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Efficiency and Responsiveness of Supply Chains in the High-Tech Electronics Industry

A System Dynamics-Based Investigation

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A System Dynamics-Based Investigation

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Dennis Minnich

Herne, December 2007

Table of Contents

List of Tables

List of Figures

Abbreviations

3PL	=	Third party logistics service provider
4PL	=	Fourth party logistics service provider
APS	=	Advanced Planning System
BP	=	Board printing
CRD	=	Customer request date
CM	=	Contract manufacturer
CPFR	=	Collaborative planning, forecasting and replenishment
ECR	=	Efficient consumer response
EDI	=	Electronic data interchange
EOL	=	End-of-life
ERP	=	Enterprise resource planning
FAT	=	Final assembly and testing
FC	=	Forecast
FG	=	Finished goods
HPM	=	High performance manufacturing
IT	=	Information technology
JIT	=	Just-in-time
LT	=	Lead-Time
MIT	=	Massachusetts Institute of Technology
MRP	=	Material requirements planning
MRP II	=	Manufacturing resource planning
MTF	=	Make to forecast
MTO	=	Make to order
MTS	=	Make to stock
ODM	=	Original design manufacturer
OEM	=	Original equipment manufacturer
OTD	=	Order to delivery
PCBA	=	Printed circuit board assembly
POS	=	Point of sales
R&D	=	Research and development
RM	=	Raw materials

SCC	=	Supply chain council
SCM	=	Supply chain management
SCOR	=	Supply chain operations reference
SD	=	System Dynamics
SKU	=	Sock keeping unit
SWF	=	Software flashing and packing
Sup	=	Supplier
TQM	=	Total quality management
WIP	=	Work in process

A. Efficient, Responsive, or Both – Strategic Supply Chain Design

Until the late 1990s and early 2000s, the structure of supply chains in the high-tech electronics industry was similar to that of automotive supply chains. Mobile phone manufacturers, for example, were vertically integrated and operated their own assembly plants.[1] Then, continuous and rapid price erosion for high-tech products and strong global competition, combined with rapid advances in technology, led to strong pressure to reduce costs, enhance flexibility and limit risk exposure. This created a more complex reality for companies such as IBM, requiring them to search global partners and build world-leading competences.[2] The 'all from one source' corporate conglomerates in the 1980s and 1990s were not able to cope with these challenges.[3] This forced many players to offshore parts of their value chains, in particular their personnel- and capital-intensive production plants, with hopes to achieve greater flexibility. For example, Ericsson, Sweden-based global leader in digital networks, was forced to sell off several of its plants in Europe to contract manufacturers abroad, such as Flextronics and Solectron.[4] Offshoring was possible because moving electronics manufacturing plants abroad is relatively easy. Primary target countries for outsourced production sites were China, India, Mexico and Brazil.[5]

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1 Cf. Appleyard, Melissa M., Clair Brown and Greg Linden: Wintel and Beyond: Leadership in the Net World Order, 2004, Working Paper cwts-01-2004, Institute of Industrial Relations, University of California, http://repositories.cdlib.org/iir/cwts/bdetwps/cwts-01-2004, retrieved on: 12 September 2006, pp. 1–2 and Alicke, Knut: Planung und Betrieb von Logistiknetzwerken – Unternehmensübergreifendes Supply Chain Management, 2nd ed., Heidelberg 2005, p. 245.

2 Cf. Lin, Grace *et al.*: Extended-Enterprise Supply-Chain Management at IBM Personal Systems Group and Other Divisions, in: Interfaces, Vol. 30 (2000), No. 1, p. 8 and Berggren, Christian and Lars Bengtsson: Rethinking Outsourcing in Manufacturing: A Tale of Two Telecom Firms, in: European Management Journal, Vol. 22 (2004), No. 2, p. 217.

3 Cf. Alicke: Planung und Betrieb von Logistiknetzwerken, p. 245.

4 Cf. Berggren and Bengtsson: Rethinking Outsourcing in Manufacturing, p. 216.

5 Cf. Roberts, Bill: Beyond the China mystique, in: Electronic Business, 1 March 2006, 2006, http://www.reed-electronics.com/eb-mag/article/CA6310932, retrieved on 8 August 2006, p. 1.

Managers at Original Equipment Manufacturers (OEMs) such as, for example, Ericsson and Nokia, argued that using contract manufacturers should improve flexibility because these companies are able to level production across several customers.[6] Significant cost savings were also projected, primarily through better availability of working capital as fixed costs are converted to variable costs.[7] However, many OEMs had missed adapting their internal processes and structures to the new environment. This created a "heterogeneous and chaotic structure of value chains", particularly because different steps in the production process are performed by different companies.[8] In the case of Ericsson, "the production efficiencies were never improved. Instead of outsourcing being an alternative to plant closure the new owners had to lay off the transferred employees and shut down the facilities".[9]

In general, OEMs were faced with collapsing supply chain performance, with both decreasing delivery performance and increasing cost. One global high-tech company, for example, at one point had an overall delivery accuracy of less than 15 percent, which caused lost sales of 20 to 30 percent.[10] Complex forecasting and planning systems that are not aligned across the supply chain, combined with the inherent complexity of the high-tech electronics market, are a primary reason for this performance failure. Such suboptimal planning in the high-tech industry is primarily caused by the complex outsourcing relationships with incompatible IT systems and unclear information flows.[11] Information flows, in general, are a major concern in complex supply chains.[12] A responsive supply chain, which Fisher suggests for innovative products, such as many high-tech electronics products, requires an information flow and policies from the market place to supply chain members in order to hedge inventory and available

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6 Cf. Berggren and Bengtsson: Rethinking Outsourcing in Manufacturing, p. 219.

7 Cf. Hilmola, Olli-Pekka, Petri Helo and Matthias Holweg: On the outsourcing dynamics in the electronics sector: the evolving role of the original design manufacturer, 2005, Working Paper 04/2005, Judge Institue of Management, University of Cambridge, http://www-innovation.jbs.cam.ac.uk/publications/hilmola_outsourcing.pdf, retrieved on: 10 September 2006, p. 2.

8 Cf. Alicke: Planung und Betrieb von Logistiknetzwerken, p. 245.

9 Berggren and Bengtsson: Rethinking Outsourcing in Manufacturing, p. 216.

10 Cf. Karlsson, Axel: Supply Chain Management Interview: Applying Our Know-How, 2006, McKinsey & Company, Inc., http://www.mckinsey.com/clientservice/operations/supplychain/ourexpertise/index.asp, retrieved on: 23 October 2006, p. 1.

11 Cf. Pande, Aditya, Ramesh Raman and Vats Srivatsan: Recapturing your supply chain data, in: McKinsey on IT, Vol. 7 (2006), p. 16.

12 Cf. Forrester, Jay W.: Industrial dynamics: A major breakthrough for decision makers, in: Harvard Business Review, Vol. 36 (1958), No. 4, pp. 40–42.

production capacity against uncertain demand.[13] In the high-tech industry, the trend to outsource production is stretching supply chains across the globe. As a consequence, access to critical data about the supply chain has become difficult or impossible, as details about quality, inventory levels or manufacturing capacity are no longer available. For example, “a computer hardware company’s supply planner, trying to meet a spike in demand for certain products, needs capacity and inventory information from several components suppliers and several contract manufacturers, but the data may be locked up in the IT systems or spreadsheets of a dozen or more companies”.[14] In this industry and elsewhere, supply chain planning and control policies are often suboptimal. This results in inefficient systems that cannot satisfy customer demand appropriately, or only at very high cost. Demand is highly uncertain, product life cycles are short, prices are eroding and supplier lead times are long.[15] Additionally, forecasting is problematic because forecasts often reflect the interests of various stakeholders in the companies that are part of the supply chain. At the same time the transmission of the forecasts through the supply chain does not work well.[16]

The changes in the structure of the high-tech electronics industry imply that “the new competitive battle is no longer between individual companies but between multi-company supply chains”[17], a perception that can be traced back to Michael Porter’s research in 1990, but also to Charles Fine’s “Clockspeed” in 1998.[18] In this dynamic industry in particular, competition is not only taking place on the level of the final product, but firms also compete on the efficiency

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13 Cf. Fisher, Marshall L.: What is the Right Supply Chain for Your Product?, in: Harvard Business Review, Vol. 75 (1997), No. 2, p. 108.

14 Pande, Raman and Srivatsan: Recapturing your supply chain data, p. 16.

15 Cf. Aertsen, Freek and Edward Versteijnen: Responsive Forecasting and Planning Process in the High-Tech Industry, in: The Journal of Business Forecasting, Vol. 25 (2006), No. 2, p. 33.

16 See, for example, Kaipia, Riikka, Hille Korhonen and Helena Hartiala: Planning nervousness in a demand supply network: an empirical study, in: The International Journal of Logistics Management, Vol. 17 (2006), No. 1, p. 95.

17 Cf. Kok, Ton G. de *et al.*: Philips Electronics Synchronizes Its Supply Chain to End the Bullwhip Effect, in: Interfaces, Vol. 35 (2005), No. 1, p. 37, see also Lambert, Douglas M. and Martha C. Cooper: Issues in Supply Chain Management, in: Industrial Marketing Management, Vol. 29 (2000), No. 1, p. 65.

18 See Porter, Michael E.: The competitive advantage of nations, New York 1990, p. 3 and Fine, Charles H.: Clockspeed: Winning Industry Control in the Age of Temporary Advantage, Reading, MA 1998, pp. 74–75 and 99–101. See also Lummus, Rhonda R. and Robert J. Vokurka: Defining supply chain management: a historical perspective and practical guidelines, in: Industrial Management & Data Systems, Vol. 99 (1999), No. 1, p. 11.

and quality of the underlying supply chain network they operate in.[19] The quality of the coordination and planning of supply chain activities becomes an important competitive differentiator.

More than two decades before a Harvard Business Review article put supply chain management on the agenda of top management as an “essential ingredient of competitive success”[20], Jay W. Forrester used a methodology called System Dynamics to develop insights on supply chain dynamics that continue to drive research in supply chain management today[21]. Considering the complexity in many industries, such as the high-tech sector, it is essential to recognize that the feedback structure of a system creates its behaviour, and that redesigning these structures influences the ability of members of the system to alter its behaviour. All decisions taken at any point in the system, such as a supply chain, are embedded in multiple feedback loops and change the behaviour of the entire system. System Dynamics provides a means to enhance the understanding of a system and assess the long-term consequences of policy changes, taking into account delays. In particular, System Dynamics simulation is a useful tool to evaluate the impact of decision rules on supply chain performance.[22]

In the following, a System Dynamics simulation model is developed and used to identify appropriate ways to design supply chains such that they can cope with these challenges. Efficiency and responsiveness are two objectives of supply chain management. Whether or not high performance can be achieved on both dimensions at the same time, however, is questionable. Responsiveness can be defined as the “the ability of the supply chain to respond purposefully and within an appropriate time-scale to customer requests or changes in the market-

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19 Cf. and Linden, Greg: Building Production Networks in Central Europe: The Case of the Electronics Industry, 1998, Working Paper 26, BRIE, University of Berkeley, http://ist-socrates.berkeley.edu/~briewww/publications/WP126.pdf, retrieved on: 21 September 2006, p. 3.

20 Cf. Sharman, Graham: The rediscovery of logistics, in: Harvard Business Review, Vol. 62 (1984), No. 5, p. 71.

21 See Forrester, Jay W.: Industrial Dynamics, Waltham, MA 1961 and Akkermans, Henk and Nico Dellaert: The rediscovery of industrial dynamics: the contribution of system dynamics to supply chain management in a dynamic and fragmented world, in: System Dynamics Review, Vol. 21 (2005), No. 3, p. 174.

22 Cf. Milling, Peter M.: Systemtheoretische und kybernetische Empfehlungen für das Supply Chain Management, in: Scholz, Christian (Ed.): Systemdenken und Virtualisierung. Unternehmensstrategien zur Vitalisierung und Virtualisierung auf der Grundlage von Systemtheorie und Kybernetik, Berlin 2002a, p. 284.

place".[23] In contrast, a supply chain can be considered to be efficient if the focus is on cost reduction and no resources are wasted on non-value added activities.[24]

As Lee notes, "the best supply chains aren't just fast and cost-effective. They are also agile and adaptable, and they ensure that all their companies' interests stay aligned".[25] Decision makers in supply chains face conflicting priorities and need to weigh and balance various performance objectives, such as delivery performance or supply chain costs, and need to find appropriate ways to improve performance on one or both of these dimensions. There may be planning approaches that achieve both, increased efficiency and increased responsiveness, at the same time and optimise the balance between the two for different types of products. By developing a System Dynamics simulation model of a multi-tier supply chain system in the high-tech electronics industry, this work investigates the impact of altering key aspects of the planning activities in the supply chain with the objective of determining the scope for potential improvements in both responsiveness and efficiency of supply chains in this industry. The model developed by the author allows simulation of the dynamics in supply chains as complex as those in the high-tech industry and supports the identification of appropriate supply chain planning approaches for high-tech electronics products. While the model serves primarily as a basis for research, the findings are of high practical relevance. The System Dynamics model can support decision makers in managing supply chains according to the goals of responsiveness and efficiency.

The simulation results show that while the current planning approach in typical supply chains in the high-tech electronics industry is not capable of supporting high responsiveness at the same time as high efficiency, the planning system can be modified to achieve simultaneous improvements in both of these dimensions. The results provide practical guidelines on how to align the supply chain planning approach with different product characteristics and their life cycle phases, with the objective to balance responsiveness and efficiency of the supply chain.

I. Conflicting Priorities in Supply Chains

The term "supply chain management" was first used by Oliver and Webber in 1982, who introduced it as a new perspective that views the supply chain as a

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23 This definition is derived and explained in more detail in section A.II, p. 15.

24 Cf. Naylor, J. Ben, Mohamed M. Naim and Danny Berry: Leagility: Integrating the lean and agile manufacturing paradigms in the total supply chain, in: International Journal of Production Economics, Vol. 62 (1999), p. 108.

25 Lee, Hau L.: The Triple-A Supply Chain, in: Harvard Business Review, Vol. 82 (2004), No. 10, p. 102.

single entity rather than splitting it into different functional areas.[26] They combine ideas from previous research to create a broader concept for addressing what is to be known as supply chain issues. The word "supply chain" can be traced back to 1978, where it was used by Burns and Sivazlian who moved beyond previous research that concentrated on inventory control for individual suppliers and analysed the "dynamic behavior of the multi-echelon supply system".[27] Already in 1958, Forrester outlined the principles of supply chain management, without calling it as such, as studying and managing the complex interrelationships within a production-distribution system.[28] Between then and today, both terms have been defined and redefined in different ways.[29] The definitions provided below characterize supply chains and supply chain management from a systems point of view, which at its core has the basic belief that coordinating across different parts of the system can produce a result greater than that possible through non-coordinated actions.[30] These thoughts are addressed subsequently, following the definitions of supply chains and supply chain management.[31]

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26 Cf. Oliver, Keith R. and Michael D. Webber: Supply-chain management: logistics catches up with strategy (reprint of the original article from 1982), in: Christopher, Martin G. (Ed.): Logistics: The strategic issues, London 1992, pp. 64–66.

27 Cf. Burns, James F. and Boghos D. Sivazlian: Dynamic Analysis of Multi-Echelon Supply Systems, in: Computers & Industrial Engineering, Vol. 2 (1978), No. 4, p. 181. The work by Burns and Sivazlian is strongly linked to System Dynamics. It is an engineering analogue to Jay W. Forresters early work at the MIT in the 1960s and originates from the servomechanism route to feedback that provided useful insights for supply chain management. Cf. section C.I.1 and Towill, Denis R.: Industrial dynamics modelling of supply chains, in: International Journal of Physical Distribution & Logistics Management, Vol. 26 (1996), No. 2, p. 23.

28 Cf. Forrester: Industrial dynamics: A major breakthrough for decision makers, pp. 40–41.

29 For a concise summary of the different supply chain schools of thought refer to Bechtel, Christian and Jayanth Jayaram: Supply Chain Management: A Strategic Perspective, in: The International Journal of Logistics Management, Vol. 8 (1997), No. 1, p. 17.

30 Cf. Bowersox, Donald J.: Physical Distribution Development, Current Status, and Potential, in: Journal of Marketing, Vol. 33 (1969), No. 1, p. 64. See also Simchi-Levi, David, Philip Kaminsky and Edith Simchi-Levi: Designing and managing the supply chain: Concepts, strategies, and case studies, 2nd ed., New York 2003, pp. 1–4.

31 For a thorough review of the different definitions of the terms supply chain and supply chain management refer to Hammer, Andreas: Enabling Successful Supply Chain Management – Coordination, Collaboration, and Integration for Competitive Advantage, Mannheim 2006, pp. 7–47.

Stevens defines the term supply chain as follows:

> "The supply chain… is the connected series of activities which is concerned with planning, coordinating and controlling material, parts and finished goods from suppliers to the customer. It is concerned with two distinct flows through the organisation: material and information. The scope of the supply chain begins with the source of supply and ends at the point of consumption. It extends much further than simply a concern with the physical movement of material and is just as much concerned with supplier management, purchasing, materials management, manufacturing management, facilities planning, customer service and information flow as with transport and physical distribution."[32]

Manufacturing supply chains, as opposed to service supply chains, which are not discussed here, transform raw materials into products that are useful for the end customer. There are multiple flows that need to be managed in industrial companies. Two of the most important ones in supply chain management are material flows and information flows. Material flows refer to products being transported between and within different supply chain nodes. Information flows refer to transferring information between the supply chain nodes, both upstream and downstream, on aspects such as customer orders, demand forecasts, inventory levels and capacity availability. Such information can be shared with some nodes and not with others, and can be updated with varying frequencies.[33] Besides material and information flows, there are also money, manpower and capital equipment flows. Forrester emphasizes that it is critical to understand that all of these flows are not independent from each other but are interlinked and influence each other in ways that are difficult to predict.[34] Stevens recognizes these interrelationships in his description of the objective of supply chain management:

> "The objective of managing the supply chain is to synchronise the requirements of the customer with the flow of material from suppliers in order to effect a balance between what are often seen as the conflicting goals

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32 Stevens, Graham C.: Integrating the Supply Chain, in: International Journal of Physical Distribution & Materials Management, Vol. 19 (1989), No. 8, p. 3. Note that this definition does not include product take back, remanufacturing and reverse logistics that are today also seen as parts of supply chain management. For more details on these aspects of supply chain management refer to Thun, Jörn-Henrik and Jan-Peter Mertens: Simulating the Impact of Reverse Logistics on the Bullwhip Effect in Closed-Loop-Supply Chains using System Dynamics, EurOMA International Conference – Moving Up the Value Chain, Glasgow 2006.

33 Cf. Selldin, Erik: Supply chain design – conceptual models and empirical analyses: http://www2.ipe.liu.se/es/dr/Avhandling%202005-02-20.pdf, 2005, Doctoral Thesis, Linköping Institute of Technology, retrieved on: 19 September 2006, p. 3.

34 Cf. Forrester: Industrial dynamics: A major breakthrough for decision makers, p. 37.

> of high customer service, low inventory investment and low unit cost. The design and operation of an effective supply chain is of fundamental importance to every company."[35]

This implies a synchronisation of the different members in supply chains, which typically are not linear chains with one-to-one, business-to-business relationships. Instead, supply chains can often be thought of as networks with multiple nodes, where different supply chain members can interact with one or multiple other nodes.[36] The goal of supply chain management can be summarized as the coordination and integration of all activities involved in delivering a product into a seamless process, focusing on managing relationships between different supply chain echelons and other parts of the supply chain system and not the optimization of individual components of that system.[37]

In line with this objective, Ellram and Cooper define the term supply chain management as:

> "Supply chain management is an approach whereby the entire network – from suppliers through to the ultimate customers, is analyzed and managed in order to achieve the "best" outcome for the whole system."[38]

While concise, the notion of achieving the "'best' outcome for the whole system", as described in the above definition of supply chain management, requires clarification. Within a single company, according to Porteus and Whang, it is difficult to align the performance measures for different departments with a single set of actions taken by all involved decision makers that maximizes the performance of the system as a whole.[39] Three different perspectives with regard to the goals of supply chain management can be distinguished. These are a (1) the strategic perspective, focusing on the long-term decisions relating to the supply chain, (2) the tactical perspective, focusing on managing the supply

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35 Stevens: Integrating the Supply Chain, p. 3.

36 Cf. Zhang, Yong and David Dilts: System dynamics of supply chain network organization structure, in: Information Systems and eBusiness Management, Vol. 2 (2004), No. 2–3, pp. 187–191 and Lambert and Cooper: Issues in Supply Chain Management, p. 65.

37 Cf. Lummus and Vokurka: Defining supply chain management, p. 11 and Larson, Paul D. and Arni Halldorsson: Logistics versus supply chain management: an international survey, in: International Journal of Logistics: Research & Applications, Vol. 7 (2004), No. 1, p. 18.

38 Ellram, Lisa M. and Martha C. Cooper: The Relationship Between Supply Chain Management and Keiretsu, in: The International Journal of Logistics Management, Vol. 4 (1993), No. 1, p. 1. See also Simchi-Levi, Kaminsky and Simchi-Levi: Designing and managing the supply chain, pp. 1–4.

39 Cf. Porteus, Evan L. and Seungjin Whang: On Manufacturing/Marketing Incentives, in: Management Science, Vol. 37 (1991), No. 9, p. 1166.

chain and implementing the strategy, and (3) the operational perspective, which is concerned with operating the supply chain on a day-to-day basis.[40] In many cases, the strategic goals of the organization cannot be aligned with the operational problems and actions taken by decision makers. Therefore decisions will be taken with respect to objectives of the decision maker that are not necessarily aligned with the objectives of the organization as a whole.

For example, the performance of employees in the sales department may be measured by the customer service level. Customer service in itself is often a major determinant of the long-term success of a company. The sales force is often responsible for preparing the forecasts, e.g. in the high-tech electronics industry, yet forecast accuracy is often not part of their incentive scheme. This can cause over-forecasting by the sales people as they attempt to build up a cushion to maintain the customer service level. For example, Williams observed at On Semiconductor in the late 1990s that "knowing how resources are allocated at the time, Sales quickly learned that the higher the forecast number the larger the capacity reservation they would get". This encouraged them to prepare extremely high forecasts that were eventually adjusted by the manufacturing, planning and finance departments to accommodate their own functional objectives.[41] Similarly, consider a central planning department whose performance is evaluated based on inventory levels, and not total supply chain cost. As a consequence, the planners may focus on lower batch sizes and stock levels without consideration for costs this might incur elsewhere in the system. The manufacturing plants, in turn, may focus on total conversion costs (vs. budget), and not on production reliability, quality, flexibility or waste. This behaviour could cause reduced flexibility, increased lot sizes, and increased fixed cost. As a final example, the purchasing department may be evaluated based on improvements in the cost of purchased materials, and not based on the reliability of the chosen suppliers. This can cause reductions in the reliability and quality of the end product, which could have a major impact on the achievement of the strategic goals of the organization.

This phenomenon of decision-makers aligning their actions to subordinate goals rather than to the organizational goals is known in organization theory as subgoal identification.[42] As a consequence, the organizational goals can be missed, even if the performance measures for different functions are achieved – for example, at a fourth-party logistics (4PL) provider in the electronics industry

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40 Cf. Stevens: Integrating the Supply Chain, p. 4 and Simchi-Levi, Kaminsky and Simchi-Levi: Designing and managing the supply chain, pp. 8–9.

41 Cf. Williams, Tim: Forecasting Journey at On Semiconductor, in: The Journal of Business Forecasting, Vol. 25 (2006), No. 1, p. 29.

42 Cf. Simon, Herbert A.: Rational Decision Making in Business Organizations, in: The American Economic Review, Vol. 69 (1979), No. 4, p. 500.

analysed by Godsell et al. the targets for performance measures are functionally driven. As a consequence, while the 3-day delivery target, which is something that is directly controllable by the organization, is consistently achieved, 99.7 percent of the orders were delivered after the date at which the customer requested the goods, with an average delay of 16 days.[43] In this case, performance measures focus on the part of the supply chain where the company is in direct control, and not on what is important to the customer. A related difficulty is that personal agendas and rivalry also frequently influence the decisions taken by people in the organization.[44]

Regarding the supply chain as a whole, individual entities in that chain may have different objectives. Supply chain managers face conflicting priorities that involve trade-offs between volume, speed, quality and costs. These trade-offs can be caused, for example, by inflexibilities in machines, people or systems, but also by an unclear guideline for decision makers on how to take decisions.[45] Such potential trade-offs that are involved in strategic decision making have an impact on how performance improvements can be achieved.[46] Performance of supply chains can be measured on various dimensions. In their decision-making processes supply chain planners need to consider a diverse set of aspects, including the potentially high costs of supply chain management, the size of inventory levels, the quality of customer service, inter-departmental conflicts and the re-structuring of goals across the supply chain.[47]

If the strategic objective of supply chain management in an organization were to maximize the responsiveness to customer requests at the lowest total cost, measured by delivery performance and inventory turnover, respectively, different outcomes are possible. In this example, the cost of potential lost sales by not being able to deliver on time needs to be balanced with the cost of carrying larger amounts of inventory, which increases as the inventory turn rate decreases. An optimum operating point would achieve 100 percent delivery performance and a very high inventory turnover. Consider the performance of the supply chains A, B and C as visualised in Figure A-1, page 12, which shows the

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43 Cf. Godsell, Janet *et al.*: Customer responsive supply chain strategy: An unnatural act?, in: International Journal of Logistics, Vol. 9 (2006), pp. 54–55.

44 This was pointed out by by Carly Fiorina, former Chairman and CEO of Hewlett-Packard, Palo Alto, during a talk on “Tough Choices” on 18 October 2006 at the Sloan School of Management. See A video recording of the talk is available at http://mitsloan.mit.edu/corporate/dils.php.

45 Cf. Porter, Michael E.: What is strategy?, in: Harvard Business Review, Vol. 74 (1996), No. 6, p. 69.

46 Cf. Porter: What is strategy?, pp. 68–70 and Sharman: The rediscovery of logistics, p. 77.

47 Cf. Stevens: Integrating the Supply Chain, p. 5.

position of the three supply chains in a two-dimensional space with respect to the degrees of efficiency and responsiveness. Assume that each of the three supply chain managers exerts the same amount of effort in achieving the strategic objective and applies the same management practices and tools to the same extent. However, based on their different individual decisions, the performance outcomes are not equal. Supply chain A achieves a high level of responsiveness at a low level of efficiency because inventory costs are relatively high. Supply chain C achieves the opposite, i.e. high efficiency and low responsiveness. Supply chain B achieves medium efficiency and medium responsiveness. The line connecting the three points in Figure A-1 then represents the maximum responsiveness that can be achieved for a given cost level if the three supply chain managers apply all management practices and tools available to them to the fullest extent. This is called the performance frontier. Given the conditions, i.e. available management practices and tools and a given cost level, no higher performance can be achieved.[48] The companies below the performance frontiers do not exploit the full potential of available management practices and technology and perform worse than possible at the benchmark. Such a performance frontier for efficiency and responsiveness of supply chains can, for example, be identified through a survey. One all respondents have been plotted on such a two-dimensional scale, the performance frontier can be identified by connecting the points that have the best linear combinations of efficiency and responsiveness.[49]

Since the strategic objective in this example is the maximization of responsiveness to customer requests at the lowest cost, one can now observe that while the three companies operate on the performance frontier none of the three supply chains truly achieves the strategic objective. Now consider another supply chain manager, who uses different management practices to manage supply chain D. While supply chain D performs better than B on both dimensions, it does not exceed the maximum performance for responsiveness achieved by A and the maximum performance for efficiency achieved by C. For a given cost level, however, D outperforms the supply chains on the original performance frontier with regard to responsiveness, i.e. the two objectives were not subject to a trade-off but simultaneously attainable. Supply chain E, finally, achieves an improvement on both dimensions that shifts the maximum performance on both dimensions to an extent that could not achieved individually by the other supply

48 Cf. Schmenner, Roger W. and Morgan L. Swink: On theory in operations management, in: Journal of Operations Management, Vol. 17 (1998), No. 1, pp. 107–110 and Hammer: Enabling Successful Supply Chain Management, pp. 22–25.

49 Cf. Selldin, Erik: Supply chain frontier: achieving excellence in efficiency and responsiveness, EurOMA International Conference on Operations and Global Competitiveness, Fontainebleau 2004, p. 542.

chains. Supply chain E dominates the other supply chains on both performance dimensions, responsiveness and efficiency.

