management efforts	(Haas, 2006)	1	1	1
Increases learning	(Haunschild and Rhee, 2004; Schilling et al., 2003; Sobrero and Roberts, 2001)	3	3	3
Decreases learning	(Lapre et al., 2000; Pisano et al., 2001; Schilling et al., 2003; Singh, 2005)	4	3	2
Increases the use of information technology	(Closs et al., 2008; Forman, 2005)	2	1	1
Decreases the use of information technology	(Tsikriktsis et al., 2004)	1	1	1
Improves the positive effects of information technology	(Bendoly et al., 2008; Chari et al., 2008; Dehning et al., 2007; Sabherwal and Sabherwal, 2005; Stratman, 2007)	5	5	4
Reduces the positive effects of information technology	(Mukhopadhyay and Kekre, 2002)	1	1	1
Increases information sharing	(Lejeune and Yakova, 2005)	1	0	
Decreases information sharing	(King, 1999)	1	1	1
Increases the benefits of integration	(Koufteros et al., 2005; Narasimhan and Kim, 2002; Stock et al., 2000)	3	3	3
Decreases the benefits of integration	(Koufteros et al., 2005; O'Leary-Kelly and Flores, 2002)	2	2	2
Reduces integration	(Saeed et al., 2005)	1	1	1
Influences process design	(Guide et al., 2003; Safizadeh et al., 2003; Stock and Tatikonda, 2000)	3	1	1
Influences relative power of organizational entities	(Atuahene-Gima and Evangelista, 2000; Bolton et al., 2003)	2	2	2

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Table A-7 (continued)

Influences the applicability of different kinds of flexibilities	(Anand and Ward, 2004; Jack and Powers, 2004; Ketokivi, 2006)	3	1	1
Reduces flexibility	(da Silveira, 2006)	1	1	1
Reduces manufacturability	(Swink, 1999)	1	1	1
Reduces mass customization capability	(Tu et al., 2004)	1	1	1
Influences media choices	(Safizadeh et al., 2003)	1	1	1
Increases setup times	(Trovinger and Bohn, 2005)	1	1	1
Influences buyer-supplier relationships	(Hoetker et al., 2007)	1	1	1
Reduces technology assimilation	(Zhu et al., 2006)	1	1	1
Increases the salaries of educated staff	(Ang et al., 2002)	1	1	1
Reduces inventory record accuracy	(DeHoratius and Raman, 2008)	1	1	1
Increases required efforts in tasks	(Fong Boh et al., 2007)	1	1	1
Increases complexity (one type of complexity increases another type)	(Dennis and Meredith, 2000; Sousa, 2003; Williams et al., 2002)	3	0	
Determines the applicability of different information technologies	(Kathuria et al., 1999)	1	0	
Has a curvilinear (∪) relationship with risk	(Choi and Krause, 2006)	1	0	

Table A-8: Other effects of uncertainty

Proposition	Studies	Total	Studied statistically	Significant effect found
Influences strategic decisions	(Amoako-Gyampah and Boye, 2001; Childerhouse et al., 2002; Corbett and Campbell-Hunt, 2002; Du and Budescu, 2005; Hayward et al., 2006; Ketokivi, 2006; Ketokivi and Jokinen, 2006; Klassen and Menor, 2007; Krajewski et al., 2005; Krause, 1999; Lee, 2003; Randall et al., 2006; Safizadeh et al., 2003; Sawhney, 2006; Ward and Duray, 2000; Wu and Knott, 2006; Youngdahl and Ramaswamy, 2008)	17	10	8
Influences the effects of strategic decisions	(Burton et al., 2002; Das and Van de Ven, 2000)	2	2	2
Leads to the use of certain practices	Proposed/supported: bundles of practices (Corbett and Campbell-Hunt, 2002), "innovative manufacturing practices" (Ketokivi and Schroeder, 2004b), quality management (Zhao et al., 2004), ISO 14001 (Melnyk et al., 2003), modular product structures and team rotation (Barry et al., 2006), knowledge management practices (Carlile and Rebentisch, 2003), variable-price contracting (Gopal et al., 2003), "ambidextrous alliance formation" (Lin et al., 2007), project management practices (Shenhar, 2001), option-based licensing of patents (Ziedonis, 2007) Not supported: total quality management (Ravichandran, 2000)	11	8	7
Reduces the use of certain practices	ISO 9000 (Sroufe and Curkovic, 2008)	1	0	
Influences the effects of certain practices	Concurrent engineering: negative (Bhuiyan et al., 2004), no effect (Koufteros et al., 2002); incremental new product development: positive (Chao and Kavadias, 2008);	3	1	0
Increases the benefits from knowledge management efforts	(Ferdows, 2006; Mendelson, 2000)	2	1	1
Influences partner selection	(Kim et al., 2008; McCutcheon and Stuart, 2000; Rabinovich et al., 2007)	3	2	2
Increases flexibility	(Pagell and Krause, 1999; 2004)	2	2	0
Reduces outsourcing	(Ellram et al., 2008; Mantel et al., 2006)	2	1	1
Has a curvilinear (∩) relationship with outsourcing	(Holcomb and Hitt, 2007)	1	0	
Increases integration	(Calantone et al., 2002; Saeed et al., 2005)	2	2	2
Reduces integration	(Vickery et al., 1999)	1	1	1
Increases the benefits of integration	(O'Leary-Kelly and Flores, 2002)	1	1	1
Influences customers' priorities	(Finch, 2007)	1	1	1

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Table A-8 (continued)

Increases the use of information technology	(Barry et al., 2006)	1	1	1
Increases the benefits from information technology	(Ahmad and Schroeder, 2001)	1	1	1
Decreases the benefits from information technology	(Sabherwal and Sabherwal, 2005)	1	1	1
Increases the search of information	(Makadok and Barney, 2001; Zellmer-Bruhn, 2003)	2	1	1
Increases information sharing	(Zhou and Benton, 2007)	1	1	1
Reduces information sharing	(Beugré and Acar, 2008)	1	0	
Influences process designs	(Guide et al., 2003; Safizadeh et al., 2003)	2	1	1
Increases risk taking	(Kocabasoglu et al., 2007)	1	1	1
Increases formalization	(Vickery et al., 1999)	1	1	1
Influences media choices	(Safizadeh et al., 2003)	1	1	1
Reduces likelihood to get capital for ventures	(Shepherd, 1999)	1	1	1
Influences relative power of organizational entities	(Atuahene-Gima and Evangelista, 2000)	1	1	1
Has a curvilinear (∩) relationship with technology assimilation	(Zhu et al., 2006)	1	1	1
Increases learning	(Srinivasan et al., 2007)	1	1	1
Reduces learning	(Lapre et al., 2000)	1	0	
Has a curvilinear (∪) relationship with learning	(Sorenson, 2003)	1	1	1
Increases the benefits from exploratory innovativeness and reduces the benefits from exploitative innovativeness	(Jansen et al., 2006)	1	1	1
Reduces manufacturability	(Swink, 1999)	1	1	0
Determines the effectiveness of different coordination mechanisms	(Faraj and Xiao, 2006)	1	0	
Makes performance measurement difficult	(Warren and Nicholls, 1999)	1	0	

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