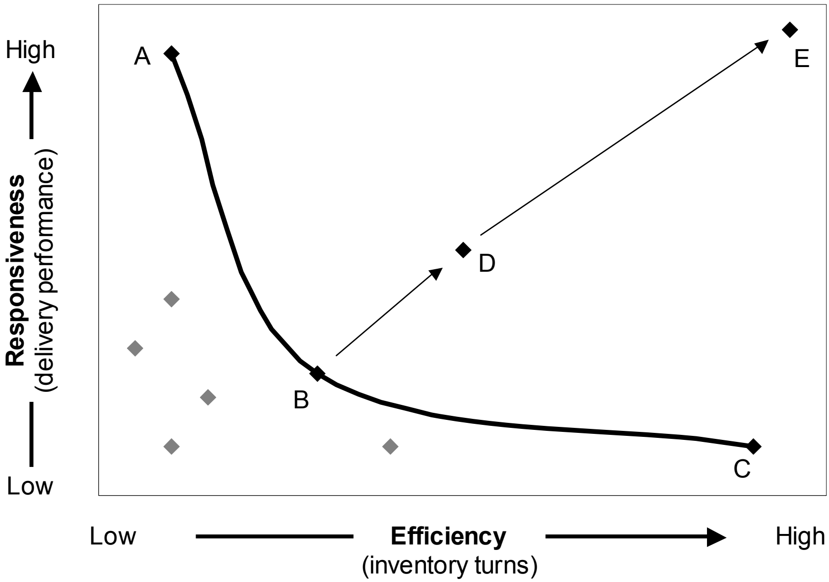

Figure A-1: Potential Responsiveness-Efficiency Trade-Off

In addition to the overall trade-offs relating to the strategic objectives of supply chain management as a whole, any member of a supply chain may attempt to optimize the chain for its own best interests, as opposed to attempting to achieve – possibly to the detriment of own performance objectives – the commonly agreed on goals for the "best" performance of the whole system. Striving for such a commonly agreed goal may involve transfer payments to those supply chain members that may experience higher costs. However, as supply chains in the high-tech electronics industry today are fragmented into operationally and legally independent companies, companies frequently optimize locally and attempt to "game the system instead of coordinating and optimizing the entire supply chain".[50] Attempting such optimization based on own goals as opposed to synchronising the supply chain may have unintended consequences. When a plant shifts ownership of inventory to its suppliers, for example, this causes an increase in inventory costs for these suppliers. This in turn

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[50] Cf. Kok *et al.*: Philips Electronics Synchronizes Its Supply Chain to End the Bullwhip Effect, p. 37.

increases component prices for the plant. Reducing the inventory levels across the entire supply chain, in contrast, can lead to a competitive advantage.[51] An integrated supply chain strategy needs to recognize these trade-offs and can then achieve a balance between supply chain responsiveness and efficiency by modifying the planning and control approaches as necessary.[52]

II. Reconciliation of Responsiveness and Efficiency

A physical function and a market mediation function can be distinguished as two functions of supply chain management. Understanding the difference is a prerequisite for understanding the concepts of responsiveness and efficiency in supply chains. According to Fisher, the physical function of a supply chain includes the conversion of materials into components and finally finished goods, storage of those items and their transportation from one point in the supply chain to the next.[53] The purpose of the market mediation function is to ensure that the "variety of products reaching the marketplace matches what customers want to buy".[54] As Yücesan and Van Wassenhove note, past research often focused more on the physical role than on the market mediation role.[55]

In an efficient supply chain, suppliers, manufacturers and retailers manage – implicitly through independent ordering processes between tiers or through explicit coordination of ordering decisions of the different supply chain elements – their activities in order to meet predictable demand at the lowest cost. The focus is on maintaining high average utilization rates in manufacturing, generating high inventory turns and generally minimizing inventory levels in the supply chain, and selecting suppliers primarily for cost and quality.[56] Coordinating a supply chain to achieve efficiency is a difficult task. In the high-tech electronics industry, for example, consider Hewlett-Packard's supply chain for computer monitors. Having outsourced much of the manufacturing process to contract manufacturers, the problem in this supply chain was that the suppliers were not always aware of their role in the supply chain – "they often didn't even know

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51 Cf. Morais, Richard C.: Damn the torpedoes, in: Forbes, 14 May 2001, 2001, p. 2.

52 Cf. Stevens: Integrating the Supply Chain, p. 3 and Sharman: The rediscovery of logistics, p. 77. See also Oliver and Webber: Supply-chain management: logistics catches up with strategy , pp. 65–69.

53 Cf. Fisher: What is the Right Supply Chain for Your Product?, p. 107.

54 Fisher: What is the Right Supply Chain for Your Product?, p. 107.

55 Cf. Yücesan, Enver and Luk N. Van Wassenhove: Supply-Chain.net: The Impact of Web-Based Technologies on Supply Chain Management, 2002, Working Paper 2002/05/TM/CIMSO 26, The Centre for Integrated Manufacturing and Service Operations, INSEAD, http://ged.insead.edu/fichiersti/inseadwp2002/2002-05.pdf, retrieved on: 19 September 2006, p. 3.

56 Cf. Fisher: What is the Right Supply Chain for Your Product?, p. 108.

that HP was the ultimate destination for their resin or compound". This encouraged the suppliers to carry a lot of inventory to be prepared for potential orders. Unexpected delivery delays that caused lost revenue for all members of the supply chain were similarly common.[57]

A responsive supply chain, in contrast, requires an information flow and policies from the market place to supply chain members in order to hedge inventory and available production capacity against uncertain demand.[58] Accurately fulfilling customer orders is an important determinant for the success of such a supply chain.[59] The notion of responsiveness in supply chains is closely linked to the origins of systems thinking. Its understanding, and along with that its definition, has evolved over time. A number of authors define the responsiveness of a system by linking it exclusively to external events. Ackoff, for example, defines the response of a system as follows:

> "A *response* of a system is a system event for which another event that occurs to the same system or to its environment is necessary but not sufficient; that is, a system event produced by another system or environmental event (the *stimulus*). Thus a response is an event of which the system itself is a coproducer."[60]

This implies that the system can only respond to external stimuli but not to internal events alone, since Ackoff considers the triggering of events without external stimuli as "acts".[61] Holweg relates responsiveness to supply chain management and responsive order fulfilment systems and considers the external "stimulus" to be the customer order, treating it as an exogenous input to the supply chain. [62] Other authors, such as Gonçalves et al., question that demand is exogenous to the system and find that considering demand as an exogenous input to the supply chain system provides results that underestimate the true feed-

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57 Cf. Hammer, Michael: The superefficient company, in: Harvard Business Review, Vol. 70 (2001), September, p. 86.

58 Cf. Fisher: What is the Right Supply Chain for Your Product?, p. 108.

59 Cf. Lee, Hau L.: Aligning Supply Chain Strategies with Product Uncertainties, in: California Management Review, Vol. 44 (2002), No. 3, p. 114.

60 Ackoff, Russell L.: Towards a System of Systems Concepts, in: Management Science, Vol. 17 (1971), No. 11, p. 664.

61 Cf. Ackoff: Towards a System of Systems Concepts, p. 664, and Reichhart, Andreas and Matthias Holweg: Creating the Customer-responsive Supply Chain: A Reconciliation of Concepts, 2006, forthcoming in: International Journal of Operations & Production Management, http://www-innovation.jbs.cam.ac.uk/publications/reichhart_creating.pdf, retrieved on: 10 September 2006, pp. 8–9.

62 Cf. Holweg, Matthias: The three dimensions of responsiveness, in: International Journal of Operations & Production Management, Vol. 25 (2005b), No. 7, p. 605.

back effects in supply chains, as demand depends on the supply chain performance.[63] It is important to take the system boundaries into account when defining responsiveness and it is a prerequisite for defining responsiveness to define the system's customers. The reason is that responsiveness can differ at different nodes in the system. When considering the end customer, high responsiveness is typically a requirement, while internal customers, such as the next stage in a production process, could require less responsiveness due to the presence of raw material buffer stocks, long lead times and large batch sizes.[64]

With regard to supply chain-related definitions of responsiveness, Holweg also emphasizes the aspect that responsiveness relates only to the response to events that are external to the system studied, as opposed to system internal events. Holweg highlights customer demand as a major external stimulus, yet there are other conceivable inputs to supply chain systems that cause responses in supply chain systems, such as changes in the marketplace. As noted above, it may not be appropriate for all purposes to model customer demand as being external to the system, yet it is appropriate to measure responsiveness to end customer demand nonetheless. Based on Holweg[65] and Reichhart and Holweg[66], for the purpose of this work the following definition of supply chain responsiveness is adopted:

> Supply chain responsiveness is the ability of the supply chain to respond purposefully and within an appropriate time-scale to customer requests or changes in the marketplace.

System internal *events*, such as machine break-downs or process output variations, as well as the overall structure of the system, have an impact on and determine supply chain responsiveness. This is captured by the concept of supply chain flexibility, defined as the generic ability of the supply chain to adapt to

63 Cf. Gonçalves, Paulo M., Jim Hines and John D. Sterman: The impact of endogenous demand on push-pull production systems, in: System Dynamics Review, Vol. 21 (2005), No. 3, pp. 211–213. See also Hanssmann, Fred: Optimal Inventory Location and Control in Production and Distribution Networks, in: Operations Research, Vol. 4 (1959), No. 4, p. 484.

64 Cf. Reichhart and Holweg: Creating the Customer-responsive Supply Chain, p. 10f, and Holweg, Matthias: An investigation into supplier responsiveness – Empirical evidence from the automotive industry, in: The International Journal of Logistics Management, Vol. 16 (2005a), No. 1, p. 111.

65 Cf. Holweg: The three dimensions of responsiveness, p. 605 and p. 608. Holweg's definitions are based on and extend Kritchanchai, Duangpun and Bart L. MacCarthy: Responsiveness of the order fulfilment process, in: International Journal of Operations & Production Management, Vol. 19 (1999), No. 8, pp. 812–817.

66 Cf. Reichhart and Holweg: Creating the Customer-responsive Supply Chain, p. 10.

internal and/or external influences.[67] Reichhart and Holweg argue that responsiveness should be measured at the end customer stage only, and that flexibility is a requirement and prerequisite to achieving responsiveness to short-term end customer demand changes. Being responsive to customer demand, as per this definition, requires internal flexibility to be able to react to problems that occur within the supply chain.[68]

Improving responsiveness in a supply chain can incur costs for three primary reasons: (1) excess inventories may need to be maintained, (2) excess buffer capacity may need to be provided and (3) investments to reduce lead times may need to be made. Boeing, for example, at the end of the 1990s failed to achieve sufficient buffer capacity or inventory levels by pursuing a lean manufacturing strategy without considering the variability of demand in the aerospace industry. As a consequence, Boeing was less able to react to a large demand increase than its sole competitor Airbus Industrie and lost market share.[69] If, as in this example, end-user demand is subject to sudden, unpredictable variations, it is not sensible to implement lean manufacturing at the interface with the end user.[70] Regarding investments made to reduce lead times, consider the automotive industry. The current car supply chain allows for little flexibility for responding to customer demand signals. This is not problematic in a market where vehicles are primarily sold from stock. However, in a build-to-order system, as Holweg et al. find, the majority of customers demand delivery within two to three weeks, which is not achievable in the current system.[71] In general, the cost resulting from investments in responsiveness needs to be compared to the opportunity cost of lost sales resulting from stockouts or generally not being able to deliver at the date desired by the customer.[72] Responsive supply chains aim to avoid

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67 Cf. Holweg: The three dimensions of responsiveness, p. 608.

68 Cf. Reichhart and Holweg: Creating the Customer-responsive Supply Chain, pp. 5–11.

69 Cf. Naylor, Naim and Berry: Leagility: Integrating the lean and agile manufacturing paradigms in the total supply chain, p. 108 and p. 112.

70 Cf. Fisher: What is the Right Supply Chain for Your Product?, p. 106 and Naylor, Naim and Berry: Leagility: Integrating the lean and agile manufacturing paradigms in the total supply chain, p. 112.

71 Cf. Holweg, Matthias *et al.*: Towards responsive vehicle supply: a simulation-based investigation into automotive scheduling systems, in: Journal of Operations Management, Vol. 23 (2005), No. 5, pp. 510–511. See also Elias, Simon: New Car Buyer Behaviour, 2002, Research Survey Report April 2002, Cardiff Business School, Cardiff University, http://www.3daycar.com/mainframe/publications/library/newcarbuyer.pdf, retrieved on: 9 October 2006, pp. 14–16.

72 Cf. Thonemann, Ulrich *et al.*: Supply Chain Excellence im Handel – Trends, Erfolgsfaktoren und Best-Practice-Beispiele, Wiesbaden 2005, p. 18.

such stockouts and therefore prioritise the ability to react to changing customer requirements.[73]

The three principal means companies have to buffer against changes in quantity demanded for specific products are inventory, capacity and time. Safety stocks, excess capacity and safety lead times all provide a time buffer to be able to react to demand variability.[74] For suppliers in a supply chain, inventory levels, lead-times, available capacity and batch size are important determinants of responsiveness.[75] One could argue that one sensible approach to increase responsiveness could be to raise the inventory levels of finished goods or components. These higher stock levels would allow more flexibility for reactions to changes in customer demand and reduce the required lead time. Increased inventory levels do, however, reduce the efficiency of the supply chain since they are costly, both in terms of storage cost and cost of capital. Also, increasing inventory for some products implies a reliance on a forecast that could be inaccurate and leave the company with either lost sales or obsolete products, or both.[76] This is related to the newsvendor or newsboy problem studied in behavioural operations research, where a newsvendor faces both overage and underage costs and needs to determine the number of newspapers to stock on a newsstand before observing customer demand.[77] In companies, the problem of determining the appropriate inventory levels before knowing demand is amplified by differences in incentive structures in different departments. Porteus and Whang remark that the trade-off between different performance measures, such as customer service level and inventory costs, arises primarily because there is no performance measure that is simultaneously maximized by a single set of actions taken by all involved decision makers.[78] The trade-off between inventory and

73 Cf. Alicke: Planung und Betrieb von Logistiknetzwerken, p. 147.

74 Cf. Hopp, Wallace J. and Mark L. Spearman: To Pull or Not to Pull: What Is the Question?, in: Manufacturing & Service Operations Management, Vol. 6 (2004), No. 3, p. 145.

75 Cf. Holweg, Matthias and Frits K. Pil: Flexibility First, in: Industrial Engineer, Vol. 37 (2005), No. 6, p. 47.

76 Cf. Kaipia, Riikka: The impact of improved supply chain planning on upstream operations, 17th Annual NOFOMA Conference, Copenhagen 2005, p. 13.

77 Thomas et al. analyse a two-component newsvendor problem in which two complementary components with different lead times must be purchased under demand uncertainty regarding the product into which they are assembled. See Thomas, Douglas J., Donald P. Warsing and Xueyi Zhang: Forecast Updating and Supplier Coordination for Complementary Component Purchases, 2005, Working Paper, Smeal College of Business, The Pennsylvania State University, http://www.personal.psu.edu/faculty/d/j/djt11/papers/forecastupdate.pdf, retrieved on: 10 September 2006, pp. 1–32.

78 Cf. Porteus and Whang: On Manufacturing/Marketing Incentives, p. 1166.

cost suggests that an increase in inventory may not be the optimal approach to increase responsiveness – or, as Hopp and Spearman phrased it: "inventory is the flower of all evil, and variability is its root"[79], i.e. high inventory levels are a sign that something is suboptimal in the supply chain, and other strategies such as variability reductions may be more beneficial than inventory increases.[80]

Providing the right degree of responsiveness and having an efficient supply chain at the same time is a goal that is hard to achieve and that typically involves trade-off decisions by management, since increased responsiveness can be perceived to come at the expense of reduced efficiency, and vice versa.[81] However, there may be strategies, such as revised planning approaches, that restructure supply chain processes to achieve both higher responsiveness and higher efficiency at the same time and enable a supply chain to be responsive and efficient simultaneously. In doing this, there may well be internal trade-offs, such as increased inventory levels at a particular point in the supply chain. Stevens points out that achieving the balance between responsiveness, e.g. service levels, and efficiency, e.g., costs, in a supply chain necessarily involves trade-offs in some parts of the chain.[82] Successful supply chain management in this view requires an integrated perspective of the entire supply chain. This is in line with research indicating that "there is always a trade-off" at some point in the system.[83] Identifying strategies that simultaneously achieve efficiency and responsiveness is the goal of the research presented in this work.

Responsiveness and efficiency are interrelated. They are directly and indirectly linked and even involve feedback. In supply chains, the interrelationships between key parts of the system are complex. There are various players in the supply chain, and each of them addresses aspects of demand, production, and supply management, distribution, planning etc. Each of these aspects also interacts with the others. These interrelationships form feedback loops that either

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79 Hopp and Spearman: To Pull or Not to Pull: What Is the Question?, p. 146.

80 Similarly, Martin Christopher notes that "uncertainty is the mother of inventory" and that inventory merely hides problems. Cf. Christopher, Martin G.: Logistics and Supply Chain Management: Creating Value-Adding Networks, 3rd ed., Harlow 2005, p. 129.

81 Cf. Simchi-Levi, Kaminsky and Simchi-Levi: Designing and managing the supply chain, pp. 113–116, Olhager, Jan: Strategic positioning of the order penetration point, in: International Journal of Production Economics, Vol. 85 (2003), No. 3, p. 328 and Blackhurst, Jennifer *et al.*: An empirically derived agenda of critical research issues for manging supply-chain disruptions, in: International Journal of Production Research, Vol. 43 (2005), No. 19 p. 4077.

82 Cf. Stevens: Integrating the Supply Chain, p. 3.

83 Cf. Hammer: Enabling Successful Supply Chain Management, pp. 72–73, and Schmenner and Swink: On theory in operations management, pp. 106–107.

reinforce or cancel out management initiatives in unintuitive ways. This is the case both when such initiatives are carried out by individual supply chain members in an uncoordinated fashion as well as when supply chain members coordinate their initiatives and attempt to align policies in the supply chain. These feedback loops make problem solving and decision making difficult because it is not at all obvious which combination of strategic or operational levers will have the desired effect in the short or long term. Catalan and Kotzab, for example, identify a responsiveness loop in mobile phone supply chains, shown in Figure A-2. They argue that the current mobile phone supply chains in Denmark are positioned in a negative feedback loop, where lack of real time information exchanges reduces the efficiency of postponement strategies. This increases the bullwhip effect, which reduces demand transparency and time efficiency and in turn again reduces the real time information exchange due to a lack of relationships.[84] The same feedback loop can also be turned into a positive reinforcing feedback loop; however, this would require structural changes, such as building information sharing systems that rely on trust between selected partners.[85]

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84 Cf. Catalan, Michael and Herbert Kotzab: Assessing the responsiveness in the Danish Mobile phone supply chain, in: International Journal of Physical Distribution & Logistics Management, Vol. 33 (2003), No. 8, p. 683.

85 Cf. Catalan and Kotzab: Assessing the responsiveness in the Danish Mobile phone supply chain, pp. 682–683.

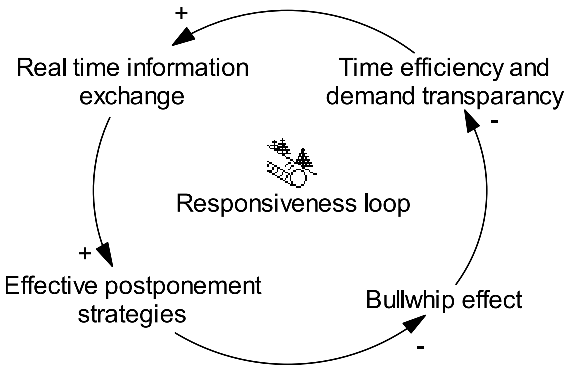

Figure A-2: Responsiveness Loop[86]

As another example of such interrelationships, a deliberate increase in safety stock may raise responsiveness through increased product availability when customer needs change unexpectedly, reducing the required lead time. At the same time, such an increase in inventory levels raises the cost level both directly, i.e. through increased cost of capital and storage costs, as well as indirectly, since the products on stock might not sell and eventually become obsolete. This increased cost level reduces the degree of efficiency. This is an example for a trade-off between efficiency and responsiveness, which is visualised in Figure A-3.[87] Specifically, it can be seen that increasing safety stock is a trade-off decision because an increase in the responsiveness goal increases the willingness to accept higher safety stock, while an increase in the efficiency goal reduces this willingness. The two goals balance each other, causing the system to finally adjust to a specific level of safety stock.

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86 Adapted from Catalan and Kotzab: Assessing the responsiveness in the Danish Mobile phone supply chain, p. 683. The snowball symbol  in Figure A-3 represents the loop polarity, indicating a reinforcing feedback loop. The definitions of link and loop polarity, related time behaviour and many examples can be found in Sterman, John D.: Business Dynamics – Systems Thinking and Modeling for a Complex World, Boston 2000a, pp. 135 et sqq.

87 Cf. Minnich, Dennis A. and Frank H. Maier: Investigating Supply Chain Responsiveness and Efficiency with a System Dynamics-Based Model, EurOMA International Conference – Moving Up the Value Chain, Glasgow 2006a, pp. 337–338 and Minnich, Dennis A. and Frank H. Maier: Supply Chain Responsiveness and Efficiency – Complementing or Contradicting Each Other?, 24th International Conference of the System Dynamics Society, Nijmegen 2006b, p. 5–6.

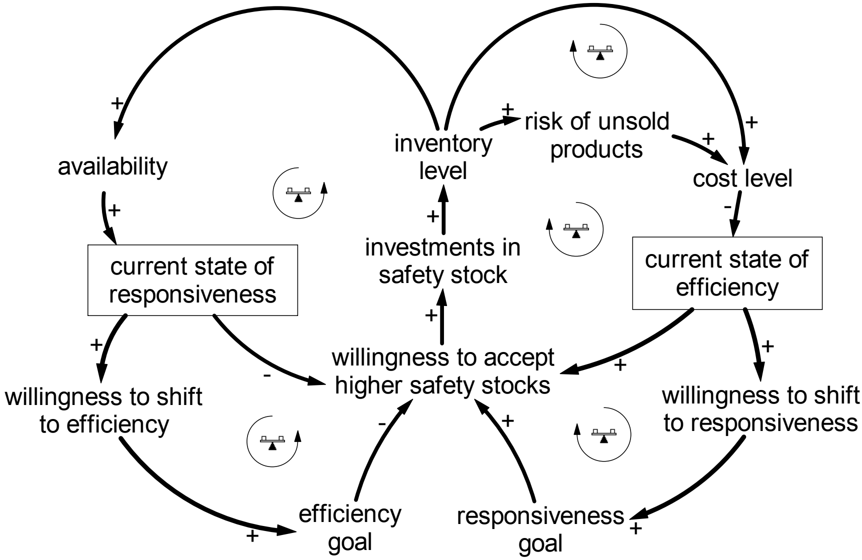

Figure A-3: Inventory Loops: Limits to Success[88]

As outlined previously, there may be investment opportunities that increase both the degree of efficiency and the degree of responsiveness of the supply chain. Hopp and Spearman describe the example of Moog, Inc., a producer of precision servo valves. This company used lean methods to eliminate waste, thus increasing efficiency. At the same time, they increased selected inventory buffers using sophisticated models to segregate certain problems in production, which were addressed later. All other inventory buffers were reduced, again increasing efficiency. The result "has been much greater responsiveness to the customer with improved service. The improved flow also resulted in an unexpected (for management) benefit – a greater than 5% improvement in productivity".[89] One other possibility for such an improvement of supply chain performance on both of these dimensions is to consider the structural conditions of both demand and supply in the (re-)design of the planning system.

Depending on product characteristics, forecast quality etc., certain options may outperform others on both dimensions, responsiveness and efficiency. This could mean, for example, that such a move leads both to improvements in the

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88 The scale symbol and the snowball symbol in Figure A-3 represent the loop polarities, indicating balancing and reinforcing feedback loops, respectively. See Sterman: Business Dynamics, pp. 135 et sqq.

89 Cf. Hopp and Spearman: To Pull or Not to Pull: What Is the Question?, p. 146.

time it takes for the supply chain to adjust to changes in demand, as well as to reductions in safety inventory because of improvements such as lead time reductions. This is visualized in Figure A-4 below.[90] Here, it can be seen that planning improvements are not a trade-off decision because both the responsiveness goal and the efficiency goal increase the willingness to invest in planning improvements. When either efficiency or responsiveness is improved through an improved planning system, willingness to invest shifts to the other goal. This behaviour causes a reinforcing feedback loop, since the investment aimed at achieving the respective other goal will again have a positive impact on the former. There is no boundary for investments in planning systems until both the efficiency and the responsiveness goal are reached, while there is one in the case of safety stock.

These feedback relationships are explained for illustrative purposes at this point. They represent a meta-level of thinking that is not represented explicitly in the System Dynamics model developed later in this work. The time horizon for the developments described here is longer than that represented in the simulation model, which simulates the supply chain behaviour for products with very short life cycles.

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[90] Cf. Minnich and Maier: Investigating Supply Chain Responsiveness and Efficiency with a System Dynamics-Based Model, pp. 338–339 and Minnich and Maier: Supply Chain Responsiveness and Efficiency, pp. 6–7.

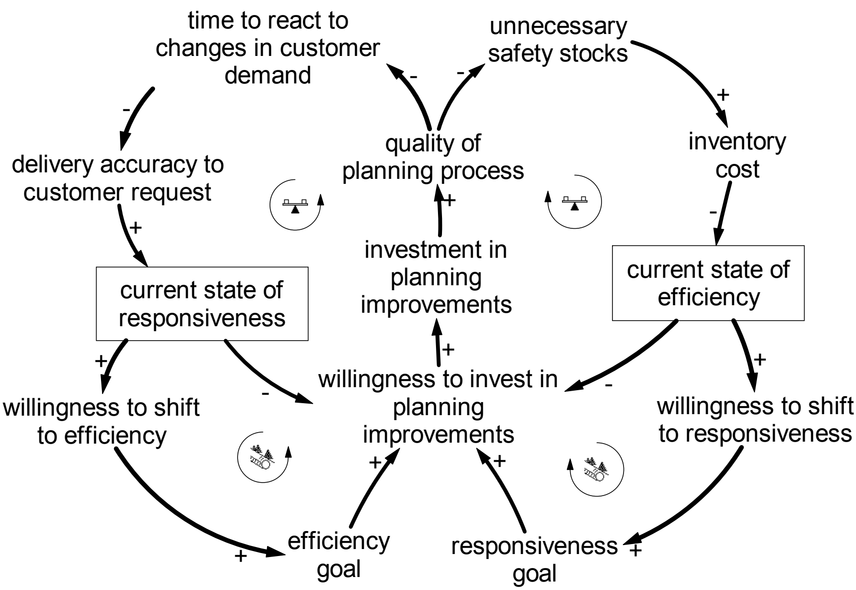

Figure A-4: Planning Loops: Improvements for Growth

There may also be performance measurement problems caused by time delays in the system, leading to suboptimal future decisions. In supply chains, time delays are prevalent at various points. In addition to, for example, long supplier lead times, information about demand takes some time until it passes through the supply chain and might even be distorted on the way. As an example for a performance measurement problem that leads to wrong future decisions, consider an investment in a manufacturing cycle time reduction. This investment may only show a measurable change in relevant performance measures after a certain time period, leading the company to believe that the investment did not cause the desired effects. Initially, performance of the process is reduced as the process is changed and throughput drops for a certain time period while improvements are being made. There is a time delay until results are obtained and the performance of the redesigned process is superior to that of the old process. This typical worse-before-better pattern, in turn, may lead decision makers to discontinue these or similar investments in the initial phase because of their perceived lack of impact, which would have a negative effect on responsiveness.[91]

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91 On the worse-before-better pattern see, for example, Keating, Elizabeth K. *et al.*: Overcoming the Improvement Paradox, in: European Management Journal, Vol. 17 (1999), No. 2.

In addition to such internal policy issues, supply chains often face several other challenges that can reduce the responsiveness of the system. Examples include long component lead times, supply chain disruptions, erroneous components, capacity constraints and missing information about actual end customer demand. Information flows, in general, are a major concern in complex supply chains. A responsive supply chain requires an information flow from the market place to supply chain members in order to hedge inventory and available production capacity against uncertain demand.[92] In the high-tech industry, access to critical data about the supply chain is difficult or impossible due to the global and fragmented supply chain structure.[93] Supply chain planning and control policies are often suboptimal, which results in inefficient systems that cannot satisfy customer demand appropriately, or only at very high cost.

The interrelatedness between responsiveness and efficiency suggests that actions taken to improve efficiency, such as investments in manufacturing cycle time reductions, or different policies, such as modified planning systems, could simultaneously lead to improvements in responsiveness. On the other hand, having achieved a high degree of responsiveness allows management to direct its attention more towards efficiency and cost considerations. In view of this interrelatedness, a focus on responsiveness or efficiency does not necessarily involve a trade-off of the other – empirical studies show that "some plants have overcome the apparent trade off between innovativeness and efficiency".[94]

Thonemann et al. conducted a study of 33 fast-moving consumer goods (FMCG) retailers in four European countries, representing 25 percent of retail revenue in Europe.[95] Their findings show that it is possible for companies to simultaneously keep investment and effort down while guaranteeing a high availability of goods. In the retail industry, high availability of goods means fully stocked shelves, i.e. this represents an inventory investment. Thonemann et al. evaluate the supply chain performance of those companies and contrast the two dimensions of goods availability, which is a measure for the responsiveness of the supply chain, and logistical effort, which is a measure for its efficiency.[96] Their results, as visualised in Figure A-5, show that several companies, which they call champions, outperform their competitors on both dimensions, responsiveness and efficiency.

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92 Cf. Fisher: What is the Right Supply Chain for Your Product?, p. 108.

93 Cf. Pande, Raman and Srivatsan: Recapturing your supply chain data, p. 16.

94 Cf. Thun, Jörn-Henrik: Supply Chain Management and Plant Performance – An Empirical Analysis of the Fisher Model, Sixteenth Annual Conference of POMS, Chicago 2005, pp. 8–9 and 14–16.

95 Cf. Thonemann *et al.*: Supply Chain Excellence im Handel, p. 14.

96 Cf. Thonemann *et al.*: Supply Chain Excellence im Handel, pp. 21–22.

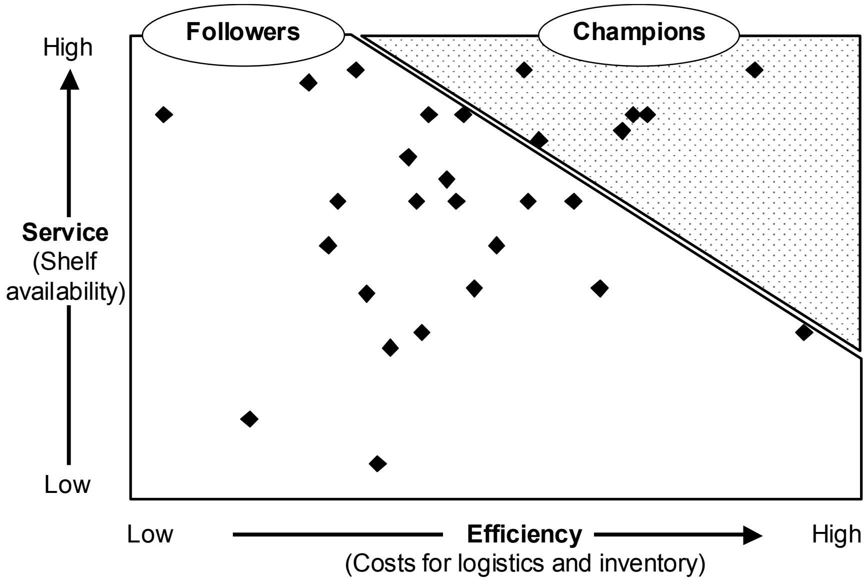

Figure A-5: Supply Chain Performance of Companies in the European Retail Industry[97]

Similarly, research findings by Auramo et al. suggest that it is possible for supply chain members to increase their own operational efficiency while at the same time improving the service provided to their customers, i.e. responsiveness. According to Auramo et al. in their study of the production equipment industry for process industries such as chemical manufacturing or pulp and paper mills, this movement away from the trade-off between responsiveness and efficiency can be achieved by cooperation between customers and suppliers, changing performance measures, using demand information for planning throughout the supply chain and reducing the number of stock keeping units

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97 Adapted from Thonemann *et al.*: Supply Chain Excellence im Handel, p. 22. Used with permission. Goods availability is measured as the number of goods available on store shelves as a percentage of all merchandise carried. Effort is captured as cost for inventory and logistics as a percentage of revenues. The group of champions was identified by expressing the dimensions of service and effort as a percentage of revenue, making the different companies comparable on both dimensions.

(SKUs) to be planned.[98] Given the current structure of supply chains in the high-tech industry, some of these measures are difficult to implement.

Actions taken by supply chain members to improve efficiency may increase their ability to be responsive, and vice versa. In particular, alternative planning systems may allow improvements in both responsiveness and efficiency. For example, Kaipia and Holmström identify this need for alternative planning approaches, particularly for OEMs with wide product portfolios in volatile markets such as the high-tech electronics industry.[99] The author is not aware of any simulation-based study indicating whether introducing alternative planning approaches is an enabler for improvements of both the responsiveness and the efficiency of a supply chain and, in general, to what extent supply chains can "push their performance frontiers to become more competitive".[100] In this context several questions need to be answered.

- Are there specific conditions under which trade-offs between efficiency and responsiveness are likely to occur and/or under which trade-offs can be avoided within the structure of a high-tech electronics supply chain? Is the currently dominant planning approach capable of supporting more responsive supply chain strategies while being efficient at the same time?
- Which supply chain planning policies are required to provide sufficient responsiveness and efficiency for different products at any stage of the product life cycle?
- How can trade-offs be resolved and both responsiveness and efficiency be achieved at the same time?
- If trade-offs can be avoided, should a supply chain focus on efficiency during the initial stages of the product life cycle and then build responsiveness, or should responsiveness come first?

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98 Cf. Auramo, Jaana, Kari Tanskanen and Johanna Småros: Increasing operational efficiency through improved customer service – a case from the process maintenance business, Logistics Research Network (LRN) 8th annual conference, London 2003, p. 2 and pp. 7–9.

99 Cf. Kaipia, Riikka and Jan Holmström: Selecting the right planning approach for a product, in: Supply Chain Management: An International Journal, Vol. 12 (2007), No. 1, p. 7 and pp. 9–12.

100 Cf.Kaipia and Holmström: Selecting the right planning approach for a product, p. 11 and Reichhart and Holweg: Creating the Customer-responsive Supply Chain, pp. 27–28.

- What are the areas of maximum leverage, where current system features pose potential inhibitors to achieving increased responsiveness and efficiency?

These are aspects investigated in this work. The objective of the model is to capture generic structures and the intrinsic dynamics of supply chains and to understand the linkages and dynamics between responsiveness and efficiency in supply chains.

B. Supply Chain Management in the High-Tech Electronics Industry

In any industry, the goal of supply chain management is to satisfy customer requirements efficiently. However, the level of difficulty of finding the appropriate balance between responsiveness to customer requirements and efficiency depends on the industry considered. Supply chains can be designed in different ways for different types of products in order to address this potential trade-off between responsiveness to customer requirements and efficiency, but they are also subject to external factors and challenges. This chapter first provides an overview of the characteristics of production processes and supply chain structures in the high-tech electronics industry. This is followed by a discussion of the challenges that these supply chains face. The chapter concludes with a section on why addressing these supply chain challenges is a critical issue for companies in the high-tech electronics industry and elsewhere.

I. Production Processes and Supply Chain Structures in the High-Tech Electronics Industry

Manufacturing companies can be classified into industrial sectors according to the nature of the products they make. As Berry and Towill note, those boundaries can become blurred when considering a supply chain, as such a chain may cross boundaries between industrial sectors.[101] For example, consider a producer of semiconductors. These are essential components of high-tech electronics products, such as fashionable mobile phones, but are also used by car manufacturers in a different industrial sector, where they face relatively stable demand.[102] Manufacturing companies operating in the high-tech industry comprise both large and small companies in semiconductors and components, enterprise computing, data communications equipment, end-user devices and consumer electronics, software and services, industrial electronics and electro-medical equipment.[103] The focus of this work is on the supply chain layers close to the end customer, thus excluding the details of the supply chain processes in, for

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101 Cf. Berry, Danny and Denis R. Towill: Material Flow in Electronic Product Based Supply Chains, in: International Journal of Logistics Management, Vol. 3 (1992), No. 2, p. 78.

102 Cf. Berry and Towill: Material Flow in Electronic Product Based Supply Chains, p. 78 and Pande, Raman and Srivatsan: Recapturing your supply chain data, p. 18.

103 Cf. n.a.: Defining the high-tech industry, American Electronics Association, 2003, p. 5.

example, semiconductor fabs, which are discussed elsewhere.[104] Similarly, software and computer-related services are excluded. Also, according to Axel Karlsson, partner at the consulting firm McKinsey & Company, Inc., the structure of typical upstream supply chains for companies that manufacture semiconductors and components differs significantly from the general structure typically found in supply chains in the high-tech electronics industry, which is similar for many products.[105] The companies making the semiconductors are suppliers for the supply chains coordinated by the OEMs. In the high-tech electronics industry, these OEMs typically have a high degree of influence on the supply network, which is why they are considered to be focal companies as they take a leadership role in their supply network.[106]

Supply chains for products in the high-tech electronics sector typically stretch from raw materials, such as silicon for wafer manufacturing and crude oil for the plastic used for injection molded cases, through several different component manufacturers who supply the final assembly plant with components.[107] From the final assembly plant, the products pass through companies such as network operators, distributors and/or electronic goods retailers to reach the end customer and ultimate user of the product.[108] There are three main production steps for most high-tech electronics products, such as network routers, mobile phones or MP3 players. These are (1) board printing, also known as printed circuit board assembly (PCBA), (2) final assembly and (3) software flashing, packaging and shipment. The final step of software flashing and packing is usually done in house by OEMs such as Nokia, Ericsson, Apple or Sony-Ericsson, while a large percentage of the rest of the supply chain is often outsourced to contract manufacturers, such as Solectron. These contract manufac-

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[104] See, for example, Gonçalves, Paulo M.: Demand Bubbles and Phantom Orders in Supply Chains, 2003, Doctoral Thesis, Massachusetts Institute of Technology; Gonçalves, Hines and Sterman: The impact of endogenous demand on push-pull production systems; Johnson, Jeffrey D.: Managing Variability in the Semiconductor Supply Chain, 2005, Master's Thesis, Massachusetts Institute of Technology and Lee, Young Hoon *et al.*: Supply chain model for the semiconductor industry in consideration of manufacturing characteristics, in: Production Planning & Control, Vol. 17 (2006), No. 5.

[105] Axel Karlsson, partner at McKinsey & Company, Inc., Stockholm, personal communication, 15 March 2006.

[106] Cf. Harland, Christine M. *et al.*: A Taxonomy of Supply Networks, in: Journal of Supply Chain Management, Vol. 37 (2001), No. 4, Fall, pp. 25–26.

[107] See, for example, Catalan and Kotzab: Assessing the responsiveness in the Danish Mobile phone supply chain, p. 671.

[108] Cf. Olhager, Jan *et al.*: Supply chain impacts at Ericsson – from production units to demand-driven supply units, in: International Journal of Technology Management, Vol. 23 (2002), No. 1/2/3, p. 47.

turers often have a role that exceeds that of providing production capacity according to customer specifications and can encompass raw material purchases as well as product design and planning.[109] Apple, for example, has an own facility for final assembly in Ireland. However, the company also relies on external vendors for final assembly, e.g. final assembly of all of Apple's portable products (PowerBooks, iBooks, iPods) is performed by third-party vendors in Japan, Taiwan and China.[110] Similarly, according to Angel Mendez, senior vice president of worldwide manufacturing at Cisco, the company has "limited internal manufacturing" and outsources most manufacturing processes to contract manufacturers.[111]

As another example, on average, 35 percent of all mobile phone production, encompassing the manufacturing and sub-assembly steps as well as final assembly, was performed by contract manufacturers in 2006.[112] Different companies in the industry take different approaches to outsourcing, as is visualised for the

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109 Cf. Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, p. 97; Mason, Scott J. *et al.*: Improving electronics manufacturing supply chain agility through outsourcing, in: International Journal of Physical Distribution & Logistics Management, Vol. 32 (2002), No. 7, p. 613 and Wendin, Christine: Electronics Manufacturing: EMS at a Crossroads, PriceWaterhouseCoopers, 2004, pp. 3–8.

110 Cf. Apple Computer, Inc.: Form 10-Q: Quarterly Report Pursuant to Section 13 or 15(d) of the Securities Exchange Act of 1934, United States Securities and Exchange Commission, 2006, p. 36.

111 Cf. n.a.: At today's Cisco Systems, the fewer suppliers the better, in: Purchasing Magazine Online, 20 April 2006, 2006, http://www.purchasing.com/index.asp?layout=articlePrint&articleID=CA6324660, retrieved on 9 March 2007, pp. 1–2.

112 Cf. Visiongain: Mobile Handset Outsourcing, 2006, Visiongain, http://www.reportbuyer.com/telecoms/handsets_devices/mobile_handset_outsourcing.html, retrieved on: 9 March 2007, p. 1. In 2004, according to another source, 40 percent of all mobile phone production was performed by contract manufacturers. See Coker, Bill: The ODM Threat to EMS, in: Circuits Assembly, February 2004, 2004, p. 34.

major mobile phone OEMs in Figure B-1. [113] Nokia and Motorola limited their share of handset production that is outsourced to about 20 percent in 2004, with Nokia deciding to "minimize outsourcing, unlike the rest of the industry" in order to keep control over the process, and Motorola attempting to "reach a balance between internal and external production".[114] Siemens outsourced around 30 percent of its handset production at that time. SonyEricsson outsourced two thirds of its production, which makes it the greatest user of contract manufacturers in this industry.[115] SonyEricsson also relies heavily on outsourcing for its other activities, ranging from design and development of the products by ODMs to outsourcing the distribution and repair processes.[116]

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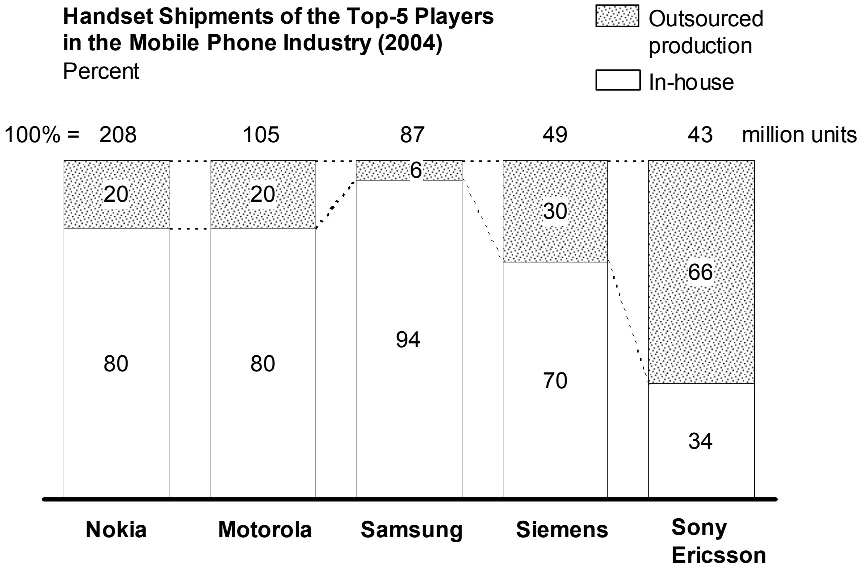
113 The information on worldwide mobile phone shipments was taken from the IDC Worldwide Quarterly Mobile Phone Tracker, published in various press releases on the IDC web site. See IDC: IDC – Press Release: Worldwide Mobile Phone Market Breaks 200 Million Unit Mark in 3Q05, 2005, IDC, http://www.idc.com/getdoc.jsp?containerId=pr2005_10_13_112836, retrieved on: 14 October 2006; IDC: IDC – Press Release: A Strong Fourth Quarter Sends Worldwide Mobile Phone Shipments over 800 Million Unis for 2005, 2006a, IDC, http://www.idc.com/getdoc.jsp?containerId=prUS20056906, retrieved on: 14 October 2006; IDC: IDC – Press Release: Worldwide Mobile Phone Market Exhibits Strong Year-Over-Year Growth on Continued Strength of Developing Markets, 2006c, IDC, http://www.idc.com/getdoc.jsp?containerId=pr2006_04_19_142525, retrieved on: 14 October 2006 and IDC: IDC – Press Release: Mobile Phone Shipments Continue Robust Growth in the Second Quarter, 2006b, IDC, http://www.idc.com/getdoc.jsp?containerId=pr2006_07_19_162102, retrieved on: 14 October 2006.

114 Cf. Coker: The ODM Threat to EMS, p. 34; Morais: Damn the torpedoes, p. 2 and Reinhardt, Andy: The Making of a Nokia Phone, in: Business Week online, 3 August 2006, 2006a, http://images.businessweek.com/ss/06/08/makingof_nokia/index_01.htm, retrieved on 9 March 2007, p. 1.

115 Cf. Wu, Jeffrey: OEMs and EMS - Foxconn makes inroads with Sony Ericsson, in: EMSNow, 7 December 2005, 2005, http://www.emsnow.com/npps/story.cfm?id=15971, retrieved on 9 March 2007, pp. 1–2.

116 Cf. Bowman, Robert J.: Looking Backward: Sony Ericsson Takes on Challenge Of Reverse Logistics, in: Global Logistics and Supply Chain Strategies 2006, http://www.pressroom.ups.com/staticfiles/articles/514.pdf, retrieved on 9 March 2007, pp. 1–4.



Sources: IDC Worldwide Quarterly Mobile Phone Tracker; Coker, Bill: The ODM Threat to EMS, in: Circuits Assembly, February 2004, 2004, pp. 34–37; Wu, Jeffrey: OEMs and EMS - Foxconn makes inroads with Sony Ericsson, in: EMSNow, December 2005, 2005, p. 1.

Figure B-1: Outsourcing in the Mobile Phone Industry: Handset Shipments of the Top-5 players in the Mobile Phone Industry (2004)

Supply chains in this industry consist of multiple fabrication, assembly, testing and packaging sites that are often located in different countries.[117] The simplified supply chain depicted in Figure B-2, for example, has two inbound

[117] Cf. Lee *et al.*: Supply chain model for the semiconductor industry in consideration of manufacturing characteristics, p. 518.

chains, even though in reality there would be multiple.[118] The upper one represents circuit boards, which are electronic components that are needed for final assembly. The chipset suppliers need to use sub-suppliers to obtain, for example, wafers. These wafer suppliers need other raw materials, such as silicon. These relationships are not represented in the figure. The lower inbound chain to final assembly (FAT) deals with other components, for example flips for mobile phones. The *Other FAT supplier* making those flips will need its own suppliers that deliver, for example, plastics (the *2nd tier supplier*). Those plastics suppliers again need raw materials, such as plastic granules, which are made from oil or through reverse logistics processes from recycled plastics parts.[119] Those upstream suppliers are not in the focus of the discussion in this work, which is why they are not represented explicitly in the graph. In this work, the focus is on policy structures at the first tier suppliers, final assembly and testing and software flashing and packing stages.

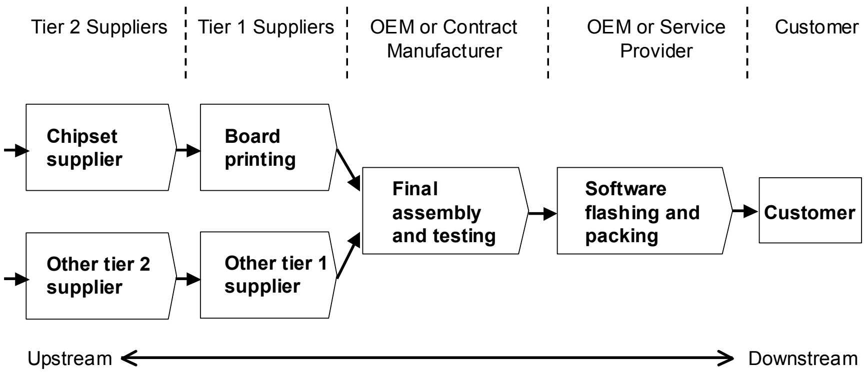


Figure B-2: Supply Chain with Two Sample Inbound Chains

118 This simplified approach to visualizing a supply chain in the high-tech industry is also taken by Olhager *et al.*: Supply chain impacts at Ericsson, p. 47. See also Catalan and Kotzab: Assessing the responsiveness in the Danish Mobile phone supply chain, p. 672, for a more complex representation of the relationships. The definition of first tier suppliers, second tier suppliers etc. depends on the position of the supply chain node considered as the focal company. In this work, while the OEMs are focal companies, software flashing and packing and final assembly and testing are considered as the central parts of the manufacturing process, even though both of these may be outsourced to other companies. The suppliers to final assembly are called the first tier suppliers in line with other representations of similar supply chains.

119 Cf. Catalan and Kotzab: Assessing the responsiveness in the Danish Mobile phone supply chain, p. 671.

Board Printing. The board printing (BP) stage is a fully automated process that is highly capital- and technology intensive.[120] The process requires standard components, such as silicon wafers, as well as more complex components, such as integrated circuits and chipsets. These components are typically imported from other countries, which creates uncertain supply lead times.[121] The circuit boards are typically assembled in this way: "after the arrival of components from suppliers…the components are mounted on both sides of the board. The primary side is mounted first. This side contains most of the components. After rotating the board, the secondary side is mounted. This stage results in a surface mounted assembly", which is then tested for quality to separate functional boards from those with defects.[122] At board printing, each product typically has only one variant; for example, 40 different mobile phone models require 40 different boards. The board printing production step is typically a bottleneck process, since excess capacity is costly. While the equipment is capable of making a high variety of board designs, it is an economic necessity to operate the equipment at board printing at a high utilization rate.[123] Nonetheless, periods with overcapacity could also be observed in the past, for example when capacity utilization dropped from 80 percent in the late 1990s to 17 percent in 2001, and later recovered to between 40 and 80 percent in 2003.[124]

Final Assembly and Testing. The second stage of manufacturing is the final assembly and testing (FAT) process. This process is usually very manual, which is why it typically happens in China or other low cost countries, leading to relatively long delivery lead times. For example, in mobile phone production, this production step involves assembling the display and keypad into the product, as well as testing the device. In mobile phone production, each product gets about 20 versions at this stage, through different types of cover or faceplate colours

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120 Cf. Chang, Shih-Chia, Neng-Pai Lin and Chwen Sheu: Aligning manufacturing flexibility with environmental uncertainty: evidence from high-technology component manufacturers in Taiwan, in: International Journal of Production Research, Vol. 40 (2002), No. 18, p. 4769 and Trovinger, Sheri Coble and Roger E. Bohn: Setup Time Reduction for Electronics Assembly: Combining Simple (SMED) and IT-Based Methods, in: Production and Operations Management, Vol. 14 (2005), No. 2, pp. 207–208.

121 Cf. Chang, Lin and Sheu: Aligning manufacturing flexibility with environmental uncertainty, p. 4769.

122 Cf. Olhager *et al.*: Supply chain impacts at Ericsson, p. 49 and Reinhardt: The Making of a Nokia Phone, p. 7.

123 Cf. Chang, Lin and Sheu: Aligning manufacturing flexibility with environmental uncertainty, p. 4769; Kok *et al.*: Philips Electronics Synchronizes Its Supply Chain to End the Bullwhip Effect, p. 40 and Aertsen and Versteijnen: Responsive Forecasting and Planning Process in the High-Tech Industry, p. 33.

124 Cf. Wendin: Electronics Manufacturing: EMS at a Crossroads, p. 12.

and localized keypads.[125] Final assembly plants typically keep small stocks of component inventories whose size depends on the type of product and the material used. For example, some components such as aluminium have longer lead times than others, such as plastics. At this stage of production, there is usually 50 percent more capacity available than needed.[126]

Software Flashing and Packing. Before the final software flashing and packing production step (SWF) there is a sizable inventory of semi-finished products, which is critical for short-term flexibility. The size of this stock is specified by the OEM and depends on the type of product. For example, stocks of standard mobile phones are typically larger than those of specialized mobile phones, such as phones co-branded with an operator, which are expensive to stock. At software flashing, after receipt of a customer order the software is flashed on the device, the manual, charger and other desired accessories are put into the box, and the package is then shipped to the customers, which are companies such as network operators or distributors.[127] The reason that this step can only begin after receipt of a customer order is that the customers, for example mobile phone operators, often require customized products, with unique software and features that they expect to be installed by the OEM.[128] This production step can happen in the same plant as final assembly and testing and is typically controlled by the OEM; for example, Nokia customizes the products at the final distribution centre with a serial number (IMEI), software, and special features, such as logoed faceplates or special keypad buttons.[129] The alternative is to ship semi-finished products to regional distribution centres and have the flashing done in the local markets, which is often more expensive. Now, there are around 1,000 product versions, while some pieces of software or chargers are the same across products. At this production stage, there is typically 400 percent more capacity available than needed.[130]

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125 Cf. Reinhardt, Andy: Nokia's Magnificent Mobile-Phone Manufacturing Machine, in: Business Week online, 3 August 2006, 2006b, http://www.businessweek.com/globalbiz/content/aug2006/gb20060803_618811.htm, retrieved on 9 March 2007, p. 1.

126 Based on personal communication with Axel Karlsson, partner at McKinsey & Company, Inc., Stockholm, on 31 March 2006.

127 Cf. Olhager *et al.*: Supply chain impacts at Ericsson, p. 47 and p. 49.

128 Cf. Reinhardt: Nokia's Magnificent Mobile-Phone Manufacturing Machine, p. 1.

129 Cf. Reinhardt: Nokia's Magnificent Mobile-Phone Manufacturing Machine, p. 1.

130 Based on personal communication with Axel Karlsson, partner at McKinsey & Company, Inc., Stockholm, on 31 March 2006.

II. Challenges for High-Tech Electronics Supply Chains

Supply chains face a number of challenges that can reduce the responsiveness of the system. Examples include long component lead times, erroneous components, capacity constraints, complex technologies and missing information about actual end customer demand. There are also internal challenges for supply chains, such as mismanagement of the planning process. In particular the high-tech electronics industry is – compared to other industries – confronted with a large number of challenges to supply chain management; the most important ones are summarized in Table B-1. The combination of these challenges leads to delays in both the flow of information and the flow of materials and requires long-term planning.[131]

Table B-1: Challenges in the High-Tech Electronics Industry[132]

Challenges	*Other industries facing these challenges (examples)*
Short product life cycle and rapid price erosion	Pharma, Retail (fashion apparel)
Volatile and unpredictable demand, especially for new products	Retail (fashion apparel)
Stock keeping unit (SKU) proliferation caused by customization requirements	Consumer packaged goods
Long lead time for key components	Retail (fashion apparel)
High supply uncertainty	Some food produce
Demanding customer requirements on lead time and volume flexibility	Automotive
Global low cost country (LCC) based supply chain leading to higher end-to-end complexity	Automotive, Retail (fashion apparel)
Complicated product design involving thousands of components	Automotive
High inventory cost and risk of obsolescence	Automotive

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[131] Cf. Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, p. 95.

[132] Adapted from Jayaram, Kartik *et al.*: Segmented Approach to Supply Chain Management System Design in High Tech, McKinsey & Company, Inc., 2006, p. 4 and extended based on Burruss, Jim and Dorothea Kuettner: Forecasting for Short-Lived Products: Hewlett-Packard's Journey, in: Journal of Business Forecasting Methods & Systems, Vol. 21 (2002), No. 4, p. 9 and Lee: Aligning Supply Chain Strategies with Product Uncertainties, p. 108.

Some of these challenges are not unique and experienced in other industries as well, such as the fashion industry. For example, Christopher et al. as well as Hochmann find that short life cycles, high volatility, seasonality and low predictability, high stock keeping unit (SKU) complexity, long materials lead times and capacity constraints are among the characteristics of the fashion industry.[133] Other challenges are present in the consumer packaged goods industry, such as SKU proliferation. Similarly, automotive companies, such as General Motors, faced an environment with national markets and trade barriers until the 1990s. Today, the environment they operate in is perceived to be more global, with fewer trade barriers and higher customer expectations. New entrants to the industry caused and continue to cause a proliferation of model offerings and brands.[134] This is similar to the development observed in the high-tech electronics industry. The combination of all of these challenges makes supply chains in the high-tech electronics industry a good example for a complex system, providing a large variety of issues to be analysed.[135]

1. Demand Pattern and Product Life Cycle Variations

Short product life cycles, volatile demand, frequent introductions of new products and price erosion are some of the characteristics of the environment that companies in the high-tech industry operate in. Product life cycles are an expression of the time behaviour of unit sales volume of a specific product, or product category, from product introduction to withdrawal of that product from the market.[136] In a broader view, the concept of a product life cycle also includes

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[133] Cf. Christopher, Martin G., Robert Lowson and Helen Peck: Creating agile supply chains in the fashion industry, in: International Journal of Retail & Distribution Management, Vol. 32 (2004), No. 8, p. 367; Christopher, Martin G. and Denis R. Towill: Developing market specific supply chain strategies, in: International Journal of Logistics Management, Vol. 13 (2002), No. 1, pp. 2–7; and Hochmann, Stephen: Flexibility – Finding the Right Fit, in: Supply Chain Management Review, Vol. 9 (2005), No. 5, p. 10.

[134] This was pointed out by by G. Richard Wagoner, Chairman and CEO of General Motors, Detroit, during a talk on “Leadership in the Automotive Industry” on 11 October 2006 at the Sloan School of Management. A video recording of the talk is available at http://mitsloan.mit.edu/corporate/dils.php.

[135] See also Beckman, Sara and Kingshuk K. Sinha: Conducting Academic Research with an Industry Focus: Production and Operations Management in the High Tech Industry, in: Production and Operations Management, Vol. 14 (2005), No. 2, p. 117.

[136] Cf. Harrell, Stephen G. and Elmer D. Taylor: Modeling the Product Life Cycle for Consumer Durables, in: Journal of Marketing, Vol. 45 (1981), No. 4, p. 70.

the research and development processes.[137] The underlying idea of the product life cycle concept is that the demand pattern for a product changes over time. The product life cycle is typically described as having four distinct phases, introduction, growth, maturity and decline, with sales following a typical pattern. Sales increase at first as more and more people adopt the product, and eventually start to decrease when the market is saturated.[138] Some authors, such as Dhalla and Yuspeh, argue that this concept is incapable of capturing the dynamics of the real world since every product and every situation is different. In particular, they find that misperceptions about expected developments can lead to suboptimal decision-making that can be avoided by not subjecting decisions to the concept of the product life cycle.[139] This point is in line with the insights drawn from the System Dynamics methodology about complex systems and has implications for decision makers in marketing and other areas. Nonetheless, the merit of the product life cycle model is that it is simple and intuitive.[140] The dynamics of the actual system are complex, which means that the development of unit sales over time may look very different from what is typically presented as the generic product life cycle. The use of the term product life cycle in this work serves the purpose to highlight that (1) products in the high-tech industry are on the market for a relatively short time and (2) the demand characteristics vary over this time period.

Product life cycles in the high-tech electronics industry are characterised by a strong increase in demand during the introduction phase, followed by a gradual downward trend during maturity and finally an end-of-life demand drop, often caused by a new product generation being introduced.[141] This is visualised for a short life cycle product in Figure B-3 below.

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137 Cf. Milling, Peter M.: Modeling innovation processes for decision support and management simulation, in: System Dynamics Review, Vol. 12 (1996), No. 3, p. 211 and Milling, Peter M. and Frank H. Maier: Invention, Innovation und Diffusion – Eine Simulationsanalyse des Managements neuer Produkte, Berlin 1996, pp. 30–35.

138 Cf. Milling and Maier: Invention, Innovation und Diffusion, p. 33.

139 Cf. Dhalla, Nariman K. and Sonia Yuspeh: Forget the product life cycle concept, in: Harvard Business Review, Vol. 54 (1976), No. 1, pp. 102–103.

140 Cf. Thorelli, Hans B. and Stephen C. Burnett: The Nature of Product Life Cycles for Industrial Goods Businesses, in: Journal of Marketing, Vol. 45 (1981), No. 4, p. 97 and Milling and Maier: Invention, Innovation und Diffusion, p. 34.

141 Cf. Burruss and Kuettner: Forecasting for Short-Lived Products, p. 10.

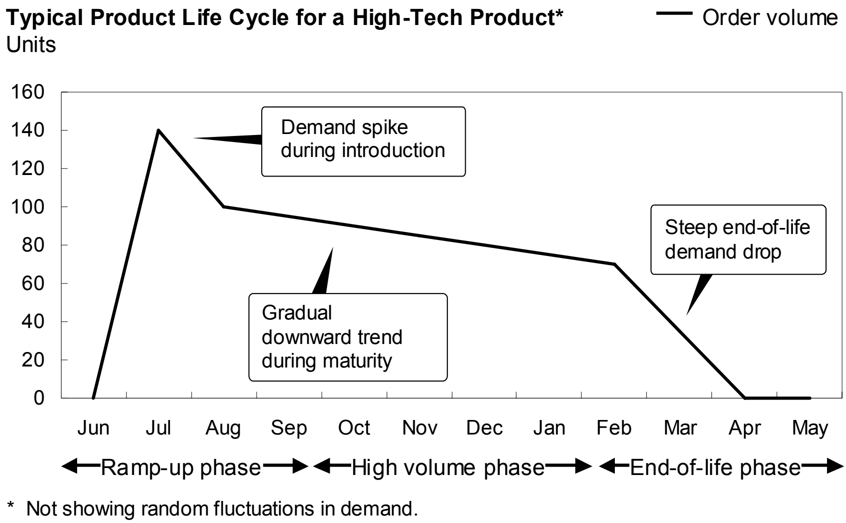

Figure B-3: Typical Product Life Cycle for a Short Life Cycle High-Tech Product[142]

a. Product Launches, Innovation and Proliferation of Product Portfolio

The fast entrance rate of new technologies in the high-tech industry causes short product life cycles for many high-tech products. In such an environment, with high expenditures for research and development and sharp declines in prices after the launch of the products, introducing new products to the market quickly is an important success factor.[143] However, the environment the companies face in the high-tech industry is complex, and it has been argued that "companies [in industries that boast high degrees of innovation] are literally innovating themselves out of business" as reductions in the product life cycle may not lead to sustained increases in revenues and profits. In particular, this may be the case when the new product generations are offered at lower prices, which is usually

142 Based on information from Burruss and Kuettner: Forecasting for Short-Lived Products, p. 10.

143 Cf. Milling, Peter M.: Understanding and managing innovation processes, in: System Dynamics Review, Vol. 18 (2002b), No. 1, p. 80 and Helo, Petri: Managing agility and productivity in the electronics industry, in: Industrial Management + Data Systems, Vol. 104 (2004), No. 7, p. 568.

the case in the high-tech industry.[144] Empirical data on personal computer life cycles between 1974 and 1992 suggest that the short and shortening product life cycles for personal computers are primarily caused by new entrants to the industry, with incumbents not systematically reducing the lifetimes of their own product lines.[145] Some companies may appear to avoid the acceleration trap as it was called by von Braun, but there are other challenges.

According to Kaipia et al. new printer models and mobile phones are today launched into the market every month, compared to once or twice a year in previous years.[146] Companies in this industry have an incentive to introduce products to the market quickly as reductions in the time to market for new products have been shown to affect market share positively.[147] For example, Nokia brings around 40 new mobile phone models to the market each year.[148] This challenge is also present in other supply chains, such as the fashion apparel industry. The Spanish apparel company Inditex, for example, famous for the Zara brand, introduces 20,000 new models per year. The design for these styles is in most

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144 Cf. Braun, Christoph-Friedrich von: The Acceleration Trap in the Real World, in: Sloan Management Review, Vol. 32 (1991), No. 4, p. 46. For a detailed discussion that uses System Dynamics modelling to analyze this so-called acceleration trap, refer to Minnich, Dennis A.: Substitution Effects and The Acceleration Trap – A System Dynamics Perspective on Substitution Effects with Shortening Product Life Cycles, 2003, Bachelor Thesis, International University in Germany.

145 Cf. Bayus, Barry L.: An Analysis of Product Lifetimes in a Technologically Dynamic Industry, in: Management Science, Vol. 44 (1998), No. 6, p. 772.

146 Cf. Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, p. 97.

147 Cf. Milling and Maier: Invention, Innovation und Diffusion, pp. 202–208; and Milling, Peter M. and Andreas Größler: Management von Material- und Informationsflüssen in Supply Chains: System-Dynamics-basierte Analysen, 2001, Arbeitspapier der Fakultät für Betriebswirtschaftslehre der Universität Mannheim, http://iswww.bwl.uni-mannheim.de/lehrstuhl/mitarbeiter/agroe/scm_sd.pdf, retrieved on: 9 August 2006, pp. 80–84, who analyse the market share effect of early or delayed market entry with a System Dynamics model. See also Datar, Srikant *et al.*: Advantages of Time-Based New Product Development in a Fast-Cycle Industry, in: Journal of Marketing Research, Vol. 34 (1997), No. 1, p. 36 and Milling, Peter M., Uwe Schwellbach and Jörn-Henrik Thun: The Role of Speed in Manufacturing, POMS First World Conference on Production and Operations Management, Sevilla 2000, p. 2.

148 Virki, Tarmo: Mobile games publishers pressured to merge, in: Reuters, 12 May 2006, 2006, http://go.reuters.co.uk/, retrieved on 16 September 2006, p. 1

cases copied from designs already available in the marketplace.[149] This particular company is only able to achieve such a high number of new product introductions by producing 75 percent of its products in Europe, close to its headquarters. Also, the company does not rely on outsourcing at all, even for areas such as store construction and information technology.[150] The Spanish apparel manufacturer can design, produce and deliver its new products to retailers within a time frame of only two weeks at the fastest and therefore quickly react to market trends.[151]

In the high-tech industry, not only is the success of each individual product highly uncertain, but there is an interplay between consecutive product generations that creates additional uncertainties.[152] Short product life cycles imply that the window of revenue opportunity, which is the time in which a financial return can be obtained on invested resources, is only available for a limited time – ramp-up and ramp-down curves are steep, but also difficult to predict, while at the same time the maturity phase can be short as newly introduced products replace older generations.[153] The margins during product introduction are particularly important, as they represent a large portion of the profit potential of a product.[154] This can also be observed in the fashion apparel industry, where companies such as Zara, with product life cycles that are often as short as one

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[149] Cf. Cordon, Carlos: Value creation and globalization, in: Conradsen, Niels, Birgitte Malm and John Sarborg Pedersen (Eds.): Værdiskabelse ifremtidens virksomhed – Nye muligheder iden globale konkurrence, Copenhagen 2005, pp. 35–36 and Kumar, Sumit: Supply Chain Strategies in the Apparel Industry: The Case of Victoria's Secret, 2005, Master's Thesis, Massachusetts Institute of Technology, p. 86.

[150] Cf. Cordon: Value creation and globalization , pp. 35–36.

[151] Cf. Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, p. 98.

[152] Cf. Erhun, Feryal, Paulo Gonçalves and Jay Hopman: Moving from Risks to Opportunities: A Process to Manage New Product Transitions, 24th International Conference of the System Dynamics Society, Nijmegen 2006, p. 3. See also Milling: Modeling innovation processes for decision support and management simulation, p. 211 and Milling and Maier: Invention, Innovation und Diffusion, pp. 89–90.

[153] Cf. Catalan and Kotzab: Assessing the responsiveness in the Danish Mobile phone supply chain, p. 677; Helo: Managing agility and productivity in the electronics industry, pp. 568–569 and p. 573 and Kok *et al.*: Philips Electronics Synchronizes Its Supply Chain to End the Bullwhip Effect, p. 45.

[154] Cf. Fisher, Marshall L. *et al.*: Making supply meet demand in an uncertain world, in: Harvard Business Review, Vol. 72 (1994), No. 3, pp. 85–87; Sterman: Business Dynamics, p. 744; and Sterman, John D.: System Dynamics in Action: Managing the Supply Chain in a High-Velocity Industry, 2000b, Unpublished Manuscript, Sloan School of Management, Massachusetts Institute of Technology, p. 1.

month, need to ensure to sell as much as possible of the product at full price.[155] In the high-tech electronics industry, the product life cycle can be as short as a few months. Personal computers and mobile phones, for example, are manufactured for only two to 13 months before a new product generation is introduced, while industrial electronics can have a life cycle of five to 15 years.[156] Therefore companies have to introduce new product generations again and again – as their products progress through the product life cycle, competing firms introduce new technologies and products that make existing products obsolete. Due to this process of product emergence and decay, companies must continuously develop and introduce new generations of products on the market, introduce a larger number of customer-specific variants and phase-out other products at the same time.[157]

It is difficult to identify and predict new trends reliably, which means that companies need to be able to respond quickly to changes in market conditions.[158] BenQ had to declare its German mobile phone subsidiary BenQ-Siemens bankrupt in 2006 following significant losses. One of the reasons for this development is alleged to be that the company was often late to recognize trends in the industry, such as mobile phones with built-in MP3 players, cameras or colour displays.[159] The characteristics of mobile phones are shifting from being complex, engineered products, to mass-oriented fashion products, which requires handset manufacturers to "expand their portfolios in order to comprehensively fulfil market demands with regard to air interface, form factor, technical specifications, multimedia capability" etc., as a research analyst notes.[160] This implies that new models and innovations are demanded by the market continuously, requiring changes to the bill of materials and possibly changes in the

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155 Cf. Hochmann: Flexibility – Finding the Right Fit, p. 11.

156 Cf. Hilmola, Helo and Holweg: On the outsourcing dynamics in the electronics sector, p. 9 and Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, p. 97.

157 Cf. Minnich: Substitution Effects and The Acceleration Trap, p. 2; Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, p. 97; Helo: Managing agility and productivity in the electronics industry, pp. 568–569; Milling and Maier: Invention, Innovation und Diffusion, p. 33 and Erhun, Gonçalves and Hopman: Moving from Risks to Opportunities, p. 2.

158 Cf. Kok *et al.*: Philips Electronics Synchronizes Its Supply Chain to End the Bullwhip Effect, p. 44.

159 Cf. Höfinghoff, Tim: Gekauft, getäuscht, geschlossen, in: Spiegel Online, 28 September 2006, 2006, http://www.spiegel.de/wirtschaft/0,1518,439862,00.html, retrieved on 28 September 2006, p. 1.

160 Cf. Catalan and Kotzab: Assessing the responsiveness in the Danish Mobile phone supply chain, p. 677 and IDC: IDC – Press Release: Worldwide Mobile Phone Market Breaks 200 Million Unit Mark in 3Q05, p. 1.

suppliers that are used. Due to their importance, the planning and execution of such product development and introduction processes in companies in the high-tech electronics industry is a critical success factor for the companies and requires a comprehensive approach with regard to decision making.[161]

b. Original and Induced Demand Uncertainty and Variability

Customer demand in the high-tech industry is highly volatile and uncertain. Additionally, variability is added to the demand signal as information about it is used by the supply chain members and communicated through the system in a distorted way. Harrison distinguishes demand uncertainty from demand variability, noting that uncertainty in demand is caused by unplanned orders or changes in order volumes, while demand variability refers to the magnitude of the fluctuations in demand that are communicated to the supply chain system.[162] The reasons for demand uncertainty and variability are diverse, and are composed of both original customer demand uncertainty, which is exogenous to the supply chain system, and self-induced customer demand variability, which is endogenous to the system.

Original Customer Demand Uncertainty

Original customer demand uncertainty may be lower than one might expect based on observations of demand data. Such original variation in demand can be attributed to seasonal and random demand fluctuations.

Seasonal fluctuations are a common phenomenon in the demand patterns of many high-tech products. In many countries, Christmas time is a period where increased sales for high-tech products can be observed – for many products, including computers, mobile phones, DVD players and video game consoles, this is the peak selling season.[163] For example, the monthly sales pattern for DVD players in the United States since their introduction in 1997 is reproduced

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[161] Cf. Erhun, Gonçalves and Hopman: Moving from Risks to Opportunities, pp. 1–21, who propose a process to facilitate decision making during product transitions and tested that process at Intel. For a comprehensive System Dynamics-based discussion of product development and introduction processes refer to Milling and Maier: Invention, Innovation und Diffusion. See also Milling: Understanding and managing innovation processes, pp. 80–82.

[162] Cf. Harrison, Alan: An Investigation of the Impact of Schedule Stability on Supplier Responsiveness, in: The International Journal of Logistics Management, Vol. 7 (1996), No. 1, p. 83.

[163] See, for example, n.a.: Seasonal But Saturated Mobile Market, in: Business & Finance Magazine, 2 December 2004, 2004, who describe Christmas sales of mobile phones in Ireland.

in Figure B-4.[164] The sales peaks around Christmas in each year can clearly be observed. In other markets, similar trends are observed during other, significant periods of the year, such as Chinese New Year at the end of January.[165] This seasonal buying behaviour is particularly important for consumer products, with less impact on corporate sales for products such as computers.[166]

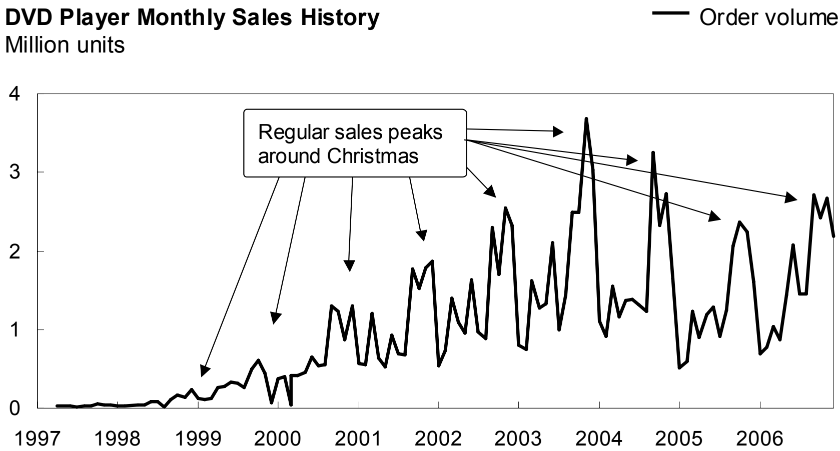

Figure B-4: History of Monthly Sales of DVD players in the US

Demand for high-tech electronics products is also subject to large random fluctuations, known as high-frequency noise, on a day-to-day basis in terms of both product options and volume, which is a challenge to companies operating in this industry. These transient variations in demand arise from reasons such as weather or changes in consumer sentiment and liquidity.[167] However, end customer demand is not observable for the OEMs, since they receive their orders from intermediaries. This structural characteristic can lead to self-induced demand variability.

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[164] The data for Figure B-4 were obtained from n.a.: CEA DVD Player Sales, 2007, http://www.thedigitalbits.com/articles/cemadvdsales.html, retrieved on: 1 April 2007.

[165] Cf. Grinsven, Lucas van: Cellphone sales exceed bullish outlooks: 510 million units in 2003: Total for 2004 will top 560 million, in: National Post, 4 February 2004, 2004, p. 1.

[166] Cf. Mills, Kristin: Christmas PC sales stable but not spectacular, in: Computerworld New Zealand, 18 January 1999, 1999, p. 1.

[167] Cf. Sterman, John D. *et al.*: Getting Big Too Fast: Strategic Dynamics with Increasing Returns and Bounded Rationality, 2007, forthcoming in: Management Science, p. 10.

Induced Demand Variability and the Bullwhip Effect

Some of the variability in demand in the high-tech industry is self-induced by the supply chain members. For example, Lertpattarapong interviewed senior managers at a manufacturer of electronics products providing components for the PC industry, i.e. an upstream supplier. Many of the people interviewed believed that the oscillations in demand that caused large variations in inventory levels were caused by exogenous factors, while the later analysis with a System Dynamics model indicated that the oscillations were in fact caused endogenously by the feedback structure of the system.[168] As an example for the large demand variability for many high-tech products, consider the time behaviour of the daily customer requested shipment dates for a mobile phone over the period of one year, which is shown in Figure B-5.[169] With orders by intermediaries, such as mobile phone operators or major retailers, fluctuating in a range between 0 percent and almost 1,000 percent of average demand, which is indexed at 100 in the diagram, forecasting turns into a gamble for the OEM. Some of this variability could be due to variability in actual end customer demand, while other parts could be caused by structural characteristics of the supply chain.

[168] Cf. Lertpattarapong, Chalermmon: Applying system dynamics approach to the supply chain management problem, 2002, Master's Thesis, Massachusetts Institute of Technology, p. 68 and p. 85.

[169] Empirical data based on a real high-tech electronics product, i.e. a mobile phone. Company name, product and the order of magnitude of actual order volume have been disguised to protect the company's proprietary information. The insights drawn from the disguised data are the same insights that were drawn from the real data. For demand patterns of other high-tech products, refer to Parmar, Varun: Supply Chain Architecture in a High Demand Variability Environment, 2005, Master's Thesis, Massachusetts Institute of Technology, pp. 15–18 and Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, pp. 103–107.

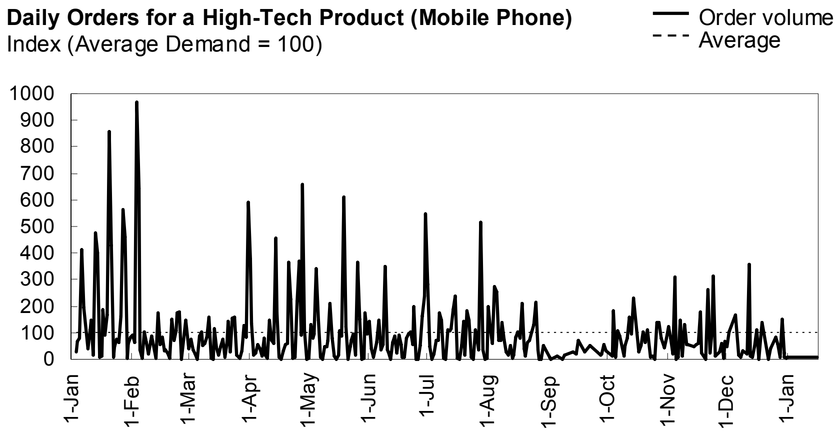

Figure B-5: Daily Orders for a Sample High-Tech Product (Mobile Phone)

The high degree of uncertainty about end customer demand is amplified through the supply chain as first the retailers and then the OEMs adjust their forecasts and orders in both quantities and delivery dates in an attempt to absorb the uncertainty in original end customer demand.[170] Forrester remarks that such adjustments can lead to oscillations in orders and production because of difficulties in demand signal processing and because of non-zero lead-times.[171] This can lead to the erroneous conclusion that sales are seasonal even in industries where sales are, in fact, not seasonal.[172] This is known as the Forrester effect.[173] A different but related dynamic behaviour pattern is the so-called rationing game, which, for example, Heikkilä observes in some supply chains within Nokia.[174] The rationing game refers to customers consistently providing forecasts that are higher than the actual demand that is later observed. The reasoning behind the

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170 Cf. Chang, Lin and Sheu: Aligning manufacturing flexibility with environmental uncertainty, p. 4769 and Parmar: Supply Chain Architecture in a High Demand Variability Environment, p. 15.

171 Cf. Forrester: Industrial Dynamics, pp. 201–206. See also Disney, Stephen M. and Denis R. Towill: On the bullwhip and inventory variance produced by an ordering policy, in: Omega, Vol. 31 (2003), No. 3, p. 157.

172 Cf. Forrester: Industrial dynamics: A major breakthrough for decision makers, p. 45.

173 Cf. Disney and Towill: On the bullwhip and inventory variance produced by an ordering policy, p. 157.

174 Cf. Heikkilä, Jussi: From supply to demand chain management: efficiency and customer satisfaction, in: Journal of Operations Management, Vol. 20 (2002a), No. 6, p. 758.

rationing game is that it occurs when the customers expect supply to be limited, for example when they experience significant delivery delays due to capacity limitations at the supplier. The customers believe that the supplier rations supply and typically face an incentive structure that encourages them to attempt not to be out of stock. Therefore they issue orders that exceed the quantity they would order if supply were unlimited in order to secure more units and secure a place in the queue at the supplier.[175] The forecasting systems at suppliers receiving those inflated orders have no possibility to identify that the data are inflated and thus treat them as regular orders. The customers, on the other hand, will cancel these additional orders, also known as phantom orders, as soon as the receive the desired products.[176] Being one of the causes of the bullwhip effect, this is known as the Houlihan effect.[177] Houlihan's findings suggest that the effect can amplify and that the over-ordering can cause even more shortages, which in turn causes additional over-ordering and increased build-up of safety stocks.[178]

It has been mentioned above that the Christmas sales surge or other similar seasonal demand surges are more pronounced with private buyers than with corporate buyers. However, "seasonal" effects can be observed even in the corporate business. For example, for one product of Cisco's Optical Networking Group, Parmar observes a demand of less than 12 units for all but one month in 2003. During December, demand increased to 78 units.[179] A reason may be the incentive system for sales people, since they typically operate based on regular, e.g. monthly, quarterly, or yearly, goals. According to Lee et al., this can lead to end-of-month, end-of-quarter or end-of-year order surges, with sales people signing orders prematurely in an attempt to fulfil their quotas.[180] This common phenomenon, often referred to as the hockey stick, could explain some of the spikes in Figure B-5 above. Also, the companies running material requirements planning (MRP) systems may generate their purchase orders at regular intervals, e.g. at the beginning of each month, which could cause order cycles to overlap

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[175] Cf. Lee, Hau L., V. Paddy Padmanabhan and Seungjin Whang: Information Distortion in a Supply Chain: The Bullwhip Effect, in: Management Science, Vol. 43 (1997b), No. 4, p. 551.

[176] Cf. Gonçalves: Demand Bubbles and Phantom Orders in Supply Chains, pp. 89–141.

[177] Cf. Disney and Towill: On the bullwhip and inventory variance produced by an ordering policy, p. 158.

[178] Cf. Houlihan, John B.: International Supply Chain Management, in: International Journal of Physical Distribution & Materials Management, Vol. 17 (1987), No. 2, p. 57 and Wendin: Electronics Manufacturing: EMS at a Crossroads, p. 13.

[179] Cf. Parmar: Supply Chain Architecture in a High Demand Variability Environment, p. 15.

[180] Cf. Lee, Hau L., V. Paddy Padmanabhan and Seungjin Whang: The bullwhip effect in supply chains, in: Sloan Management Review, Vol. 38 (1997a), No. 3, p. 96.

and contribute to the bullwhip effect through “MRP jitters”.[181] Order batching can also lead to increased upstream variability in the supply chain, and refers to the practice of placing orders in batches in order to gain economies of scale in the ordering process. This could, for example, be the result of the calculation of economic order quantities and is known as the Burbridge effect.[182] Finally, seasonality in corporate sales could be driven by financial concerns; e.g. in the pharmaceutical industry large orders may be placed by distributors at the end of the financial year for tax purposes or to look less attractive to a potential acquirer.[183] The author experienced the hockey stick behaviour himself in a case where incoming orders surged at the end of every month, causing significant turbulence in the planning systems of the company that was affected. The author also obtained anecdotal evidence from several other similar cases, including e.g. the German operations of a Taiwanese computer company, where corporate sales for personal computers spike every December.[184]

Speculative buying to take advantage of unstable prices is an additional source of self-induced demand variability.[185] Sales promotions, for example, can cause erratic order patterns and distort original demand data, as demand is now different than it would have been without the promotion.[186] Customers stock up on the cheaper products, which causes sales to drop as soon as the promotion ends.[187] With insufficient information sharing between supply chain members, this can become a major reason for upstream demand volatility. In a related case, Bhattacherjee describes that in the generic drugs industry speculative buy-

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181 Cf. Lee, Padmanabhan and Whang: Information Distortion in a Supply Chain: The Bullwhip Effect, pp. 96–97.

182 Cf. Disney and Towill: On the bullwhip and inventory variance produced by an ordering policy, p. 158.

183 Cf. Bhattacherjee, Anol: Beginning SAP R/3 Implementation at Geneva Pharmaceuticals, in: Communications of the Association for Information Systems, Vol. 4 (2000), No. 2, p. 7.

184 Since these are corporate sales, this observation is unlikely to be related to the Christmas sales surge for home computers.

185 Moyaux and McBurney argue for the contrary. In their preliminary work, they present a computer simulation model that indicates that speculative buying could be a means to reduce the bullwhip effect and thus volatility in the supply chain. See Moyaux, Thierry and Peter McBurney: Reduction of the Bullwhip Effect in Supply Chains through Speculation, 2006, Working Paper, Department of Computer Science, University of Liverpool, http://www.csc.liv.ac.uk/~moyaux/moyaux06ae.pdf, retrieved on: 17 October 2006, pp. 6–9.

186 Cf. Lee, Hau L. and Seungjin Whang: Information sharing in a supply chain, in: International Journal of Technology Management, Vol. 20 (2000), No. 3/4, p. 378 and Alicke: Planung und Betrieb von Logistiknetzwerken, p. 108.

187 Cf. Alicke: Planung und Betrieb von Logistiknetzwerken, p. 108.

ing by customers is a major cause of difficulties. In this industry, "prices of drugs are typically reassessed at the start of every fiscal year, and the distributors may place very large orders at the end of the previous year to stock up on drugs whose prices are expected to increase next year".[188] This cannot be addressed with safety stock due to the high cost of keeping inventories and low margins in the industry.[189]

All of these behaviours are related to what is known as the bullwhip effect, which is a term used to describe the amplification of demand variability from a downstream supply chain node to an upstream supply chain node.[190] However, the systematic errors made by decision-makers who face a complex environment with multiple feedback loops, time delays and nonlinearities lead to the existence of the bullwhip effect even in the absence of the aforementioned behaviours. Even when demand is stationary and fully known to all members in a supply chain, without forecasts being submitted through the supply chain, without any reasons for the hockey stick phenomenon, without sales promotions and without speculative buying (as prices are constant), the bullwhip effect still occurs, as demonstrated by Croson and Donohue, Sterman and Dogan and Sterman.[191] Reasons for this observation relate to the bounded rationality of decision makers, discussed in more detail in section C.I.1, and include cognitive limitations and inherent difficulties in managing a complex system. More specifically, these boundedly rational behaviours of decision makers in supply chains include anchoring in the choice of the desired inventory level to the initial level (as opposed to determining the optimal inventory levels), misperceptions of time lags (e.g., between placing and receiving orders), and not accounting appropriately for the supply line of materials on order.[192]

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188 Bhattacherjee: Beginning SAP R/3 Implementation at Geneva Pharmaceuticals, p. 7.

189 Cf. Bhattacherjee: Beginning SAP R/3 Implementation at Geneva Pharmaceuticals, p. 7.

190 Cf. Lee, Padmanabhan and Whang: Information Distortion in a Supply Chain: The Bullwhip Effect, p. 546.

191 Cf. Croson, Rachel and Karen Donahue: Behavioral Causes of the Bullwhip Effect and the Observed Value of Inventory Information, in: Management Science, Vol. 52 (2006), No. 3, pp. 327–335; Sterman, John D.: Modeling Managerial Behavior: Misperceptions of Feedback in a Dynamic Decision Making Experiment, in: Management Science, Vol. 35 (1989), No. 3, pp. 328–338; Dogan, Gökhan and John D. Sterman: "I'm not hoarding, I'm just stocking up before the hoarders get here", 24th International Conference of the System Dynamics Society, Nijmegen 2006, pp. 6–33.

192 Cf. Croson and Donahue: Behavioral Causes of the Bullwhip Effect and the Observed Value of Inventory Information, pp. 332–333 and Sterman: Modeling Managerial Behavior, pp. 334–335.

c. Pressure for Reduced Cost Levels

Short product life cycles create a pressure for companies to reduce both the time to develop new products and the time it takes to introduce them on the market. This needs to be achieved without major cost increases, as Morita et al. point out, because the prices of new product generations are in many cases lower than those of previous generations.[193] Such decreases in product prices over time can be observed for many mass-produced goods. Price erosion is typically caused by advances to manufacturing processes, learning effects and increased competition.[194] The pace at which prices fall in the high-tech industry is particularly fast, which poses a challenge for companies operating in this industry. For example, the mobile phone Motorola V290 experienced a 20 percent drop in selling price within three months, after a period of five months of relatively constant prices.[195] The average retail price of DVD players in the United States of America declined by nearly 40 percent between the first half of 1997 and the second half of 1998.[196] The average retail price of desktop PCs was found to decline by more than 50 percent over the first year of the product life cycle, while many component prices decline between one percent per week (a 40 percent reduction in one year) and two percent per week (a 65 percent reduction in one year).[197] Holding large amounts of inventory in such an environment is therefore not desirable due to the reduction in value. Similarly, for notebook computers the selling price of a model typically erodes faster than the price of its components, making it necessary to “upgrade [the] model periodically to maintain profit margins”.[198] Price erosion thus creates a pressure to manage

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193 Cf. Morita, Michiya *et al.*: High Speed Competence and Short Product Life Cycle, POMS First World Conference on Production and Operations Management, Sevilla 2000.

194 Cf. Helo: Managing agility and productivity in the electronics industry, p. 569.

195 Cf. Liu, Bin *et al.*: Two-Stage Ordering Decision for a Short-Life-Cycle Product, in: Journal of Systems Science and Systems Engineering, Vol. 15 (2006), No. 3, p. 343.

196 Cf. Liegey, Paul R.: Developing an Hedonic Regression Model For DVD Players In the U.S. CPI, 2001, U.S. Department of Labor: Bureau of Labor Statistics, http://www.bls.gov/cpi/cpidvd.htm, retrieved on: 20 October 2006, p. 1.

197 Cf. Lee, Hau L. *et al.*: Price Protection in the Personal Computer Industry, in: Management Science, Vol. 46 (2000), No. 4, p. 467, Khouja, Moutaz and Sungjune Park: Optimal lot sizing under continuous price decrease, in: Omega, Vol. 31 (2003), No. 6, p. 539 and Kapuscinski, Roman *et al.*: Inventory Decisions in Dell's Supply Chain, in: Interfaces, Vol. 34 (2004), No. 3, p. 191. See also Milling: Modeling innovation processes for decision support and management simulation, pp. 211–212.

198 Rutherford, Derek P. and Wilbert E. Wilhelm: Forecasting notebook computer price as a function of constituent features, in: Computers & Industrial Engineering, Vol. 37 (1999), No. 4, p. 826.

supply chains efficiently and is closely linked to the short duration of the product life cycles in this industry.

2. Product Complexity

Another reason that makes supply chains in the high-tech industry, for example, difficult to manage is the high complexity of the products. A typical mobile phone consists of 400 components, ranging from resistors and capacitors to processors, colour displays, and keypads; a mobile phone OEM such as Nokia assembles up to 275 million parts per day.[199] Product complexity may even be increasing, as new products may have a more complex manufacturing process than previous generations. Such increased complexity may lead to higher manufacturing times and lead times, which reduces the ability to respond to changes in demand.[200] Managing material flows is a key capability that is needed to successfully operate in such an environment. A study on the relationship between product complexity and vertical integration in the automotive industry by Novak and Eppinger suggests that vertical integration may be more suitable for complex products than outsourcing; they find a significant positive relationship between product complexity and vertical integration.[201] Their finding suggests the outsourcing trend in high-tech may be suboptimal as the complex products may be handled better by a vertically integrated supply chain.

3. Mismatch of Customer Requirements and Supplier Capabilities

Companies in the high-tech industry face a situation where the supplier lead times for some components are very long while at the same time their customers demand short order-to-delivery (OTD) lead times as well as a high degree of customization. The mismatch between long planning horizons and market requirements for lead time and volume flexibility may lead to significant problems in the supply chain.[202] During the last decades, companies in many industries have come under pressure to meet increasing standards in the variety of prod-

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[199] Cf. Reinhardt: Nokia's Magnificent Mobile-Phone Manufacturing Machine, p. 1.

[200] Cf. Lertpattarapong: Applying system dynamics approach to the supply chain management problem, p. 7 and p. 35.

[201] Cf. Novak, Sharon and Steven D. Eppinger: Sourcing By Design: Product Complexity and the Supply Chain, in: Management Science, Vol. 4 (2001), No. 1, p. 189 and pp. 202–203.

[202] Cf. Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, p. 96 and Reinhardt: Nokia's Magnificent Mobile-Phone Manufacturing Machine, p. 1.

ucts offered and their delivery performance.[203] In particular, since the beginning of the 1990s the critical success factors for manufacturing companies have evolved from including only cost and quality to also including time. This development is regarded as an important turning point in operations management as it has an influence on many different markets, with particular relevance for the business to business market.[204] Companies in the high-tech electronics industry are especially influenced by this trend of customers demanding more differentiated products within shorter delivery times. This is leveraged by companies such as Dell, a company focusing on the direct delivery of customized computer products within short lead times.[205] Customers demand not only continuous reductions in lead times but also expect that their orders are delivered punctually – an aspect that well-designed supply chains can exploit as a potential competitive advantage.[206]

A complication to achieving this goal is that some components needed for manufacturing high-tech products have long and variable manufacturing lead times. In the case of Cisco, components for networking products have lead times ranging between two and 24 weeks.[207] Expensive application-specific integrated circuits (ASICs), for example, are unique to the respective product.[208] In mobile phone production, for instance, each mobile phone model uses boards with different integrated circuits. Producing the wafers required to make the integrated circuits is a complex process characterised by long lead times, yield variations and capacity limitations.[209] Equipment can also fail as machines break down. Also, the lead times in the supply chain and the output of the processes may

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203 Cf. McCutcheon, David M., Amitabh S. Raturi and Jack R. Meredith: The Customization-Responsiveness Squeeze, in: Sloan Management Review, Vol. 35 (1994), No. 2, pp. 91–92.

204 Cf. Milling, Schwellbach and Thun: The Role of Speed in Manufacturing, p. 2; Helo: Managing agility and productivity in the electronics industry, pp. 568–589. and Thun, Jörn-Henrik *et al.*: Production Cycle Time as a Source of Unique Strategic Competitiveness – An Empirical Analysis based on the "World Class Manufacturing"-Project, POMS First World Conference on Production and Operations Management, Sevilla 2000, pp. 1–2.

205 Cf. Helo: Managing agility and productivity in the electronics industry, pp. 567–568 and Christopher, Martin G. and Denis R. Towill: Supply chain migration from lean and functional to agile and customised, in: Supply Chain Management, Vol. 5 (2000), No. 4, p. 212.

206 Cf. Milling, Schwellbach and Thun: The Role of Speed in Manufacturing, pp. 2–3.

207 Cf. Parmar: Supply Chain Architecture in a High Demand Variability Environment, p. 20.

208 Cf. Kok *et al.*: Philips Electronics Synchronizes Its Supply Chain to End the Bullwhip Effect, p. 39.

209 Cf. Gonçalves: Demand Bubbles and Phantom Orders in Supply Chains, p. 72–81.

vary and prices can change.[210] All of these uncertainties in the supply chain affect the performance of the system. The process of wafer and integrated circuit production is a bottleneck in many high-tech electronics supply chains and requires planners to consider the possibility of disruptions in the flow of components from the suppliers.[211] In 2000, for example, a fire caused by lightning damaged millions of microchips in a Philips plant. Customers of that plant included Nokia and Ericsson. While Nokia was able to switch production to other suppliers almost immediately, Ericsson employed a single-sourcing policy and as a consequence faced disrupted production for months, causing lost sales of US$400 million.[212] As setting up a wafer-fabrication facility (fab) takes a long time and is very expensive, with the equipment used being extremely complex and costly, high utilization rates need to be maintained and it is expensive to provide excess capacity.[213] However, the level of preparedness for such disruptions differs for different companies, as the above example showed.

Regarding the duration of the manufacturing and shipment processes, the process of making the wafers alone, including wafer testing, can take 12 weeks. Assembly of the integrated circuits is also a complex process. This involves fabricating complex devices on the silicon wafers, testing these for functionality, separating them into dies and mounting these in substrates, final testing and

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210 Cf. Kaipia: The impact of improved supply chain planning on upstream operations, p. 1. For an example of how the interplay of limited capacity, short product life cycles, technological innovations and complex technology can create major price changes, see Helo: Managing agility and productivity in the electronics industry, p. 571.

211 Cf. Kok *et al.*: Philips Electronics Synchronizes Its Supply Chain to End the Bullwhip Effect, p. 40 and Kaipia: The impact of improved supply chain planning on upstream operations, p. 3.

212 Cf. Chopra, Sunil and ManMohan S. Sodhi: Managing Risk To Avoid Supply-Chain Breakdown, in: Sloan Management Review, Vol. 46 (2004), No. 1, p. 53.

213 Setting up a new wafer fab usually costs several billion dollars (doubling time three years), with equipment representing around 80 percent of the total cost. Construction takes around four to five years. During this time, demand can deviate as much as 80 percent from the original forecast. Cf. Padillo, José M. and Doron Meyersdorf: A strategic domain, in: IIE Solutions, Vol. 30 (1998), No. 3, p. 37; Vaidyanathan, Viswanath, Dave Metcalf and Douglas Martin: Using Capacity Options to Better Enable Our Factory Ramps, in: Intel Technology Journal, Vol. 9 (2005), No. 3, p. 186; Gonçalves: Demand Bubbles and Phantom Orders in Supply Chains, p. 76 and Beckman and Sinha: Conducting Academic Research with an Industry Focus, p. 120.

configuration.[214] This process can take another 3 weeks.[215] Finally, transportation times can be an additional cause of long lead times, since the components for many products come from multiple countries and regions.[216] Ritter and Sternfels note that sending high-tech electronics products by sea, with shipment times of several weeks, can translate into price declines of two to six percent.[217] In the high-tech industry, this particular problem can often be addressed by using air shipments, as the volume per kilo is small. Nevertheless, in sum, the complete turn time for a supply chain can be several months.[218]

Cisco's Optical Networking Group, for example, faces a low volume of orders combined with a high configurability of the products. For most components that are built into Cisco's equipment, lead times range between 10 and 16 weeks. At the same time, its customers require shipment of 90 percent of the orders within 15 days. This situation, combined with large order variability and uncertainty, requires Cisco to build the products to stock and ship them as the customers order them.[219] The car industry is confronted with similar problems. Holweg et al. note that the average order-to-delivery lead time for built-to-order volume cars in Europe is 48 days. While studies show that customers are interested in being able to configure cars to their personal preferences, many are not willing to wait more than three weeks to receive them.[220] This phenomenon is called the customization-responsiveness squeeze.[221] Additionally, suppliers further upstream in the car supply chain also face the problem of customers de-

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214 The individual devices obtained when sawing the wafer are called dies. These are then assembled with substrates that provide physical protection and electrical connectivity. Cf. Bean, John W. *et al.*: Optimizing Supply-Chain Planning, in: Intel Technology Journal, Vol. 9 (2005), No. 3, p. 223.

215 Cf. Kok *et al.*: Philips Electronics Synchronizes Its Supply Chain to End the Bullwhip Effect, p. 39.

216 Cf. Chang, Lin and Sheu: Aligning manufacturing flexibility with environmental uncertainty, p. 4770.

217 Ritter, Ronald C. and Robert A. Sternfels: When offshore manufacturing doesn't make sense, in: The McKinsey Quarterly, Vol. 4 (2004), p. 126.

218 See also Helo: Managing agility and productivity in the electronics industry, p. 571f., who provides an example of an electronics supply chain with a total turn time of 90 days.

219 Parmar: Supply Chain Architecture in a High Demand Variability Environment, p. 12.

220 Cf. Holweg *et al.*: Towards responsive vehicle supply, p. 508.

221 Cf. McCutcheon, Raturi and Meredith: The Customization-Responsiveness Squeeze, p. 89. See also Salvador, Fabrizio and Cipriano Forza: Configuring products to address the customization-responsiveness squeeze: A survey of management issues and opportunities, in: International Journal of Production Economics, Vol. 91 (2004), No. 3, pp. 273–275.

manding short lead times while their raw materials suppliers operate unresponsive, large-scale batch production systems[222], which is similar to the situation in the high-tech industry.

Short product life cycles require that demand can be met particularly in the first weeks after the product launch. This implies that forecasts for long lead time components, such as integrated circuits, need to be developed and production quantities may need to be committed several months before the launch of the product.[223] This task is complex, since it may be difficult to estimate customer demand accurately, especially for innovations. When Philips, for example, introduces a new DVD player model the planners initially prepare only a rough estimate of total life cycle sales, with forecasts that look up to 26 weeks into the future being very inaccurate.[224] For products with many variants that are sold in several different markets, such as mobile phones, this is even more difficult, particularly when forecasting variant-specific components with long lead-times. To complicate the problem further, contract manufacturers are often responsible for the procurement of long lead-time raw materials and components from second tier suppliers.[225] Due to the lack of transparency in supply chains in the high-tech industry, the information that is available to the contract manufacturers for preparing forecasts is often distorted and insufficient, and does not correspond to “end-customer demand information with a short information lead-time” that Kaipia et al. identify as prerequisites to manage this process well.[226] This problem is well known in other industries with unpredictable demand, such as the fashion apparel industry. With lead times of several months, component manufacturers can be left with either excess inventory of unpopular items or face shortages of items that are in high demand.[227]

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222 Cf. Holweg *et al.*: Towards responsive vehicle supply, p. 521.

223 Cf. Kaipia and Holmström: Selecting the right planning approach for a product, p. 3.

224 Cf. Kok *et al.*: Philips Electronics Synchronizes Its Supply Chain to End the Bullwhip Effect, p. 40.

225 Cf. Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, p. 97.

226 Cf. Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, p. 97. On the lack of transparency see, for example, Pande, Raman and Srivatsan: Recapturing your supply chain data, p. 16, and refer to section B.II.4.b on sales forecasting. See also Helo: Managing agility and productivity in the electronics industry, pp. 571–572.

227 Cf. Fisher *et al.*: Making supply meet demand in an uncertain world, p. 85, Fisher: What is the Right Supply Chain for Your Product?, p. 115, and Ritter and Sternfels: When offshore manufacturing doesn't make sense, p. 126.

4. *Supply Chain Complexity*

The complexity of supply chains in the high-tech electronics industry is high relative to many other industries. Managing such supply chains is particularly difficult because the industry is fragmented due to outsourcing and related developments, forecasts are inaccurate and planning systems are complex. Complexity can be understood as consisting of two components, detail complexity and dynamic complexity. Detail complexity itself is constituted by the number of elements in a system and the number and type of interconnections and relationships between these elements. Dynamic complexity, in contrast, is caused by variability of the behaviour of a system over time or by variability of the structure of a system.[228] The fragmented structure of the high-tech electronics industry with many players itself creates detail complexity, and time delays and other aspects of the new system structure contribute to dynamic complexity.

a. Fragmentation of Industry and Outsourcing

Most companies in the high-tech electronics industry were vertically integrated until the late 1990s or early 2000s. Strong global competition and pressure for cost reductions, along with an increasingly competitive environment and shortening product life cycles, meant that the traditional approach of vertical integration seemed to not provide sustainable competitive advantage.[229] One of the major reasons for the shift to outsourcing in many industries is that the companies were not able to manage the complexity and risk of a large and complex supply chain within a single company and believed that outsourcing and global diversification would solve this problem.[230] Contrary to what many managers may have expected, their actions often did not simplify processes. Instead, they created highly fragmented networks of independent and semi-independent organizations, with decentralized decision-making, lack of central coordination and regional division of labour.[231] The complexity of these fragmented networks overwhelms managers and greatly limits their ability to focus on the most important opportunities. Chang et al. argue that such fragmentation creates even greater environmental uncertainty and a higher need for flexibility, as plants that

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[228] Cf. Größler, Andreas, André Grübner and Peter M. Milling: Organisational adaptation processes to external complexity, in: International Journal of Operations & Production Management, Vol. 26 (2006), No. 3, p. 255. See also Milling: Understanding and managing innovation processes, p. 85.

[229] Cf. Hilmola, Helo and Holweg: On the outsourcing dynamics in the electronics sector, p. 2, and Berggren and Bengtsson: Rethinking Outsourcing in Manufacturing, p. 217.

[230] Cf. Akkermans and Dellaert: The rediscovery of industrial dynamics, p. 175.

[231] Cf. Akkermans and Dellaert: The rediscovery of industrial dynamics, p. 175.

produce for divisions within the same vertically integrated company are more insulated from market pressures than companies operating in the open market.[232] However, the advantages and disadvantages of vertical integration depend on the product, as for generic products with multiple customers contract manufacturers are able to level demand better than the customers could if they were to produce the products themselves.[233]

Supply chains in the high-tech industry are often spread over multiple countries with an elaborate regional division of labour.[234] Typically, a high-tech electronics OEM in a high-cost country represents the centre of gravity in high-tech electronics supply chains and will coordinate activities in medium- and low-cost countries that are often carried out by contract manufacturers.[235] For example, wafers may be produced in Germany that are sent to Singapore, where the integrated circuits are produced. These are shipped to China, were the boards are printed. Final assembly happens in Mexico, and the customer receives the product from a distribution centre in the United States. The process is coordinated from corporate headquarters in Japan. This material flows are visualised in Figure B-6. The total lead time can range between two and six months, including several weeks of transit time. For example, Philips Electronics faces a total value chain lead time of between 17 and 22 weeks for its DVD players, CD players and personal computers.[236] Such global production processes inevitably create logistics challenges. Transportation delays increase the amount of planning that is necessary as well as the risk of product obsolescence, while inventories may need to be kept at strategic points to ensure that customer demand can be fulfilled within the expected lead time.[237]

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232 Cf. Chang, Lin and Sheu: Aligning manufacturing flexibility with environmental uncertainty, p. 4777.

233 Cf. Berggren and Bengtsson: Rethinking Outsourcing in Manufacturing, p. 219.

234 Cf. Linden: Building Production Networks in Central Europe, p. 3 and Mason *et al.*: Improving electronics manufacturing supply chain agility through outsourcing, pp. 12–14.

235 Cf. Linden: Building Production Networks in Central Europe, p. 3 and Hilmola, Helo and Holweg: On the outsourcing dynamics in the electronics sector, p. 6.

236 Cf. Kok *et al.*: Philips Electronics Synchronizes Its Supply Chain to End the Bullwhip Effect, pp. 39–40.

237 See also Bowen, Gary N.: Offshored Manufacturing Brings Inevitable Supply Chain Logistics Changes, 2006, Everest Partners, L.P., http://www.outsourcing-offshore.com/supply.html, retrieved on: 11 October 2006, p. 1.

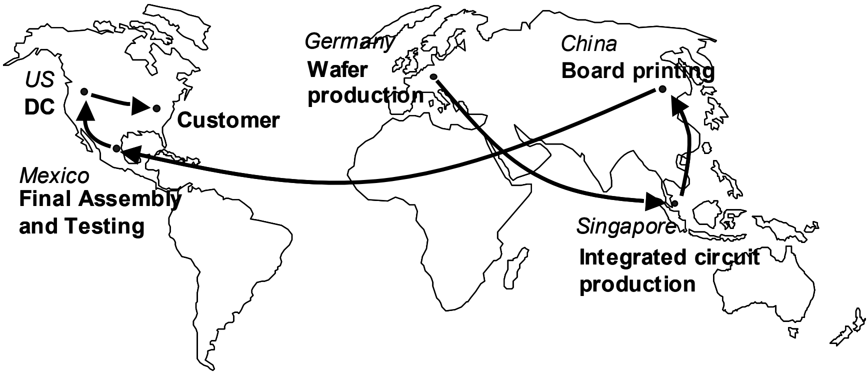

Figure B-6: Global Supply Chain Example

The task of contract manufacturers was originally limited to printed circuit board assembly. Today, these companies play a large role in high-tech electronics supply chains. Their capabilities allow them to manage and handle almost every aspect of the manufacturing process at the same level of quality as the established electronics manufacturers.[238] These capabilities reach beyond the manufacturing and logistics operations, as original design manufacturers (ODMs) are able to carry out the complete development processes for new products.[239] The expected benefits of such relationships for the OEMs include reductions in the amount of capital required, the ability to turn fixed costs into variable costs, access to know-how about production processes, increased flexibility and reduced time to market.[240] For example, when Nokia was facing increasing pressure in 2005 to introduce a so-called clamshell phone in their product range they decided to buy the complete product design from a Japanese ODM, BenQ. This step reduced the investment risk resulting from conducting the research and development in-house and simultaneously allowed them to

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[238] Cf. Mason *et al.*: Improving electronics manufacturing supply chain agility through outsourcing, p. 612.

[239] Cf. Hilmola, Helo and Holweg: On the outsourcing dynamics in the electronics sector, p. 2 and Vakil, Bindiya: Design Outsourcing in the High-Tech Industry and its Impact on Supply Chain Strategies, 2005, Master's Thesis, Massachusetts Institute of Technology, pp. 26–29.

[240] Cf. Heikkilä, Jussi: Outsourcing: a core or non-core strategic management decision?, in: Strategic Change, Vol. 11 (2002b), No. 4, pp. 185–186 and Cordon: Value creation and globalization , p. 39; and Wendin: Electronics Manufacturing: EMS at a Crossroads, pp. 5–6.

introduce the product to the market relatively quickly.[241] Nonetheless, OEMs wishing to engage in such relationships need to consider the risks involved in using contract manufacturers or original design manufacturers, which include loss of market visibility, loss of the ability to manufacture the product, less control of the manufacturing process and less inventory visibility.[242]

b. Sales Forecasting

Low forecast accuracy exacerbates the structural challenges to the business further. The forecast error of demand increases the higher the inherent deviations in demand are and the worse the planning capabilities of the company are.[243] Inherent deviations of demand can be measured using the coefficient of variation of demand. The second aspect that influences the uncertainty of a demand forecast are the forecasting abilities of the company, which generally are not well developed before the product is introduced and at the initial stage of a product's life cycle. However, in the high-tech industry forecasts several months into the future are required, particularly for long lead-time components, and currently drive the business, as flexibility is expensive.[244] At this early stage, the manufacturer does not know with any certainty what the life cycle pattern will be, which causes forecast accuracy to decrease the longer the forecasting horizon is.[245] Forecasts are adjusted based on the interests of different stakeholders, their expectations and actual demand that is observed, all of which can be misleading indicators.[246]

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241 Cf. Hilmola, Helo and Holweg: On the outsourcing dynamics in the electronics sector, pp. 2–3.

242 Cf. Mason *et al.*: Improving electronics manufacturing supply chain agility through outsourcing, p. 613.

243 Cf. Baiker, Alban: Anforderungen dynamischer Produkteigenschaften an die Gestaltung von Supply Chains, 2002, Diploma Thesis, Universität Karlsruhe (TH), pp. 64–66.

244 Cf. Burruss and Kuettner: Forecasting for Short-Lived Products, p. 9.

245 Cf. Aitken, James, Paul Childerhouse and Denis R. Towill: The impact of product life cycle on supply chain strategy, in: International Journal of Production Economics, Vol. 85 (2003), p. 127 and Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, p. 106.

246 Cf. Erhun, Gonçalves and Hopman: Moving from Risks to Opportunities, pp. 16–18. See also section A.I on conflicting priorities in supply chains.

Particularly for new products, standard forecasting techniques that depend heavily on historical data are not applicable.[247] Predicting which of the new products introduced in any given year are going to succeed and which are going to fail is very error-prone. Maier finds that most products fail in the marketplace, with 60 percent of the products that are introduced into the market failing for economic reasons.[248] Even more difficult is the prediction of the development of sales in the first few weeks of the product life cycle, i.e. during the ramp-up phase. Initially slow demand often increases very quickly at some point, with uncertainty remaining about the timing and the final volume.[249] This creates an environment where creating the initial forecasts sent to suppliers becomes similar to taking a bet. This is one of the major challenges to companies operating in the high-tech industry, which is often addressed by inflating the original realistic forecast.[250]

While it is difficult to accurately forecast demand before and shortly after the market introduction of a new product, this becomes easier as the product reaches the maturity stage of the product life cycle. The forecasting capabilities of a company are influenced by a learning curve.[251] However, imperfect information sharing and coordination within and across companies in the high-tech electronics industry is one of the most important challenges that slow this learning process and leads to unrealistic forecasts.[252] Demand is also inherently volatile, which means that there is a possibility of developing an inaccurate forecast near the end of the product life cycle. This can lead to high inventory levels of components or finished goods that may become obsolete as the product is taken from the market, which is particularly costly in the high-tech electronics industry due to high product costs and short product life cycles. For example, until 2005 Cisco's Optical Networking Group incurred excess and obsolescence inventory expenses of around US$13 million per year. At the same time, the company was facing a large demand forecast error, which exceeded 1,000 percent in

247 Cf. Fisher, Marshall L. and Kumar Rajaram: Accurate Testing of Retail Merchandise: Methodology and Application, 1996, Working Paper, Operations and Information Management Department, The Wharton School, The University of Pennsylvania, http://knowledge.wharton.upenn.edu/papers/817.pdf, retrieved on: 26 September 2006, p. 3.

248 Cf. Maier, Frank H.: New product diffusion models in innovation management – a system dynamics perspective, in: System Dynamics Review, Vol. 14 (1998), No. 4, p. 286. See also Erhun, Gonçalves and Hopman: Moving from Risks to Opportunities, pp. 1–3.

249 Cf. Helo: Managing agility and productivity in the electronics industry, p. 573.

250 Cf. Erhun, Gonçalves and Hopman: Moving from Risks to Opportunities, p. 16.

251 Cf. Aitken, Childerhouse and Towill: The impact of product life cycle on supply chain strategy, p. 135.

252 Cf. Erhun, Gonçalves and Hopman: Moving from Risks to Opportunities, p. 3.

some cases, delays in customer order fulfilment and increasing inventory levels.[253] The items on stock were often not the ones requested by the customers. To address this issue, Burruss and Kuettner developed a forecasting model that is explicitly designed for products that face high demand volatility, short life cycles and become obsolete quickly.[254] Their approach begins with a normalized base line product life cycle forecast that is based on past experience with other, similar products. This forecast is then adjusted for known seasonality patterns in the product segment, planned promotions or planned price reductions.[255] Also, companies in this industry frequently plan market exit and production ramp-down of products that are replaced by newer product generations significantly before a decline in sales can actually be observed. Such a reduction in the forecast when sales are still high may, however, pose a psychological problem for planners as they observe stockouts and increasing sales but are simultaneously required to reduce the forecasts for a planned product phase-out.[256] Nonetheless, the actual ramp-down may be volatile and unpredictable as some customers may want to stock up on spare parts or cheap prices increase the demand for the product.[257]

Figure B-7 shows the accuracy of the 13-week forecast for an actual high-tech consumer product, such as a computer.[258] With forecast volumes fluctuating between zero percent and 400 percent of actual customer orders, unplanned shortages in production capacity or key component supply are likely to arise, particularly if there are long supplier lead times.

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253 Cf. Parmar: Supply Chain Architecture in a High Demand Variability Environment, p. 14.

254 Cf. Burruss and Kuettner: Forecasting for Short-Lived Products, pp. 9–10.

255 Cf. Burruss and Kuettner: Forecasting for Short-Lived Products, pp. 12–14.

256 Cf. Sterman: Managing the Supply Chain in a High-Velocity Industry, p. 5 and Gonçalves: Demand Bubbles and Phantom Orders in Supply Chains, p. 28.

257 Cf. Helo: Managing agility and productivity in the electronics industry, p. 574.

258 Cf. Jayaram *et al.*: Segmented Approach to Supply Chain Management System Design in High Tech, p. 10. Figure B-7 was adapted from this source. Company name, product and the order of magnitude of actual order volume have been disguised to protect the company's proprietary information. The insights drawn from the disguised data are the same insights that were drawn from the real data.

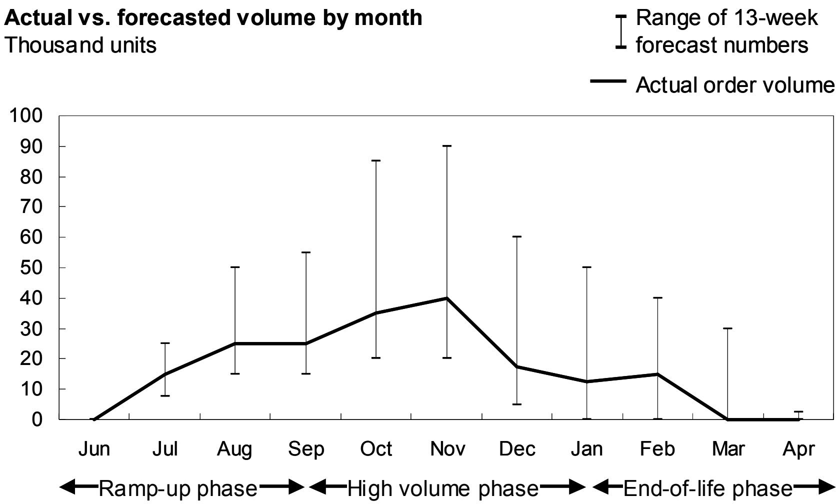

Figure B-7: Forecast Accuracy for a Sample High-Tech Consumer Product

Similarly, in a sample of six supply chains of Nokia Networks, with customers for technology used in mobile telecommunications networks in six different countries, the forecasts prepared by the customers had forecast errors, as measured by the mean absolute deviation[259], that range between 41 percent and 105 percent.[260] The reason for the large differences in the forecasts lies primarily in the nature of demand, which is highly volatile. New information that becomes available on the market as well as order acquisitions and cancellations require numerous adjustments and updates to the initial forecasts for a particular time period.[261]

The quality of information available to decision-makers is also suboptimal, since OEMs receive their orders from intermediaries, such as network operators, distributors and/or electronic goods retailers, and not directly from the end customer.[262] This means that the people involved in the forecasting process at the OEM have limited access to demand data, while at the same time the information they receive may be delayed and distorted, for example due to conflicting

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259 The mean absolute deviation is a measure of forecast error that is calculated as the average of absolute values of the forecast deviations from actual demand divided by the number of observations.

260 Cf. Heikkilä: From supply to demand chain management, p. 757.

261 Cf. Kok *et al.*: Philips Electronics Synchronizes Its Supply Chain to End the Bullwhip Effect, pp. 40–41.

262 Cf. Olhager *et al.*: Supply chain impacts at Ericsson, p. 47.

priorities of decision-makers at various points in the supply chain.[263] For example, information on a sales promotion or on the repositioning of a product to a new market might not be passed on to suppliers, which for them means a sudden, unpredictable increase in demand. Information sharing and collaboration are important, but often difficult to achieve.[264] The common behaviour of individual forecast adjustments at each supply chain node is one of the primary causes of the bullwhip effect, which increases upstream volatility in supply chains.[265] These adjustments amplify small changes in end-customer demand and also reflect other aspects, such as information about supply constraints or management expectations, and have an impact on demand forecasts throughout the supply chain.[266] For example, in his analysis of mobile phone supply chains Heikkilä concludes that such multi-step forecasting processes lead to lower supply chain efficiency.[267] Similarly, at Cisco individual forecast adjustments at each supply chain node caused inflated demand forecasts throughout the supply chain, which encouraged inventory build-up. In a situation where sales were in fact going down rather than up, Cisco had to write off inventory worth US$2.2 billion.[268]

It has been argued that increased demand visibility in the supply chain can reduce the bullwhip effect in supply chains, but not completely eliminate it. Chen et al., for example, find that making demand information available throughout the supply chain reduces the bullwhip effect, but does not eliminate it.[269] In the high-tech industry, some authors observe a recent increase in the visibility of downstream demand through making point-of-sales (POS) data,

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263 See also section A.I on conflicting priorities in supply chains. Cf. Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, p. 95.

264 See Hammer: Enabling Successful Supply Chain Management, pp. 48–71, for a discussion of the importance of cooperation through coordination, collaboration and integration in supply chains.

265 Cf. Lee, Padmanabhan and Whang: The bullwhip effect in supply chains, pp. 93–95 and Lee, Padmanabhan and Whang: Information Distortion in a Supply Chain: The Bullwhip Effect, pp. 546–552.

266 Cf. Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, p. 104.

267 Cf. Heikkilä: From supply to demand chain management, p. 758.

268 Cf. Berinato, Scott: What Went Wrong at Cisco, in: CIO Magazine, 1 August 2001, 2001, http://www.cio.com/archive/080101/cisco.html, retrieved on 9 October 2006, p. 1 and p. 4.

269 Cf. Chen, Frank *et al.*: Quantifying the Bullwhip Effect in a Simple Supply Chain: The Impact of Forecasting, Lead Times, and Information, in: Management Science, Vol. 46 (2000), No. 3, pp. 439–442. See also Lee and Whang: Information sharing in a supply chain, p. 374f.

sell-through data and inventory levels accessible throughout the supply chain.[270] Observations from supply chains of major companies in high-tech supply chains today suggest, however, that while there is a trend to attempt to make such information more readily available this is often not possible at the moment. For example, there is often little transparency in inventory levels and is perceived to be difficult to realize such transparency. Companies in the industry often share such information only for a few critical long lead time components, e.g. using diagrams on walls or Excel sheets. Often the willingness to share information is there, but such exchanges are done on an ad hoc basis using e-mails and spreadsheet documents.[271]

In some cases, the forecasts generated by teams of experts using detailed and sophisticated modelling that requires expensive IT infrastructure have a lower forecasting accuracy than the original sales forecast. In other cases, history-based forecasts that rely only on extrapolation of past orders, for example through moving averages or exponential smoothing, provide a lower forecast deviation even for a high-volatility market segment than forecasts prepared by forecasters who "tend to massage the data".[272] In an experiment conducted by Paich and Sterman, subjects consistently fail to forecast the sales peak for a product, even after having earned extensive expertise with the task, which leads to excess capacity and large losses.[273] Therefore there is not necessarily a positive correlation between the effort put into forecasting and the quality of the

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270 Cf. Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, p. 97.

271 Cf. Pande, Raman and Srivatsan: Recapturing your supply chain data, p. 16 and Billington, Corey *et al.*: Accelerating the Profitability of Hewlett-Packard's Supply Chains, in: Interfaces, Vol. 34 (2004), No. 1, pp. 59–60. This was confirmed by Axel Karlsson, partner at the consulting firm McKinsey & Company, Inc., Stockholm, on 31 March 2006 in personal communication.

272 Cf. Sterman, John D.: Operational and Behavioral Causes of Supply Chain Instability, in: Torres, Octavio A. Carranza and Felipe A. Villegas Morán (Eds.): The Bullwhip Effect in Supply Chains: A Review of Methods, Components And Cases, New York 2006, p. 7; Sterman *et al.*: Getting Big Too Fast, p. 21; Williams: Forecasting Journey at On Semiconductor, p. 30; Alicke, Knut: Forecasting and Demand Planning, McKinsey & Company, Inc., 2006, p. 29; Erhun, Gonçalves and Hopman: Moving from Risks to Opportunities, pp. 16–18; and Rao, Sanjay-kumar: An Empirical Comparison of Sales Forecasting Models, in: The Journal of Product Innovation Management, Vol. 2 (1985), No. 4, pp. 236–241.

273 Cf. Paich, Mark and John D. Sterman: Boom, Bust, and Failures to Learn in Experimental Markets, in: Management Science, Vol. 39 (1993), No. 12, pp. 1446–1456.

result, possibly allowing companies to reduce forecasting and planning effort by planning only important products in detail and extrapolating others.[274]

c. Complexity of Planning Systems

Supply chain planning can be defined as the “set of supply chain activities that focus on matching demand with material and production capacity availability and formulate plans and schedules based on meeting that demand and company goals.”[275] According to Williams, supply chain planning has four components: (1) demand management and forecasting, (2) inventory planning and sourcing, (3) planning and scheduling and (3) materials management.[276] As demand management and forecasting, sourcing and materials management are addressed in the previous sections, this section focuses on the practical problems of the planning and inventory management systems in supply chains in the high-tech electronics industry. Scheduling is not in the focus of the discussion. More details on the fit of different planning systems in different circumstances are provided later in section B.II.5.

Many supply chains in the high-tech industry are driven by a push logic. The term “push-based system” has been defined and used in many different ways, along with “pull-based system”[277], and for the purpose of this work the following definitions are adopted. In a push-based system, material processing is started when (1) material is available and (2) processing capacity of the next step is available. In a pull-based system, material processing is started when (1) material is available, (2) processing capacity of the next step is available and (3) an external trigger arrives. In other words, as visualised in Figure B-8 below, a push-based system is driven by a forecast, while a pull-based system is driven by actual downstream demand.

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274 Cf. Alicke: Forecasting and Demand Planning, p. 34.

275 Cf. Kaipia: The impact of improved supply chain planning on upstream operations, p. 2.

276 Cf. Williams, Hugh: Supply-Chain Planning – Winning The Game, in: Logistics & Transport Focus, Vol. 4 (2002), No. 5, p. 48.

277 See Hopp and Spearman: To Pull or Not to Pull: What Is the Question?, pp. 133–144.

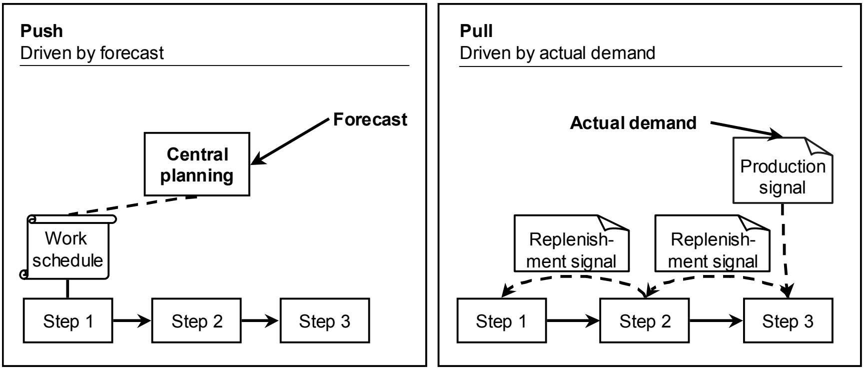

Figure B-8: Decision rules and production control – Push vs. Pull (simplified illustration)

Planning systems often rely on accurate and reliable forecasts, which facilitate the balancing of demand requirements and supply capabilities.[278] In the automotive industry, for example, vehicle production in many markets is still primarily driven by forecasts and not by customer orders, with vehicles being sold to the customers from existing finished goods inventory.[279] In the high-tech industry, accurate forecasts are often not available. The transparency on supply chain metrics, such as inventory levels at other nodes in the chain, is also low.[280] Inaccuracy in the forecast that is pushed through the system months before the product is launched to the market leads to several difficulties.

Firstly, the forecasts are adjusted by each member of the supply chain before this new, updated forecast, which is now less related to the original forecast, is passed on to the next upstream supply chain node, as can be seen in Figure B-9 below. Multiple planning systems are involved in adjusting the forecasts, which implies that production through the push-based supply chain is driven by inaccurate forecasts. As discussed in the previous section, the information that is used as an input for planning is also often flawed. Additionally, the planning systems relying on MRP logic are subject to intrinsic "nervousness", i.e. low stability of the plans, due to managerial decision-making as well as the com-

278 Cf. Kaipia: The impact of improved supply chain planning on upstream operations, p. 2.

279 Cf. Holweg *et al.*: Towards responsive vehicle supply, p. 507.

280 Cf. Kaipia: The impact of improved supply chain planning on upstream operations, p. 2 and Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, p. 96.

puter control algorithms used.[281] For example, Kaipia et al. analyse the supply chain of a global electronics manufacturer and find that the demand that the suppliers face is highly unstable, e.g. for the first tier suppliers even the plans for the next week have a forecast error of more than 70 percent.[282] Also, different components with different lead times are produced based on different forecasts, as for products with shorter lead times more recent information about actual demand can be gathered and used in developing the forecasts.[283] Nonetheless, the delays involved in communicating these adjusted forecasts to the suppliers are often very long, which means that it could take several weeks until fundamental a change in customer demand has an impact on the production processes at suppliers.[284]

For any member of such a system, these complex interrelationships are very difficult to understand and manage. As the planning systems are often extremely complex, requiring decisions at multiple stages and covering different parts of the supply chain, understanding how the system functions as a whole becomes impossible.[285] Decision makers also face complications such as unclear objectives and lack information they would need in order to make informed decisions. This aspect is exacerbated due to the reliance on outsourcing in this industry as well as through the nature of the first-generation enterprise resource planning (ERP) systems that are frequently used. Both of these aspects make it more difficult to share information across company boundaries as there is a lack of close collaboration and supply chain integration.[286] As Akkermans and Dellaert note, "the irony we face in supply networks today [is]: companies have been split into smaller, independent units because it was so difficult to coordinate their opera-

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281 Cf. Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, p. 100; Akkermans and Dellaert: The rediscovery of industrial dynamics, p. 176; Morecroft, John D. W.: Influences from Information Technology on Industry Cycles – A Case Study in Manufacturing Industry, 1979, Doctoral Thesis, Massachusetts Institute of Technology, pp. 222–224; and Wilding, Richard D.: Chaos Theory: Implications for Supply Chain Management, in: International Journal of Logistics Management, Vol. 9 (1998), No. 1, pp. 47–55.

282 Cf. Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, p. 105.

283 Cf. Thomas, Warsing and Zhang: Forecast Updating and Supplier Coordination for Complementary Component Purchases, p. 1.

284 Cf. Kok *et al.*: Philips Electronics Synchronizes Its Supply Chain to End the Bullwhip Effect, p. 40.

285 Cf. Kaipia: The impact of improved supply chain planning on upstream operations, p. 2.

286 Cf. Akkermans and Dellaert: The rediscovery of industrial dynamics, p. 175 and Catalan and Kotzab: Assessing the responsiveness in the Danish Mobile phone supply chain, p. 682.

tions, but this has made such coordination even more difficult, at a time when one of the main original reasons for this difficulty, inadequate information technology, is no longer relevant".[287] There are various limitations of enterprise resource planning (ERP) systems, which are used for planning, controlling and recording the transactions of running a business and provide real-time access to information in a consistent manner throughout an organisation, with regard to supply chain management.[288] For example, there is insufficient functionality in crossing organizational boundaries, which is exacerbated by the use of different ERP packages by different members of the supply chain. Also, ERP systems lack flexibility in reacting to changes in supply chain requirements, particularly as these systems sometimes make it difficult to accommodate different modes of collaboration with different supply chain partners. In supply chains that need to be highly responsive to market needs, the composition of the supply chain may change from one customer order to the next, which is difficult to handle with such systems. Such limitations make information sharing and, as a consequence, decision making difficult and allow only little reliance on data obtained from other companies. Therefore, the plans are often not coordinated and frequently modified.

As a consequence of these difficulties, employees working in the operations of a firm often generate their own forecasts for their work after determining that what they receive from, for example, the marketing department is "always wrong". Plans that lack credibility and are fundamentally and frequently changed subsequently can be neglected in terms of execution. This could be observed at Cisco, for example.[289] Similarly, if in a company that uses a push production system for its supply chain the sales forecast is not linked to demand planning, this forces production planners to constantly make short-term adjustments and routinely override the material requirements planning (MRP) system. As a result, such a company may face difficulties to keep production running at a stable rate. This high level of uncertainty causes companies to be unable to

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[287] Akkermans and Dellaert: The rediscovery of industrial dynamics, p. 175. See Huang, George Q., Jason S.K. Lau and K.L. Mak: The impacts of sharing production information on supply chain dynamics: a review of literature, in: International Journal of Production Research, Vol. 41 (2003), No. 7 for a research review on information sharing in supply chains.

[288] The limitations described in the following are identified by Akkermans, Henk A. *et al.*: The impact of ERP on supply chain management: Exploratory findings from a European Delphi study, in: European Journal of Operational Research, Vol. 146 (2003), No. 2, pp. 297–299. See also Webster, Scott: Principles and Tools for Supply Chain Management, New York 2008, pp. 13–20.

[289] Cf. Parmar: Supply Chain Architecture in a High Demand Variability Environment, p. 14.

manage supply chains to fit the demand pattern and market requirements, leaving the system such as that shown in Figure B-9 unable to satisfy customer demand appropriately and on time.[290] At the same time, these same companies may carry high safety stocks.[291]

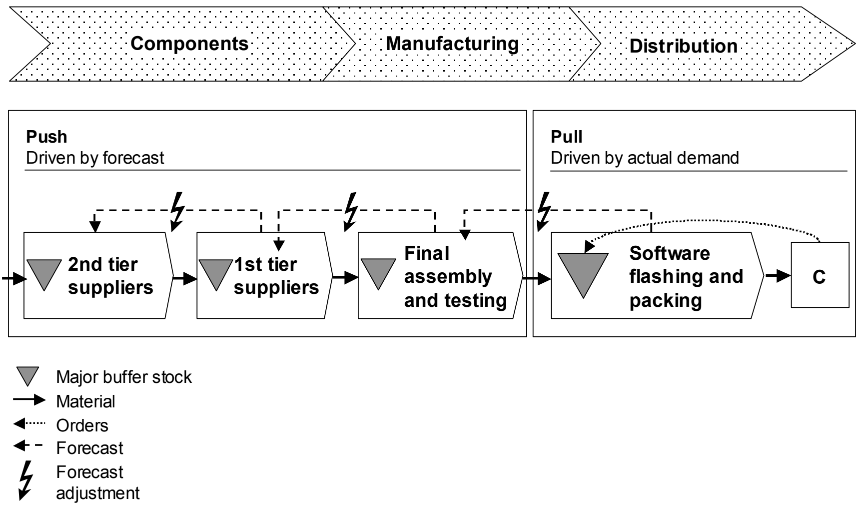

Figure B-9: Push Logic in Supply Chain Creates High Inventory Levels and/or Stockouts

This leads to the second difficulty in supply chain planning, which is that buffer stocks are set-up by each of the different entities of the supply chain based on individual incentives, aimed at covering the uncertainty arising from both demand and supply volatility. These stocks often build up unintentionally and cannot always considered to be strategically placed inventory positions.[292] Additionally, inventory can build up at the downstream end of the supply chain if actual demand is lower than the forecast, while shortages can occur in the opposite case. Due to the short product life cycles, plans for component procurement and production need to be ramped down already significantly before the product is eventually taken from the market, maybe even before it has

[290] See also Vorst, Jack G.A.J. van der and Adrie J.M. Beulens: Identifying sources of uncertainty to generate supply chain redesign strategies, in: International Journal of Physical Distribution & Logistics Management, Vol. 32 (2002), No. 6, p. 413.

[291] Cf. Parmar: Supply Chain Architecture in a High Demand Variability Environment, p. 14 and Kaipia: The impact of improved supply chain planning on upstream operations, pp. 2–3.

[292] Cf. Catalan and Kotzab: Assessing the responsiveness in the Danish Mobile phone supply chain, p. 682.

reached its sales peak, which may be a psychological problem for planners.[293] Excess inventory is costly because material can become obsolete, capital is tied up that could be used for other items, items can get lost, space is wasted on the wrong types of inventory, time is wasted looking for items and time is wasted counting items that are not needed. Similarly, shortages are costly because products cannot be produced as they wait for raw materials, purchase orders need to be expedited, material needs to be shipped between stores or warehouses, the tendency to over-order grows with the same item being ordered multiple times, and ordering costs go up.

Third, the performance of competing products is also unpredictable. Short periods of low availability may drive customers to competing products, changing a predicted top selling product into a weak seller – or, vice versa, tuning one of the weak sellers into an unexpected success if a competitor needs to delay the introduction of a product for a few weeks.[294] In a push-based system, the forecast continues to drive the supply chain system, so variations in demand can lead to large inventory write-offs due to obsolescence or to situations in which demand cannot be fulfilled due to stock-outs, causing costs in both cases. A main reason for this risk are the long lead times that require plans to be submitted to suppliers months ahead of the customer order and delivery date.[295]

Fourth, the high amount of product variants that is often observed in the high-tech electronics industry creates additional difficulties. In order to plan the supply for components properly, demand needs to be known on a detailed variant level several weeks or even several months before the customer places an order. With mobile phones, for example, there are different product types, country-specific variants e.g. relating to the logo-print or the keypad, as well as different colours, leading to a large number of forecast positions to be planned.[296] For example, if there are 20 different product types, sold in 60 countries, with each variant being available in 10 different colours, there would be 12,000 different variants to be planned, which represents a large challenge for the OEMs. Modelling the planning processes for a product mix with different variants is

293 Cf. Sterman: Managing the Supply Chain in a High-Velocity Industry, p. 5 and Gonçalves: Demand Bubbles and Phantom Orders in Supply Chains, p. 28.
294 Cf. Sterman: Managing the Supply Chain in a High-Velocity Industry, p. 6.
295 Cf. Kaipia and Holmström: Selecting the right planning approach for a product, p. 3.
296 Cf. Reinhardt: Nokia's Magnificent Mobile-Phone Manufacturing Machine, p. 1.

beyond the scope of this work, but researchers have suggested a variety of tools to reduce the complexity of planning and increase the accuracy of the plans.[297]

5. *Alignment of Product Characteristics and Supply Chain Design over the Product Life Cycle*

Differences in the characteristics of products and their markets create different requirements for supply chain management. In volatile markets, for example, supply chain capabilities may be required that are less important for products where demand is highly predictable. Also, these requirements may change over the product life cycle. Supply chain design therefore needs to consider the requirements of the products to be supplied via that chain. Different planning approaches may provide a means to tailor supply chains to different products. In general, the alignment of products, supply chains and planning systems is an area of academic interest.[298] Past contributions focus on the alignment of manufacturing processes and product characteristics[299], on the alignment of planning approaches and product characteristics[300] and on the alignment of supply chain design with product characteristics[301]. A comprehensive analysis of the alignment different planning approaches and products in a multi-echelon supply chain, using a System Dynamics simulation model, has not yet been completed. In the following, the potential of strategically matching supply chain types with certain types of products is evaluated, followed by a discussion of the importance of selecting appropriate planning processes for a supply chain.

Many authors see responsiveness and efficiency as distinct strategies that are closely linked to different types of products. Multiple characteristics can be used

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297 See, for example, Framiñán, José M., Andreas Reichhart and Matthias Holweg: Modelling Supply Chain Responsiveness, EurOMA International Conference – Moving Up the Value Chain, Glasgow 2006, pp. 215–224, who analyze mix responsiveness using a computer simulation model. Approaches that consider the attach rates, i.e. the percentage of orders that have a certain option, are also suggested to reduce planning complexity. See n.a.: The Product Mix challenges of the Electronics Industry – Option and Parts Forecasting, 2005, Emcien Whitepaper, Emcien, http://www.emcien.com/emcien_resources/documents/eForecastwhitepaper6_26_05.pdf, retrieved on: 15 October 2006, pp. 2–3, and Kapuscinski *et al.*: Inventory Decisions in Dell's Supply Chain, pp. 195–205.

298 Cf. Selldin: Supply chain design, p. 5.

299 Cf. Hayes, Robert H. and Steven C. Wheelwright: Link manufacturing process and product life cycles – Focusing on the process gives a new dimension to strategy, in: Harvard Business Review, Vol. 57 (1979), No. 1, pp. 134–138.

300 Cf. Berry, William L. and Terry Hill: Linking Systems to Strategy, in: International Journal of Operations & Production Management, Vol. 12 (1992), No. 10, p. 10.

301 Cf. Fisher: What is the Right Supply Chain for Your Product?, p. 109.

to describe and distinguish products from a supply chain perspective. These include production volume, number of variants, accepted lead-time, demand uncertainty, demand volatility and in general the product life cycle over time.[302] Fisher, for example, distinguishes innovative products with short product life cycles and functional, more commodity-like products.[303] Functional products "satisfy basic needs, which don't change much over time…, have a stable, predictable demand and long life cycles".[304] They are also characterised by relatively low contribution margins, low product variety and long order lead times.[305] Innovative products, in contrast, are characterised by short product life cycles, high contribution margins, high product variety and unpredictable demand. Electronic products and fashion goods are examples for this category.[306] Fisher then provides recommendations for the strategic alignment of supply chains. According to Fisher, the requirements for supply chain management are different for these distinguished types of products – for products that are innovative and reflect new trends demand is less predictable than for products that fulfil basic needs, such as sugar.[307] He suggests that functional products require a focus on efficient processes, while innovative products require a focus on responsive processes, as visualised in Table B-2 below.[308] The uncertainty of demand for innovative products makes supply chain responsiveness a critical capability, since stockouts should be avoided in particular if the products have high contribution margins. For functional products aspects of efficiency, i.e. focusing on the elimination of waste or non-value added activities across the chain, prevail management's attention.[309]

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302 Cf. Selldin: Supply chain design, p. 2.
303 Cf. Fisher: What is the Right Supply Chain for Your Product?, p. 106.
304 Fisher: What is the Right Supply Chain for Your Product?, p. 106.
305 Cf. Childerhouse, Paul and Denis R. Towill: Engineering supply chains to match customer requirements, in: Logistics Information Management, Vol. 13 (2000), No. 6, p. 339.
306 Cf. Childerhouse and Towill: Engineering supply chains to match customer requirements, p. 344.
307 Note that every product initially is innovative – even certain types of sugar were at one point in time an innovation. See Fisher: What is the Right Supply Chain for Your Product?, p. 106.
308 Cf. Fisher: What is the Right Supply Chain for Your Product?, p. 109.
309 Cf. Huang, Samuel H., Mohit Uppal and Jan Shi: A product driven approach to manufacturing supply chain selection, in: Supply Chain Management, Vol. 7 (2002), No. 4, p. 193.

Table B-2: Matching Supply Chains with Products – The Fisher Model[310]

Supply Chain Design		Functional Products	Innovative Products
	Efficient Supply Chain	Match	Mismatch
	Responsive Supply Chain	Mismatch	Match
		Product Characteristics	

A small number of empirical tests of the Fisher model have been carried out by different authors. Two important questions arise: (1) do companies match supply chain design and product type and (2) how is the supply chain performance affected by a match or a mismatch. Selldin and Olhager survey 128 Swedish manufacturing companies and then map their fit between product characteristics and supply chain design on a scatter diagram.[311] Similarly, using data from the international High Performance Manufacturing-research project, Thun analyses the fit between responsiveness and efficiency in a sample of 96 manufacturing companies with a high degree of SCM implementation, as defined by measures such as supply chain planning, customer involvement, supplier partnership and supplier involvement.[312] Relating to the first question, both studies identify that the plants are positioned around a downward-sloping diagonal when plotting the points into a diagram similar to Table B-2, which indicates an aggregate tendency of companies fitting their supply chains with the type of product, as claimed by Fisher. Both studies also find significant variation of data points around this downward trend line, suggesting that there is no clear-cut matrix as suggested by Fisher, but that instead supply chains are positioned on a

310 Adapted from Fisher: What is the Right Supply Chain for Your Product?, p. 109.

311 Cf. Selldin, Erik and Jan Olhager: Linking products with supply chains: testing Fisher's model, in: Supply Chain Management: An International Journal, Vol. 12 (2007), No. 1, pp. 44–49.

312 Cf. Thun: Supply Chain Management and Plant Performance, pp. 8–16.

continuum between responsiveness and efficiency, while products are positioned on a continuum between innovativeness and functionality.[313]

Selldin and Olhager perform statistical analyses on the data and find that the companies with responsive supply chains use them for both functional and innovative products, and that companies with innovative products use both responsive and efficient supply chains for these products. Specifically, they find that the combination of functional products with efficient supply chains, and vice versa, is statistically significant at the 0.01 level, while the combinations involving innovative products and responsive supply chains are not, indicating that fewer companies with innovative products match the responsive supply chain to these products compared to companies with functional products using an efficient supply chain.[314] Thun's findings relating to the second question about how supply chain performance is affected by a match or mismatch can be linked to this finding by Selldin and Olhager. In general, Thun's results indicate that plants that match their supply chain structure with the product perform better on several performance measures. Plants in efficient supply chains perform better on three of the six dimensions analysed, i.e. unit cost of manufacturing, inventory turnover and cycle time, when the supply chain is matched with the product type, i.e. functional products, as opposed to the mismatch case of innovative products being handled with an efficient supply chain. Plants in efficient supply chains perform worse on fast delivery and flexibility to change volume when they handle functional products than when they handle innovative products. This result is counter-intuitive, but Thun remarks that the significance level is not always satisfactory due to sample size limitations[315]. No significant difference between match and mismatch could be observed for on-time delivery performance. When responsive supply chains are matched with innovative products, they perform better than the mismatch cases (i.e. responsive supply chains handling functional products) on the dimensions of fast delivery and flexibility, but worse on unit cost of manufacturing, inventory turnover and cycle time, indicating a trade-off between responsiveness and efficiency. Again, no difference could be observed for on-time delivery performance, which could potentially indicate, according to Thun, that "on-time delivery functions as a key driver for efficient supply chains and responsive supply chains. A high on-time delivery ratio supports both, efficiency and responsiveness".[316] In addition,

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313 Cf. Selldin and Olhager: Linking products with supply chains, pp. 46–47 and Thun: Supply Chain Management and Plant Performance, p. 13. The trend line identified by Selldin and Olhager is non-significant, with a number of companies being in the mismatch cells.

314 Cf. Selldin and Olhager: Linking products with supply chains, pp. 46–47.

315 Cf. Thun: Supply Chain Management and Plant Performance, p. 15.

316 Cf. Thun: Supply Chain Management and Plant Performance, pp. 14–15.

however, Thun also finds, similar to Selldin and Olhager, that the supply chain performance differences between match and mismatch cases are smaller for responsive supply chains than for efficient supply chains, which could mean that "some plants have overcome the apparent trade off between innovativeness and efficiency".[317] In a study of 22 supply chains in North America, South America and Europe, Ramdas and Spekman find that high-performing companies that deal with innovative products "are more likely to engage in supply chain management to enhance revenue" and that practices and reasons for engaging in supply chain management that distinguish high-performers from low-performers differ depending on the product category the companies deal with, i.e. functional or innovative. [318] This also indicates potential differences between firms' ability to achieve high performance in their supply chains.

These findings are in contrast with Fisher, who argues for a strict categorization with a matrix structure matching supply chains and products as in Table B-2.[319] Selldin and Olhager perform similar analyses on the Swedish dataset, and find that significant differences between matches and mismatches in Fisher's matrix can be observed for the performance measures supply chain cost, delivery speed and dependable deliveries. The results of Selldin and Olhager as well as those of Thun are summarized in Table B-3 below. Similar to Thun's results, Selldin and Olhager also find that some companies are attempting to get the "best of two worlds" by mixing characteristics from responsive and efficient supply chains.[320]

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[317] Cf. Thun: Supply Chain Management and Plant Performance, pp. 8–9. and pp. 14–16.

[318] Cf. Ramdas, Kamalini and Robert E. Spekman: Chain or Shackles: Understanding What Drives Supply-Chain Performance, in: Interfaces, Vol. 30 (2000), No. 4, p. 18 and p. 21. The authors note that further research is needed to establish causal relationships.

[319] Cf. Fisher: What is the Right Supply Chain for Your Product?, p. 109. See also Selldin and Olhager: Linking products with supply chains, p. 49.

[320] Cf. Selldin and Olhager: Linking products with supply chains, p. 48.

Table B-3: Empirical Tests of the Fisher Model: An Overview[321]

Supply Chain Design		Functional Products	Innovative Products
	Efficient Supply Chain	(1) Match Thun: outperform (2) on unit cost of inventory, inventory turnover, cycle time S&O: outperform (2) and (3) on supply chain cost; outperform (2) on dependable deliveries; outperform (3) on delivery speed	(2) Mismatch Thun: outperform (1) on fast delivery, flexibility to change volume
	Responsive Supply Chain	(3) Mismatch Thun: outperform (4) on unit cost of manufacturing, inventory turnover, cycle time	(4) Match Thun: outperform (3) on fast delivery, flexibility to change volume S&O: outperform (3) on supply chain cost
		Product Characteristics	

While Fisher's seminal contribution has been widely quoted in relation to responsiveness[322] and his principal ideas about the alignment of supply chain strategies with the type of product are plausible, some concerns with regards to the applicability of the Fisher model remain, both in general and specifically in the high-tech industry. One central issue is that some products can be either functional or innovative, or something in-between. An example for such products are cars, which Fisher also acknowledges.[323] Holweg explains that in this industry, functional and innovative products are being built alongside each other "in the same factories, are using the same manufacturing processes and suppliers, and thus invariably share the same supply chain".[324] Additionally, Fisher's seven criteria to distinguish functional and innovative products – product life cycle, contribution margin, product variety, average margin of error in the fore-

321 Based on results by Thun: Supply Chain Management and Plant Performance and Selldin and Olhager: Linking products with supply chains.

322 For example, see Aitken, Childerhouse and Towill: The impact of product life cycle on supply chain strategy, p. 131, and Lee: Aligning Supply Chain Strategies with Product Uncertainties, p. 106.

323 Cf. Fisher: What is the Right Supply Chain for Your Product?, p. 111.

324 Holweg: An investigation into supplier responsiveness, p. 97.

cast at the time production is committed, average stockout rate, average forced end-of-season markdown as percentage of full price and lead time required for make-to-order products – do not allow for a categorization of products into two groups that are both mutually exclusive and collectively exhaustive, and Fisher does not clarify how to categorize the products if only some of the criteria are fulfilled.[325] As a consequence, attempting to categorize products using Fisher's definitions results in some products being neither functional nor innovative, and in others being functional on some and innovative on other criteria. Airplanes, for example, fulfil most of the criteria for functional products as identified by Fisher, except long-term demand predictability.[326] As the case of Boeing (see section A.II) shows, a focus on efficiency in the supply chain for such a product can cause a loss of market share to more flexible competitors, such as Airbus.[327] It appears to be more sensible to think of products as being positioned on a continuum between functionality and innovativeness. In their empirical studies, both Thun and Selldin and Olhager find that both products and supply chains are positioned such on a continuum, as mentioned above. Fisher's strict matrix categorization as in Table B-2, with products being strictly either innovative or functional, and supply chains being strictly either responsive or efficient, is not sufficient to characterise products and supply chains to their full extent, as products could have characteristics from both product types and supply chains could have characteristics from both supply chain types.[328]

A second problem is that some functional products may also have quick response requirements of the supply chain – for example, milk and other dairy products are perishables with relatively stable demand patterns but limited shelf life. Also, companies often carry out promotions that can drastically change the otherwise stable and predictable demand patterns of products such as generic food. In such cases, pipeline stock is often "drained to no-one's real advantage".[329]

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325 Cf. Fisher: What is the Right Supply Chain for Your Product?, pp. 106–109.

326 See Fisher: What is the Right Supply Chain for Your Product?, p. 106.

327 Cf. Naylor, Naim and Berry: Leagility: Integrating the lean and agile manufacturing paradigms in the total supply chain, p. 112.

328 See Fisher: What is the Right Supply Chain for Your Product?, p. 109. See also Selldin and Olhager: Linking products with supply chains, p. 48; Selldin: Supply chain design, pp. 16–17; and Wong, Chee Yew *et al.*: Assessing responsiveness of a volatile and seasonal supply chain: A case study, in: International Journal of Production Economics, Vol. 104 (2006), No. 2, pp. 719–720.

329 Cf. Childerhouse and Towill: Engineering supply chains to match customer requirements, p. 338 and Fuller, Joseph B., James O'Conor and Richard Rawlinson: Tailored Logistics: The Next Advantage, in: Harvard Business Review, Vol. May-June (1993), p. 91.

Thirdly, demand uncertainty is an important aspect that is linked to the classification of innovative or functional products. In Fisher's terms, innovative products are often characterized by a high degree of unpredictable demand uncertainty, whereas functional, commodity-like products face a high degree of demand stability. This point needs to be seen critically, since many commodities are confronted with the typical bullwhip effects – one of the major concerns in supply chain management – upstream in the supply chain, with order batching, speculative buying, delays and suboptimal planning being the major reasons. Therefore, upstream supply chain members can be confronted with rather unpredictable demand, even for commodities. Consequently, the required responsiveness in a supply chain depends on the anticipated uncertainty of demand. This means that the required responsiveness depends on both the inherent deviations in demand and on the planning capabilities of the companies.[330] This relates not only to estimating the quantities demanded of certain products, but more generally to using market knowledge to exploit profitable opportunities in a volatile market place.[331] A company's ability to forecast and serve the demand for its products changes during a product's life cycle – during ramp-up and phase-out, demand is less predictable than during maturity.[332] This means that the supply chain requirements also change over the product life cycle, which is a factor many companies do not consider.

There is a history of research focusing on the alignment of supply chain and manufacturing processes with the different phases of the product life cycle.[333] Hayes and Wheelwright suggest different manufacturing approaches for different phases of the product life cycle, beginning with a job shop processes during the start-up phase and continuing via batch processes, assembly line processes and continuous flow.[334] Pagh and Cooper extend this discussion and, in focusing on supply chain postponement and speculation strategies, suggest that the focus during the initial stages of the product life cycle, introduction and growth, should be primarily on customer service. The authors also suggest anticipatory

330 Cf. Baiker: Anforderungen dynamischer Produkteigenschaften an die Gestaltung von Supply Chains, p. 64 and Chang, Lin and Sheu: Aligning manufacturing flexibility with environmental uncertainty, p. 4769.

331 Cf. Naylor, Naim and Berry: Leagility: Integrating the lean and agile manufacturing paradigms in the total supply chain, p. 108.

332 Cf. Alicke: Planung und Betrieb von Logistiknetzwerken, p. 147.

333 See Jüttner, Uta, Janet Godsell and Martin G. Christopher: Demand chain alignment competence – delivering value through product life cycle management, in: Industrial Marketing Management, Vol. 35 (2006), No. 8, pp. 991–992, for a brief overview of the literature.

334 Cf. Hayes and Wheelwright: Link manufacturing process and product life cycles, pp. 134–136.

manufacturing and logistics during this initial phase. For the rest of the product life cycle, maturation and decline, they suggest a strategy that "minimizes risk, uncertainty, and costs".[335] However, neither Pagh and Cooper nor Hayes and Wheelwright proceed to a discussion of how planning approaches in an entire supply chain should be designed in order to be appropriate for the entire product life cycle, particularly in industries where product life cycles are short.

The objective of supply chain planning is to match supply chain capabilities, such as available material and production capacity availability, with the demand characteristics faced by the supply chain. Planning is therefore concerned with developing plans and schedules that allow to efficiently capture sales opportunities and to satisfy customer needs in terms of speed, location and product variability.[336] The decision rules in different planning approaches that relate to the activities necessary in supply chain planning, such as demand forecasting, inventory planning or materials management, have significant differences. In this context, pull systems, push systems and hybrid systems can be distinguished.

In a push-based supply chain, material processing is started when (1) material is available and (2) processing capacity of the next step is available. In other words, a push-based system is driven by a forecast as production and distribution decisions are based on long-term estimates of demand.[337] This can be advantageous in situations where product life cycles are short, as production can be started before the growth phase of the product and reduced before the sales decline at the end of the product life cycle[338] – the timing of these phases, however, may be highly uncertain, requiring a high degree of discipline from the planners. In a push-based supply chain, assumptions are made about the system and its losses in order to attempt to match the final output with the customer requirements. Typical assumptions in push-based MRP systems, which are rela-

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335 Pagh, Janus D. and Martha C. Cooper: Supply Chain Postponement and Speculation Strategies: How to Choose the Right Strategy, in: Journal of Business Logistics, Vol. 19 (1998), No. 2, p. 22.

336 Two parts of supply chain planning can be distinguished. Strategic planning is concerned with the identification and evaluation of resource acquisition options with the objective of sustaining and enhancing a company's competitive position over the long term. This work is more concerned with tactical planning, focusing on resource adjustment and allocation decisions over shorter planning horizons, e.g. for one product generation in the high-tech electronics industry. Cf. Shapiro, Jeremy F.: Modeling the Supply Chain, Duxbury 2007, pp. 307–308, Kaipia and Holmström: Selecting the right planning approach for a product, p. 3 and Kaipia: The impact of improved supply chain planning on upstream operations, p. 2.

337 See, for example, Simchi-Levi, Kaminsky and Simchi-Levi: Designing and managing the supply chain, p. 121.

338 Cf. Webster: Principles and Tools for Supply Chain Management, p. 39.

tively complex, include fixed demand and fixed lead times – if these conditions are not fulfilled, the original plan needs to be overridden. This can cause accumulations of inventory, for example at the suppliers with capacity limits.

In a pull-based supply chain, material processing is started when (1) material is available, (2) processing capacity of the next step is available and (3) an external trigger arrives. The external trigger would be the order from the immediate customer of the process, which can be either an internal or an external customer. In other words, the production and distribution processes in a pull-based system are driven by actual downstream demand and not forecasted demand.[339] According to Ohno, who, among other things, devised a pull-based system for Toyota:

> "Manufacturers and workplaces can no longer base production on desktop planning alone and then distribute, or push, them onto the market. It has become a matter of course for customers, or users, each with a different value system, to stand in the front line of the marketplace and, so to speak, pull the goods they need, in the amount and at the time they need them."[340]

A pull-based system is simpler to implement than a push-based system and requires fewer interventions as the system reacts very quickly to small variations in demand. However, larger variations do require intervention by the planners as backlog situations are likely to occur. Since a pull-based planning approach is not driven by forecasted demand, difficulties may arise when demand is highly volatile and capacity is inflexible.[341] On the other hand, another advantage of pull-based systems is the prevention of overproduction and excessive inventory levels, which are core objectives of the lean philosophy, through an explicit limit of the amount of orders that can be in the system.[342] Other advantages are that pull-based systems are simple and easy to understand and that all processes in the supply chain are synchronised with the customer.[343]

A hybrid supply chain, also known as a push-pull system, combines the characteristics of pure push-based supply chains and pure pull-based supply chains. The initial stages of the supply chain, such as component suppliers, op-

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339 See, for example, Simchi-Levi, Kaminsky and Simchi-Levi: Designing and managing the supply chain, p. 121.

340 Ohno, Taiichi: Toyota Production System: Beyond Large Scale Production, Cambridge, MA 1988, p. xiv. See also Hopp and Spearman: To Pull or Not to Pull: What Is the Question?, p. 140.

341 Cf. Webster: Principles and Tools for Supply Chain Management, p. 38.

342 Cf. Hopp and Spearman: To Pull or Not to Pull: What Is the Question?, pp. 142–143.

343 See Simchi-Levi, Kaminsky and Simchi-Levi: Designing and managing the supply chain, p. 122 and Hopp and Spearman: To Pull or Not to Pull: What Is the Question?, p. 137–138.

erate based on long-term forecasts, while the rest of the supply chain, for example the assembly and shipment processes, is driven by realized demand.[344] In the high-tech electronics industry, most supply chains are hybrid supply chains, as the last steps of software flashing and testing are mostly performed after receipt of an actual customer order. However, the planning approach used for the rest of the supply chain may vary and could be either be push-based or pull-based. This is represented in the different planning approaches analysed in this work.

The different planning approaches may be more or less suitable for different types of products and at different phases of their life cycles. Selecting a planning approach that is appropriate to the environment can potentially improve the performance of the supply chain.[345] For example, Simchi-Levi, Kaminsky and Simchi-Levi argue that push systems are more suitable if demand uncertainty is low, while pull systems are more suitable if demand uncertainty is high.[346] Also, different phases of the product life cycle pose different challenges to the supply chain. When the product is introduced to the market, frequent design changes may need to be incorporated at all levels of the supply chain, with high requirements for innovation and responsiveness. Also, capacity needs to be ramped up quickly as the design becomes standardized, while at the same time stockouts should be avoided. In the maturity and decline phase excess inventories should be avoided, while at the same time efficiency of the system in general becomes important.[347] It remains to be analysed whether pull-based or push-based supply chains are suitable even for short life cycle products with extremely high demand volatility. The impact of long component lead times on the appropriateness of the planning approach is a further issue of concern. One important consideration is whether responsiveness can be achieved without adding complexity to the planning system, as additional complexity of the planning system would potentially work against the objective of having a responsive supply chain, par-

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[344] Cf. Simchi-Levi, Kaminsky and Simchi-Levi: Designing and managing the supply chain, p. 122 and Gonçalves: Demand Bubbles and Phantom Orders in Supply Chains, p. 69.

[345] Cf. Olhager, Jan and Erik Selldin: Manufacturing planning and control approaches for supply chains: market alignment and performance, in: International Journal of Production Research, Vol. 45 (2007), No. 6, pp. 1481–1482; Kaipia: The impact of improved supply chain planning on upstream operations, pp. 11–14 and Byrnes, Jonathan: You Only Have One Supply Chain?, 2005, Working Knowledge for Business Leaders, Harvard Business School, http://hbswk.hbs.edu/archive/4929.html, retrieved on: 11 October 2006, pp. 1–3.

[346] Cf. Simchi-Levi, Kaminsky and Simchi-Levi: Designing and managing the supply chain, pp. 123–125.

[347] Cf. Richardson, Peter R. and John R.M. Gordon: Measuring Total Manufacturing Performance, in: Sloan Management Review, Vol. 21 (1980), No. 2, pp. 48–49.

ticularly if unexpected events occur.[348] For example, Berry and Hill describe a manufacturer of telecommunications switchgear that decided to outsource the production of components that were previously made in-house. The goal of such a move is often to increase the flexibility of the system, which is expected to have a positive effect on responsiveness. The company decided to retain its previous MRP system. The complex MRP system, however, was not able to handle issues of vendor scheduling and component inventory management well. This resulted in shortages and consequential reductions in the delivery performance because the planning system, while complex, was unable to cope with the new situation.[349]

In their study of the lighting industry, Childerhouse et al. suggest a segmentation of products and supply chains and identify different planning approaches as optimal for different products in different phases of the product life cycle. Through a categorization with five dimensions, i.e. product variety, demand variability, duration of the product life cycle, demand volume and time window for delivery, they match different products to different planning approaches.[350] Over the product life cycle the authors propose for the analysed products to use "design and build" in the introduction phase, "MRP" in the growth phase, "Kanban" in the maturity phase, "packaging centre" in the saturation phase and "MRP" in the product's decline phase.[351] In subsequent research based on this case study and a literature review, they suggest to "pick and mix" from different supply chain management options, such as different production technologies, product modularization techniques, logistics, postponement, etc.[352]

Similarly, Jüttner et al. analyse the alignment of different supply chain strategies, which are aligned with the customer strategies followed by the organisation, with the product life cycle phases in the case of tobacco company. The authors find that product life cycle management and demand chain alignment have a mutually reinforcing relationship and that continuous monitoring, appraisals and changes are required in order to support the dynamic product

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348 Cf. Prater, Edmund, Markus Biehl and Michael A. Smith: International supply chain agility: Tradeoffs between flexibility and uncertainty, in: International Journal of Operations & Production Management, Vol. 21 (2001), No. 5/6, p. 835–838 and Kaipia: The impact of improved supply chain planning on upstream operations, p. 4.

349 Cf. Berry and Hill: Linking Systems to Strategy, p. 4.

350 Cf. Childerhouse, Paul, James Aitken and Denis R. Towill: Analysis and design of focused demand chains, in: Journal of Operations Management, Vol. 20 (2002), No. 6, p. 679 and p. 681.

351 Cf. Childerhouse, Aitken and Towill: Analysis and design of focused demand chains, p. 686.

352 Cf. Aitken, James *et al.*: Designing and Managing Multiple Pipelines, in: International Journal of Logistics, Vol. 26 (2005), No. 2, p. 92.

routing.[353] The authors propose that merely selecting the right product-process strategies and running parallel systems is not sufficient.[354]

Kaipia and Holmström segment the product portfolio in the high-tech company they analyse in four categories, i.e. (1) commodity items with stable demand, (2) seasonal or fashion items, (3) consumer durables, where total demand is predictable but sales of variants are not, and (4) new and innovative products.[355] For each of these product categories, the authors suggest a different planning approach. For commodity items, the authors suggest an efficient replenishment approach, which however requires inventory buffers in the supply chain to which the OEM has visibility. This is often not the case in current supply chains in the high-tech electronics industry. For seasonal or fashion items, the authors suggest once-off sales planning, in which new products are introduced continuously and as the decided production quantity of a product is sold, the product is replaced by a new product. For consumer durables with many variants the authors suggest streamlined planning using attach rates, where existing plans for planning other products' demand are used. This approach, however, is also difficult to implement in the high-tech electronics industry due to the difficulty in predicting the success or failure of a specific product, independent of their similarity to other, similar products. Finally, for innovative new products or product introductions the authors suggest expert-driven planning with accurate response to early sales, as originally suggested by Fisher et al.[356] For the reasons outlined earlier, including long lead times for components, this is also difficult to implement in the high-tech electronics industry.

An important consideration for the selection of appropriate supply chain planning processes in the high-tech electronics industry are the long supplier lead times and the potential for supply disruptions.[357] Therefore, Christopher, Peck and Towill suggest a taxonomy based on lead times and demand predictability. For products with long replenishment lead times, they suggest lean supply chain design if demand is predictable, which would mean to "make or

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353 Cf. Jüttner, Godsell and Christopher: Demand chain alignment competence, p. 998.

354 Cf. Jüttner, Godsell and Christopher: Demand chain alignment competence, p. 998. See also Collin, Jari: Selecting the Right Supply Chain for a Customer in Project Business, 2003, Doctoral Thesis, Helsinki University of Technology, pp. 43–58.

355 Cf. Kaipia and Holmström: Selecting the right planning approach for a product, pp. 9–11.

356 Cf. Kaipia and Holmström: Selecting the right planning approach for a product, pp. 9–11. For expert-based planning, see Fisher *et al.*: Making supply meet demand in an uncertain world, pp. 83–93 and Fisher, Marshall L. and Ananth Raman: Reducing the Cost of Demand Uncertainty through Accurate Response to Early Sales, in: Operations Research, Vol. 44 (1996), No. 1, pp. 1–20.

357 Cf. Lee: Aligning Supply Chain Strategies with Product Uncertainties, p. 114.

source ahead of demand in the most efficient way".[358] While this is necessary to some extent in the high-tech electronics industry due to the long component lead times and potential for supply shortages and disruptions, such an approach entails problems for supply chain management that need to be addressed with appropriate planning mechanisms, for example through excess capacity or inventory.[359] If demand is unpredictable – as typical is in the high-tech electronics industry – Christopher et al. suggest leagile production and logistics postponement, where the final assembly steps are performed only after customer demand has been encountered.[360] To some extent, the hybrid supply chains in the high-tech electronics industry already follow such a hybrid, "leagile" strategy, as the software flashing and packing steps are only performed as actual demand is observed. The product specificity of some of the components, however, makes supply chain planning a challenge even if postponement strategies are implemented. This requires different approaches to design the supply chain efficiently and avoid costly inventory build-ups or stockouts.

The methodology used in the studies presented in the preceding paragraphs is mostly case-based and does not verify the recommendations through computer simulation modelling or similar techniques, which some authors recognize as a limitation.[361] Also, for short life cycle products it may be infeasible to adjust the planning approach over the product life cycle, requiring a choice that is flexible enough to be adaptable to unexpected situations and other developments that occur over the product life cycle.[362] The challenge for planners in the high-

[358] Cf. Christopher, Martin G., Helen Peck and Denis R. Towill: A taxonomy for selecting global supply chain strategies, in: The International Journal of Logistics Management, Vol. 17 (2006), No. 2, p. 284.

[359] Cf. Lee: Aligning Supply Chain Strategies with Product Uncertainties, p. 114, who explains that such actions can lead to "agility" of the supply chain. In Lee's terms, responsiveness focuses on being responsive to changing customer demand at the front end, while agility also includes responsiveness to supply disruptions. Responsiveness, defined as the ability of the supply chain to respond purposefully and within an appropriate time-scale to customer requests or changes in the marketplace, implicitly includes the concept of agility, as supply disruptions require the flexibility of the supply chain to enable responsivness of the system. Therefore, agile supply chains are not separately discussed in this work.

[360] Cf. Christopher, Peck and Towill: A taxonomy for selecting global supply chain strategies, pp. 283–284 and Childerhouse and Towill: Engineering supply chains to match customer requirements, p. 343–344. See also Lee: Aligning Supply Chain Strategies with Product Uncertainties, pp. 113–114.

[361] See, for example, Kaipia and Holmström: Selecting the right planning approach for a product, pp. 11–12.

[362] Cf. Jüttner, Godsell and Christopher: Demand chain alignment competence, p. 992 and Selldin and Olhager: Linking products with supply chains, p. 49.

tech industry today, where companies sell a wide portfolio of products in volatile markets, is to design the planning approaches in the supply chain appropriately and implement them successfully. This is one possibility for achieving both increased efficiency and responsiveness in such supply chains as good planning approaches reduce the need for management attention. The scarce resources of management can then be dedicated to extraordinary situations, such as supply chain disruptions.[363]

III. Strategic Relevance of Supply Chain Challenges

Supply chains in the high-tech electronics industry face a large number of challenges, caused both by the market characteristics and by past and current actions of the supply chain members. Addressing those challenges involves catering to multiple objectives. These include the responsiveness of supply chains to changing customer requirements and their overall efficiency. Both of these issues in supply chain design and management currently receive wide attention in the scientific community as well as in practice. Management of supply chain responsiveness is particularly important when operating in a competitive market where short lead times might be critical and inventory – which can allow fast response – is risky (e.g., because of product obsolescence), costly and therefore reduces efficiency. These aspects become even more important for innovative products with short product life cycles, where management of supply chain responsiveness is seen as a crucial capability and demand surges during product introduction need to be handled as well as market downturns.[364] In the high-tech electronics sector, the share of purchased goods varies between 30 percent and 90 percent of total manufacturing costs. The high value of many long-lead time components leads to high stock-out costs and simultaneously increases the importance of inventory level and working capital management.[365] At the same time, more commodity-like, functional products are generally assumed to require more efficient supply chains[366], combined with minimisation of the bullwhip effect. When supply chains are more able to react to changing market requirements than necessary – i.e., having achieved a higher than necessary degree of responsiveness – customers will have to carry the additional cost, which

363 Cf. Kaipia and Holmström: Selecting the right planning approach for a product, p. 11.
364 Cf. Wu, S. David, Murat Erkoc and Suleyman Karabuk: Managing Capacity in the High-Tech Industry: A Review of Literature, in: The Engineering Economist, Vol. 50 (2005), No. 2, p. 126.
365 Cf. Helo: Managing agility and productivity in the electronics industry, p. 569.
366 Cf. Fisher: What is the Right Supply Chain for Your Product?, p. 112.

is also problematic.[367] The goal is to design the supply chain such that the "products may flow as required by the customer throughout the life cycle".[368]

In a project that established a new supply chain planning approach at Philips Electronics, numerous improvements in both efficiency and responsiveness could be observed: reductions in inventory levels and obsolescence save US$5 million per year on a US$300 million turnover, while the abilities to respond to upturns in the market and to make changes to the product mix were increased. At the same time, the delivery performance to the committed date could be improved, which represents an increase in the reliability in serving its customers. Those improvements represent an important competitive advantage, since the customers of Philips Electronics rely heavily on their products, with supply chain performance being a key differentiator. "For customers, a well-coordinated supply chain is crucial for fast and flexible responses to changes in the market and a proactive attitude towards market opportunities", as a manager involved in the project of introducing the new planning approach notes.[369] Managing such a change in supply chain strategy well is crucial, since a drastically different approach is likely to have an impact on other members of the supply chain, and potentially incurs additional costs in some parts of the chain.[370]

Dell's supply chain is an example for a responsive supply chain. The OEM in the computer industry delays assembly and configuration of computers until an order is placed by a customer. At the same time, it designs products to use many common parts and uses expedited freight selectively to achieve increased flexibility.[371] Component shortages are addressed by instant price reductions for some and increases for other components, consequently shaping demand, which is also used to reduce order fluctuations.[372] The key characteristics of the Dell supply chain are speed, responsiveness, low inventory levels, and end to end visibility and connection.[373]

Supply chains can react to changes in a product's demand volatility in various ways. For example, in the retail industry, there are three primary methods to

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367 Cf. Fisher: What is the Right Supply Chain for Your Product?, p. 110.

368 Cf. Aitken, Childerhouse and Towill: The impact of product life cycle on supply chain strategy, p. 127.

369 Cf. Kok *et al.*: Philips Electronics Synchronizes Its Supply Chain to End the Bullwhip Effect, pp. 42–45. This paper also provides a more detailed account of the planning process improvements at Philips Electronics.

370 Cf. Holweg *et al.*: Towards responsive vehicle supply, p. 508.

371 Cf. Hochmann: Flexibility – Finding the Right Fit, p. 10.

372 Cf. Kapuscinski *et al.*: Inventory Decisions in Dell's Supply Chain, p. 195.

373 Cf. Christopher and Towill: Supply chain migration from lean and functional to agile and customised, p. 211 and Kapuscinski *et al.*: Inventory Decisions in Dell's Supply Chain, pp. 191–193.

control material flow – manual pull, automatic pull and push. Push, where the product is rolled out to the stores based on a central plan that considers experience from the past, information on demography, buyer behaviour, product and salvage value etc., is considered to be best suited for the initial ramp-up period by Thonemann et al.[374] Later on, once demand is more predictable, automatic pull can be used where the IT system considers historical demand in the stores to reorder the product. Manual pull, where individual stores reorder based on the subjective judgements of store management, could be useful when special influences such as promotions need to be considered.[375]

A survey of consumer packaged goods companies in 2005 indicates that of those companies that tailor their supply chain approach to the product, the ones that consider changes in volatility of demand over time for the segmentation of their product portfolio are more successful. As shown in Figure B-10, 50 percent of the best performing companies in supply chain management used volatility as a segmentation criterion, compared to only 27 percent of the other companies, which tend to use simpler criteria such as volume.[376] This indicates that many companies do not realise the importance of tailoring the supply chain to the requirements a particular product has during the various stages of its life cycle. As the above examples show, there is no "one fits all" approach for successful management of the supply chain, but different strategies may be appropriate in different industries, for different products and potentially at different stages of their product life cycles.

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374 Cf. Thonemann *et al.*: Supply Chain Excellence im Handel, p. 131.

375 Cf. Thonemann *et al.*: Supply Chain Excellence im Handel, p. 131.

376 Cf. Alldredge, Kari *et al.*: Winning with Customers to Drive Real Results – The 2005 Customer and Channel Management Survey, 2005, GMA – The Association of Food, Beverage and Consumer Products Companies, http://www.gmabrands.com/publications/docs/winning.pdf, retrieved on: 13 November 2005, p. 5 and 21. Figure B-10 was adapted from this source. Winners for the Supply Chain Management area of the survey are defined based on a combination of AC-Nielsen data and P&L results.

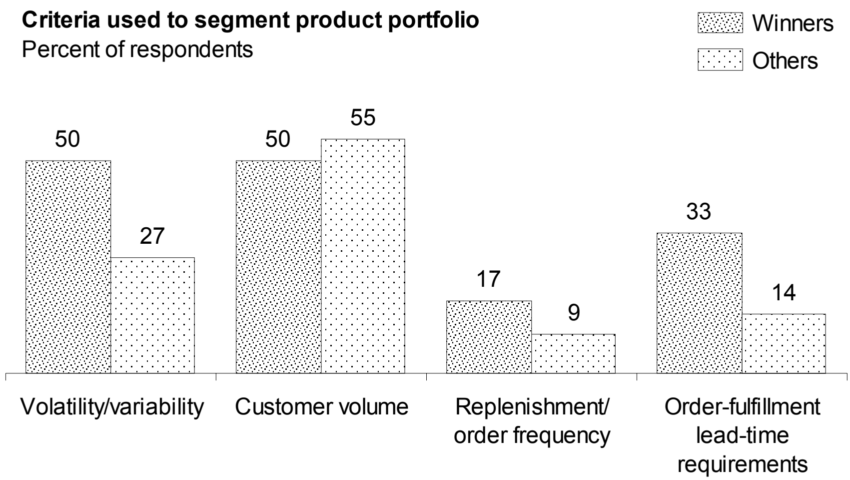

Figure B-10: Criteria Used to Segment Product Portfolio

C. Modelling Supply Chains in the High-Tech Electronics Industry with System Dynamics

The research objective is to capture the generic structures and intrinsic dynamics of supply chains in the high-tech electronics industry. An understanding of the linkages and dynamics between responsiveness and efficiency in supply chains allows the identification of policies that achieve increased responsiveness and efficiency at the same time. The methodology used to achieve this goal is System Dynamics (SD) and has its origins in control engineering and management. The SD perspective is based on explicitly modelling information feedback and delays to understand the dynamic behaviour of complex physical, biological, and social systems.[377] In the following, the System Dynamics methodology is introduced. The rest of the chapter is devoted to describing the System Dynamics model developed to analyse the balance between responsiveness and efficiency in the high-tech electronics industry.

I. Model Overview

1. Applying the System Dynamics Methodology

In the 1950s, Jay W. Forrester developed the field of System Dynamics at the Massachusetts Institute of Technology (MIT)[378]. System Dynamics is grounded on several theories reaching further into the past that were put together to form a new field. One of these is servomechanism theory, which Forrester linked to the social sciences. Forrester himself, during World War II, developed servomechanisms, or feedback control mechanisms, for the control of radar antennae and gun mounts, which linked the mathematical servomechanism theory with prac-

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[377] Cf. Angerhofer, Bernhard J. and Marios C. Angelides: System Dynamics Modelling in Supply Chain Management: Research Review, Winter Simulation Conference, Orlando 2000, p. 342.

[378] The first paper to be published on System Dynamics was the MIT D-memo zero that appeared on 5 November 1956, titled “Note to the faculty research seminar”. It outlines the distinction between System Dynamics and previously used modeling approaches. The paper was recently republished as: Forrester, Jay W.: Dynamic models of economic systems and industrial organizations (Archive Paper from 1956), in: System Dynamics Review, Vol. 19 (2003), No. 4, pp. 329–345.

tice.[379] Forrester then laid the foundation for research on supply chain behaviour and characteristics with his seminal work on "Industrial Dynamics", which is how he initially called the field.[380] Servomechanism theory is one of the foundations of System Dynamics as it is known today. The other is general systems theory, a field that was developed by von Bertalanffy in the 1940s and then extended, focusing on mathematically organising relationships into a coherent system.[381] A third is control theory, with its roots in physics.[382] With that there exists an "elegant and rigorous mathematical foundation" for the models developed in the System Dynamics field.[383]

System Dynamics provides a systematic approach to linking cause and effect in complex, dynamic situations. Systems can be complex for two reasons, (1) the structure of the system and (2) its dynamics.[384] Even when the structural parameters of a system are known, it is not possible to determine how the system behaves dynamically.[385] System Dynamics recognizes that the structure of a system drives its behaviour over time. The central idea of System Dynamics is that the internal causal structure and characteristics of the whole system determine the behaviour we observe, and not single decision, external disturbances or

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379 Cf. Forrester, Jay W.: The beginning of system dynamics, in: The McKinsey Quarterly, Vol. 4 (1995), p. 6. This paper also provides a short history of System Dynamics. For one of the first papers linking servomechanism theory and operations management, refer to Simon, Herbert A.: On the Application of Servomechanism Theory in the Study of Production Control, in: Econometrica, Vol. 20 (1952), No. 2. Simon uses servomechanism theory and its associated analytic techniques for inventory control purposes, which was later extended to multi-echelon supply systems by Burns and Sivazlian: Dynamic Analysis of Multi-Echelon Supply Systems.

380 Cf. Forrester: Industrial dynamics: A major breakthrough for decision makers, Forrester: Industrial Dynamics and Holweg, Matthias and John Bicheno: Supply chain simulation – a tool for education, enhancement and endeavour, in: International Journal of Production Economics, Vol. 78 (2002), No. 2, p. 163.

381 See Bertalanffy, Ludwig von: The history and status of general systems theory, in: Academy of Management Journal, Vol. 15 (1972), No. 4; Boulding, Kenneth E.: General Systems Theory – The Skeleton of Science, in: Management Science, Vol. 2 (1956), No. 3; Ackoff: Towards a System of Systems Concepts and Hammer: Enabling Successful Supply Chain Management, pp. 7–8.

382 Cf. Maxwell, James C.: On Governors, in: Proceedings of the Royal Society of London, Vol. 16 (1868).

383 Cf. Sterman, John D.: All models are wrong: reflections on becoming a systems scientist, in: System Dynamics Review, Vol. 18 (2002), No. 4, p. 503.

384 Cf. Größler, Grübner and Milling: Organisational adaptation processes to external complexity, p. 255. See also Milling: Understanding and managing innovation processes, p. 85.

385 Cf. Holweg *et al.*: Towards responsive vehicle supply, p. 511.

the characteristics of individual parts of the system.[386] The theory of complex feedback loop systems developed by Forrester enables an understanding of the important causal relationships in the system.[387] A feedback loop, as defined by Forrester, is “the structural setting within which all decisions are made”.[388] Any decision made at some point in the system alters the system state, i.e. the behaviour of the system is now different from what it would otherwise have been. This is known as a feedback control system, where the environment causes a decision that in turn has an effect on the original environment.[389] Future decisions will now be based on this new, changed system state. Therefore, the system “produces the decision which produces the action which produces change in the system”; there is an implied circularity of cause and effect.[390]

Decisions in any system are not based on the actual system state, but can only use information that is actually available to the decision makers.[391] This information is only in rare cases complete, unbiased and current.[392] Additionally, human decision makers are subject to psychological and cognitive limitations. Bounded rationality, an idea that is at the centre of the System Dynamics theory and has its roots in what is known as the Carnegie School, suggests that “decision making can never achieve the ideal of perfect (objective) rationality, but is destined to a lower level of intended rationality” and that the performance and success of an organization is primarily determined by the ability of the

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386 Cf. Forrester: Industrial dynamics: A major breakthrough for decision makers, p. 40 and Schieritz, Nadine and Peter M. Milling: Modeling the Forest or Modeling the Trees – A Comparison of System Dynamics and Agent-Based Simulation, 2003, http://iswww.bwl.uni-mannheim.de/Forschung/pr/sd03/p-na.pdf, retrieved on: 9 September 2006, p. 3.

387 Cf. Shantzis, Steven B. and William W. Behrens III: Population Control Mechanisms in a Primitive Agricultural Society, in: Meadows, Dennis L. and Donella H. Meadows (Eds.): Towards Global Equilibrium: Collected Papers, Cambridge, MA 1973, p. 259.

388 Forrester, Jay W.: Market Growth as Influenced by Capital Investment, in: Industrial Management Review (currently published as the Sloan Management Review), Vol. 9 (1968), No. 2, p. 84. This paper, pp. 83–86, provides a succinct introduction to Forrester’s ideas on systems.

389 Cf. Forrester: Industrial dynamics: A major breakthrough for decision makers, p. 39.

390 Cf. Forrester: Market Growth as Influenced by Capital Investment, p. 84.

391 This is referred to as the Baker Criterion, indicating that the inputs to all decision rules in models must be restricted to information actually avaiable to decision makers. Cf. Sterman: Business Dynamics, pp. 516–518.

392 Cf. Schieritz and Milling: Modeling the Forest or Modeling the Trees, p. 4.

members of the system to process information in a meaningful way.[393] In supply chain management, Sterman uses the System Dynamics methodology to evaluate how human "misperceptions of feedback" and the lacking ability to account for the supply line of orders affect the behaviour of a four-stage supply chain by conducting an experiment with human subjects. Sterman finds that even perfectly reasonable decision processes in a supply chain lead to unintended and dysfunctional results, such as oscillation and increased variability.[394] Diehl and Sterman extend this work and find that when the feedback complexity of the supply chain system they studied was low, subjects could outperform a very simple "make no changes to system"-decision rule. However, most subjects were outperformed by the "make no changes to system"-rule as the complexity of the system was increased, e.g. through delays and more feedback effects.[395] Therefore, even locally rational heuristics used by, for example, supply chain managers, can have unintended consequences, such as supply chain instability.[396] System dynamics models recognize bounded rationality explicitly when representing the structure of the decision-making processes in the system as feedback loops.[397]

Dynamic decision making problems such as those in supply chains, involving high-order systems of nonlinear integral and differential equations, pose significant computational burdens for a computation of an optimal solution, or

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[393] Cf. Morecroft, John D.W.: System Dynamics: Portraying Bounded Rationality, in: Omega, Vol. 11 (1983), No. 2, pp. 131–132. The Carnegie School is based on the notion that decisions made by human decision makers are influenced by severe limitations of their information processing and computing abilities.

[394] Cf. Sterman: Modeling Managerial Behavior, p. 337.

[395] Cf. Diehl, Ernst and John D. Sterman: Effects of feedback complexity on dynamic decision making, 1993, Sloan Working Paper 3608-93-MSA, Sloan School of Management, Massachusetts Institute of Technology, https://dspace.mit.edu/bitstream/1721.1/2491/1/SWP-3608-28936061.pdf, retrieved on: 16 October 2006, pp. 15–16. See also Gonçalves: Demand Bubbles and Phantom Orders in Supply Chains, p. 19.

[396] Cf. Gonçalves: Demand Bubbles and Phantom Orders in Supply Chains, pp. 18–19.

[397] Cf. Größler, Andreas, Peter M. Milling and Graham Winch: Perspectives on rationality in system dynamics – a workshop report and open research questions, in: Omega, Vol. 20 (2004), No. 1, pp. 78–79.

make that impossible.[398] One can choose not to model the decision-making processes in a certain problem explicitly, introduce simplifying assumptions and thus reduce the problem sufficiently to face a problem that can be solved for an optimal solution. For example, one line of research on supply chain management assumes fully rational agents, as opposed to locally and boundedly rational agents as mentioned above. Lee et al. attribute the bullwhip effect only to the infrastructure and related processes of the supply chain and not the decision makers' locally and boundedly rational behaviour, arguing that the decision makers are fully rational.[399] In contrast to Sterman's work[400], Lee et al. assume that the decision makers in the supply chain are "rational and optimizing" and they use "simple mathematical models…to explain the outcome of rational decision making".[401] Lee et al. do, however, acknowledge the work done by Forrester, Sterman and others to explain the bullwhip effect.[402] The approach of assuming perfect rationality and optimizing the performance has the disadvantage of potentially leading to results that differ from observed reality.[403] For example, Croson and Donohue find that the bullwhip effect still exists even when the operational causes of the bullwhip effect that were identified by Lee et al. (shortage gaming, demand signalling, order batching and price fluctuations) are removed from the system and demand is known to all parties.[404] Modellers always face a trade-off between optimizing a simplified system that may not represent the real world well and developing a more realistic model that can lead to satis-

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398 Cf. Simon: Rational Decision Making in Business Organizations, p. 499 and Gonçalves: Demand Bubbles and Phantom Orders in Supply Chains, p. 32. See also Jain, Sanjay: Supply Chain Management Tradeoffs Analysis, Winter Simulation Conference, Washington, D.C. 2004, p. 1358; Holweg, Matthias and Stephen M. Disney: The evolving frontiers of the bullwhip problem, EurOMA International Conference on Operations and Global Competitiveness, Budapest 2005, p. 713; and Lertpattarapong: Applying system dynamics approach to the supply chain management problem, p. 91.

399 Cf. Lee, Padmanabhan and Whang: The bullwhip effect in supply chains, p. 95.

400 Cf. Sterman: Modeling Managerial Behavior, pp. 321–322.

401 Lee, Padmanabhan and Whang: Information Distortion in a Supply Chain: The Bullwhip Effect, p. 548.

402 Cf. Lee, Hau L., V. Paddy Padmanabhan and Seungjin Whang: Comments on "Information Distortion in a Supply Chain: The Bullwhip Effect", in: Management Science, Vol. 50 (2004), No. 12, p. 1887.

403 Cf. Simon: Rational Decision Making in Business Organizations, p. 505; Sterman: Modeling Managerial Behavior, pp. 321–322. and Gonçalves: Demand Bubbles and Phantom Orders in Supply Chains, p. 19.

404 Cf. Croson and Donahue: Behavioral Causes of the Bullwhip Effect and the Observed Value of Inventory Information, pp. 323–324.

factory solutions.[405] Simon calls this satisficing – “decision makers can satisfice either by finding optimum solutions for a simplified world, or by finding satisfactory solutions for a more realistic world”.[406] System Dynamics aims for the latter by aiming at representing the decision rules in the system realistically.

In System Dynamics models, real-world processes are represented as stocks and flows between those stocks, using a set of integral and differential equations to mathematically capture the characteristics of the system. Those are the only two types of variables required to represent the activity within a feedback loop.[407] Mathematics “forces clarity and precision upon the conjectures [about underlying mechanisms], thus enabling meaningful comparison between the consequences of basic assumptions and empirical facts”.[408] Stock variables, or levels, represent the system condition at any point in time. They are accumulations within the system; mathematically, level variables are integrations of the net difference between inflow and outflow to the stock over time.[409] The consequence of this modelling technique is that single objects flowing through the system cannot be identified; instead, the system is modelled from an aggregate point of view, representing the characteristics of objects via average properties.[410] Flow variables, or rates, describe how and when decisions are made. “The rate equations are the policy statements in the system that define how the existing conditions of the system produce a decision stream controlling action”.[411] Flow variables represent the inflows and outflows to stock variables, hence their name. In the case of a supply chain model, those flows can be, for example, material flows or information flows, which are influenced by decision rules on orders, production etc.

Computer simulation is a sophisticated means to understand the often highly counter-intuitive dynamics of the complex interrelations found in supply chains, particularly because it allows to study the overall effects of modifications on the whole supply chain, rather than limiting the analysis to the local effects in a single manufacturing process or a single buffer.[412] System Dynamics simulation creates an environment where new decision making structures can be tested sys-

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405 Cf. Simon: Rational Decision Making in Business Organizations, p. 499.

406 Cf. Simon: Rational Decision Making in Business Organizations, p. 498.

407 Cf. Forrester: Market Growth as Influenced by Capital Investment, p. 84.

408 May, Robert M.: Uses and Abuses of Mathematics in Biology, in: Science, Vol. 303 (2004), p. 791.

409 Cf. Forrester: Market Growth as Influenced by Capital Investment, p. 85.

410 Cf. Schieritz and Milling: Modeling the Forest or Modeling the Trees, p. 8.

411 Forrester: Market Growth as Influenced by Capital Investment, p. 85.

412 Cf. Shapiro: Modeling the Supply Chain, p. 240 and Hieta, Saku: Supply Chain Simulation with Logsim-Simulator, Winter Simulation Conference, Washington, D.C. 1998, p. 323.

tematically without the necessity of having access to empirical data on the structure. Such system modifications can be analysed and simulated in a controlled environment before carrying out similar changes in the real system. System Dynamics allows predicting the behaviour in complex systems by establishing a link between the structure of a system and its behaviour.[413] It provides a framework for understanding the complexity in such systems, e.g. supply chains.[414]

Traditional modelling methods, such as static spreadsheet models, often do not sufficiently account for the real factors that affect the dynamics of complex systems, such as supply chains in the high-tech industry.[415] Akkermans and Dellaert argue that many of the approaches developed in the past to develop SCM theory necessarily rely on assumptions that "are perhaps not even close to being realistic in practice".[416] System Dynamics is an approach that can capture many of the elements that are often ignored or assumed, by explicitly modelling feedback, perceived delays, bounded rationality and goal setting. SD "becomes therefore a perfect candidate to analyse the more complex settings of today's supply chains and supply chain networks", in particular because it is also useful in analysing process improvements in supply chains.[417] While the System Dynamics approach necessarily relies on assumptions as well, its intention is to capture the real decision making processes that can be observed in the system. In complex supply chains, this aspect is particularly important, as a large number of variables need to be considered in order to enable a balanced analysis of the factors influencing responsiveness and efficiency.[418] Other modelling approaches often do not capture interactions among processes that evolve over time, which can lead to potentially inaccurate results. Most importantly, such models may not consider feedback effects.

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413 Cf. Schieritz and Milling: Modeling the Forest or Modeling the Trees, p. 8.

414 Cf. Lee, Paul and Martin Davies: Reap or weep, in: Supply Management, Vol. 2 (1997), No. 18, p. 38, and Avni, Tayfun: Simulation modeling primer – A review of simulation modeling, in: IIE Solutions, Vol. 31 (1999), No. 9, p. 39.

415 Note that it is possible to develop a dynamic spreadsheet model, following the System Dynamics methodology. However, modern software packages simplify the process significantly. For examples of spreadsheet-based System Dynamics models, see Evans, Gary N., Mohamed M. Naim and Denis R. Towill: Application of a simulation methodology to the redesign of a logistical control system, in: International Journal of Production Economics, Vol. 56–57 (1998) and Holweg *et al.*: Towards responsive vehicle supply.

416 Akkermans and Dellaert: The rediscovery of industrial dynamics, p. 180.

417 Akkermans and Dellaert: The rediscovery of industrial dynamics, pp. 179–180. See also Forrester: Industrial Dynamics and Sterman: Business Dynamics.

418 Cf. Holweg: The three dimensions of responsiveness, p. 603.

While the empirical studies discussed in section B.II.5 identify links between the supply chain type, product type and performance, the task remains to identify causal relationships.[419] Many of the features observed in high-tech supply chains, such as delays in information and material flow and long planning horizons, are connected to the systemic problems in supply chains identified by Forrester.[420] Following Simon's remarks on model construction, the holistic System Dynamics model developed in this work retains a rich set of properties of the real world by modelling the total supply chain from customer order through to the component suppliers. This allows finding "satisfactory solutions for a more realistic world", as opposed to determining optimal solutions that can only be found in a significantly simplified model that does not reflect reality as well.[421]

Previous System Dynamics studies into the high-tech supply chain have focused on subsystems of the supply chain, e.g. the work by Gonçalves and Gonçalves et al. on a semiconductor manufacturer[422] and that by Forrester focusing on decision structures relating to market growth for a high-tech company[423]. Lertpattarapong presents a System Dynamics simulation model relating to the supply chain structure of a high-tech company, but does not proceed to show how the system could be changed to achieve greater responsiveness and efficiency.[424] Kamath and Roy's System Dynamics model analyses the costs of two-echelon supply chains for short life cycle products, with a focus on capacity expansion decisions, which are not relevant over the short life cycle of the prod-

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419 See, for example, Ramdas and Spekman: Chain or Shackles: Understanding What Drives Supply-Chain Performance, p. 21 and Holweg: The three dimensions of responsiveness, p. 617 and p. 613.

420 Cf. Forrester: Industrial Dynamics, pp. 172–186; and Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, p. 95.

421 Cf. Simon: Rational Decision Making in Business Organizations, p. 498. See also Holweg *et al.*: Towards responsive vehicle supply, who develop a simulation model of the automotive supply chain that has similar characteristics.

422 See Gonçalves: Demand Bubbles and Phantom Orders in Supply Chains and Gonçalves, Hines and Sterman: The impact of endogenous demand on push-pull production systems.

423 See Forrester: Market Growth as Influenced by Capital Investment.

424 See Lertpattarapong: Applying system dynamics approach to the supply chain management problem.

ucts considered in this work.[425] Additionally, such two-echelon supply chains are by their nature a highly simplified abstraction from reality.

The model developed in this work has the objective of investigating responsiveness and efficiency in a multi-echelon high-tech electronics supply chain. The research objective is achieved by modelling the planning approaches in such a supply chain and identifying appropriate planning approaches for products with different structural characteristics of demand and supply. By varying the structure of the system, i.e. simulating different planning approaches, operating points can be identified that achieve the desired responsiveness and efficiency. Also, both centralised and decentralised planning processes throughout the supply chain are represented in the model presented in the following, which is an aspect that so far has not been examined with such models in detail.[426] This work explicitly acknowledges the existence of feedback effects that affect decisions elsewhere in the supply chain and endeavours to examine how these effects affect supply chain responsiveness and efficiency. The author develops a mathematical model that captures the underlying structure and dynamics of the processes in supply chains in the high-tech electronics industry. The System Dynamics model explicitly includes the impact that decision variables, such as desired safety stock levels, and the planning heuristics used have on supply chain performance.

The model serves primarily as a basis for research, but research findings are expected to be of high practical relevance. The System Dynamics model can support decision makers in managing supply chains according to the goals of responsiveness and efficiency. Through cooperating with the consulting firm McKinsey & Company, Inc., a generic structure of supply chains similar to that described by Sterman[427], Forrester[428] and others, is combined with case-based input from practice and expert insights on the model results.

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425 Cf. Kamath B., Narasimha and Rahul Roy: Supply Chain Structure Design for a Short Lifecycle Product: A Loop Dominance Based Analysis, Hawaii International Conference on System Sciences, Hawaii 2005, p. 4 and Kamath B., Narasimha and Rahul Roy: Capacity augmentation of a supply chain for a short lifecycle product: A system dynamics framework, 2006, forthcoming in: European Journal of Operational Research, pp. 4–6.

426 Cf. Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, p. 101 and Fransoo, Jan C., Marc J.F. Wouters and Ton G. de Kok: Multi-echelon multi-company inventory planning with limited information exchange, in: Journal of the Operational Research Society, Vol. 52 (2001), No. 7, pp. 830–832 and 836f.

427 Cf. Sterman: Business Dynamics, pp. 709 et sqq.

428 Cf. Forrester: Industrial Dynamics.

2. Model Boundary and Model Sectors

The System Dynamics model represents different planning systems that are either currently in place in typical supply chains in the high-tech industry or are conceived to be potential yet realistic approaches. Even though it may be theoretically possible to devise a system that incorporates all of the suggestions made by researchers on successful supply chain strategies, many of these are difficult to implement in practice, which is why the aspect of realism and implementability is a consideration in this work. Typically, supply chains for high-tech electronics products, such as mobile phones or network routers, are set up as hybrid push–pull production systems, with a varying extent of the use of each planning approach in the supply chain.[429] The key distinction between different planning approaches in this System Dynamics model is achieved through differences in the decision-making policies of the supply chain members. Those locally rational decisions affect material orders, production levels and shipment rates in each period, and are based on information known to the different players in the supply chain, e.g. a forecast provided to them, as well as on own beliefs about future developments. Due to the aspects of bounded rationality outlined previously, such policies can lead to unexpected dynamic behaviour in the system.

The supply chain planning approach that currently predominates in the high-tech industry is a push-based supply chain planning approach, based on a system with cascading forecasts through the supply chain, where the different supply chain members each use their own material requirements planning (MRP) system. This push approach, based on long-term demand forecasts, is used by the supply chain members upstream of software flashing, up to a major buffer stock of semi-finished products. This buffer stock is located at the software flashing and packing production step. From there, the customer pulls the product and the final customization steps and shipment are performed within a very short lead time and driven by customer orders. In the mobile phone industry, for example, operators, such as T-Mobile or Vodafone, place their orders directly with the country representatives of the mobile phone OEMs, such as Nokia. Cisco calls such an approach “build to stock and ship to order”.[430] This push approach until the major buffer stock, with forecasts that cascade upstream through the supply chain and are adjusted by each echelon, is the first planning approach that is modelled. The second approach replaces the cascading forecasts by central

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429 See also Gonçalves, Hines and Sterman: The impact of endogenous demand on push-pull production systems, p. 191, who describe the production process for semiconductors at Intel.

430 Parmar: Supply Chain Architecture in a High Demand Variability Environment, p. 12.

planning. The third approach is a pull-based system from the customer until the board printing stage. Suppliers to board printing, e.g. semiconductor chip manufacturers, still use a push approach, since the lead time for these components is very long, i.e. several weeks up to months. Each of these modelled planning approaches receives several different demand patterns as an input. This allows identification of the most appropriate approaches for the supply chain planning and ordering mechanisms for each of several demand scenarios with different demand uncertainty.

The model considers the flows of information and materials through the supply chain, beginning with the forecasts used for early component orders and the initial customer order for a single product and ending with its delivery. Financial flows can easily be added but are not in the focus of the current model and are therefore omitted. The underlying supply chain set-up is based on the structure of a typical high-tech supply chain and currently represents decision policies for four nodes plus the customer. The structure represented in the System Dynamics model consists of a customer, software flashing and packing, final assembly and testing, and two first tier suppliers in order to obtain a fundamental understanding of the underlying structure of the decision-making processes at the different supply chain nodes. In addition to board printing, a further first tier supplier to the final assembly stage is explicitly included in the model. Considering fewer supply chain tiers would have been a serious limitation of the research. From this generalized structure, insights can be gained into the dynamic performance of the system and opportunities for improvement.

Figure C-1 provides an overview of the model structure. At each step in the supply chain materials are converted to finished goods, while the finished goods at the supplier and board printing level then become inputs for the production process at the final assembly stage, and the finished goods at final assembly become inputs for the customization process at software flashing. At each of these echelons, there are thus materials, work in process and finished goods inventory levels.

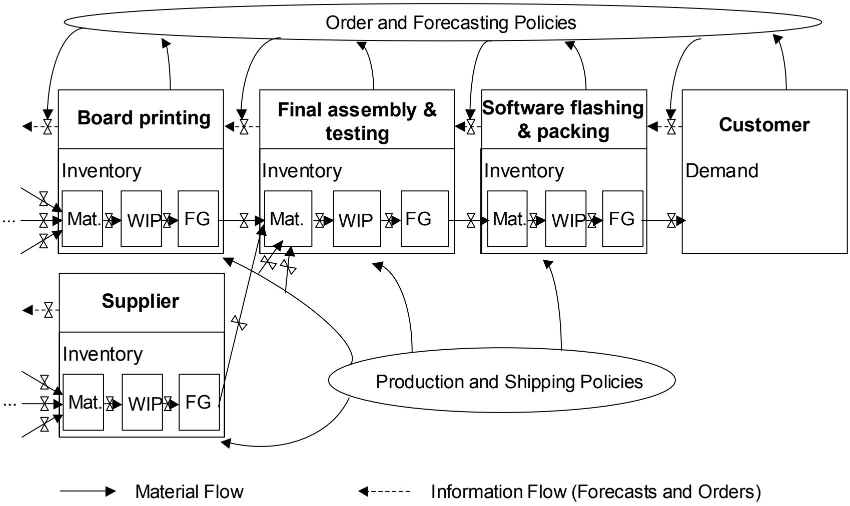

Figure C-1: Overview of the Structure of the System Dynamics Model

The model boundary chart below summarizes the scope of the model by categorising the key variables as endogenous, exogenous and excluded from the model.[431] Endogenous variables ("arising from within") are defined within the scope of the model. Exogenous variables ("arising from without") are input parameters that are constant over time or input variables that are dynamic over time. Excluded variables are outside the scope of the model. Listed below are concepts, not specific variables. The number of exogenous variables is kept as small as possible[432], yet due to its nature several parameters are needed.

[431] Cf. Sterman: Business Dynamics, p. 97.

[432] Cf. Sterman: Business Dynamics, pp. 96–97.

Table C-1: Model Boundary Chart

Endogenous	*Exogenous*	*Excluded*
Material orders	Initial values of stocks	Competition
Forecast adjustments	Original customer demand	R&D costs
Production processes	Initial forecasts	Product variants
Order backlog	Production capacity	Customer demand changes due to delivery performance
Inventory levels	Standard production and shipment delays	Capacity adjustments
Expected demand	Machine failures and other external supply disruptions	
Inventory cost	Desired days of stock	
Delivery performance	Capacity limits	
Emergency orders		

Out of the criteria distinguishing different types of products, the model focuses on demand uncertainty, demand volatility and in general the product life cycle over time. The number of variants is beyond the scope of this work and therefore excluded from the model. The model covers one representative product at a time.

3. *Measuring System Performance*

To assess the quality of policies and structural changes to the model, two key performance indicators (KPIs) are used to quantify the performance of the supply chain. There are many possible performance measures that can be used to track the efficiency and responsiveness of the modelled supply chain, which are the two areas of supply chain performance most commonly tracked in supply chain simulation models.[433] The two most relevant ones for this work, covering many of the aspects of responsiveness and efficiency, are the total inventory cost incurred in the system, measured through inventory turns, and delivery performance to customer request. These performance measures are strongly influenced by a company's business processes and important determinants for cus-

433 Cf. Beamon, Benita M.: Measuring supply chain performance, in: International Journal of Operations & Production Management, Vol. 19 (1999), No. 3/4, pp. 277–278.

tomer satisfaction.[434] Other performance measures relating to supply chain costs, such as operating costs, distribution costs and manufacturing costs[435], are not explicitly measured because the different planning approaches, as modelled in this System Dynamics model, do not lead to changes in these performance measures. However, aspects of capacity utilization, for example, are discussed as they influence the operative efficiency of production at the suppliers.

Delivery Performance to Customer Request. Delivery performance to customer request is defined as the share of orders received by the customer on or before the requested delivery date. The value for delivery performance calculated in the model therefore in each time period refers to the delivery performance of all previous time periods. It is calculated as the fraction of cumulated demand delivered on or before the customer request date divided by the cumulated customer demand[436]:

```
delivery performance to customer request =
   XIDZ
   ((cum demand requested for the current day
     - cum orders not filled on time)
    ,cum demand requested for the current day,1)
```

The level of responsiveness of a supply chain is considered to be higher if the products can be delivered more reliably and with better quality.[437] While product quality is excluded from the model, the delivery performance can be measured as the share of orders that are received by the customer on time, i.e. on or before the requested delivery date. This performance measure also implicitly considers lost sales, as low delivery performance, i.e. late deliveries, could cause customers to switch to competitors.[438] The backlog building up at the different echelons of the supply chain can also be separately measured.[439]

The variable *cum orders not filled on time* is calculated as follows. The change of the value of this variable depends on the customer backlog in a period, which measures the extent to which the demand by the customer has been

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[434] Cf. Reiner, Gerald: Customer-oriented improvement and evaluation of supply chain processes supported by simulation models, in: International Journal of Production Economics, Vol. 96 (2005), No. 3, p. 5.

[435] See Beamon: Measuring supply chain performance, p. 282.

[436] The XIDZ function performs division except when that division would be by 0, in which case it returns the third argument.

[437] Cf. Reichhart and Holweg: Creating the Customer-responsive Supply Chain, pp. 25–26.

[438] A different, and arguably less intuitive, approach to measuring the cost of lost sales is taken by Holweg et al., who include lost sales in the calculation of inventory cost. See Holweg *et al.*: Towards responsive vehicle supply, p. 513.

[439] See Beamon: Measuring supply chain performance, p. 283.

filled. Customer backlog is a stock variable that is increased by demand and reduced by shipments received by the customer. The inflow to the customer backlog is therefore *demand for the current day*, while the outflow is the *receiving rate cust*.

```
customer backlog =
   INTEG (inflow customer backlog-outflow customer backlog,0)
```

If the customer backlog at the end of a day, considering the demand and deliveries of that day, is less than or equal to zero, all orders for that day have reached the customer on or before the requested delivery date. Therefore, in such a case the value of cumulative orders not filled on time is not changed. On the other hand, if the customer backlog at the end of the day is larger than zero, it means that some of the customer orders have not been filled on time. There are three possibilities in such a case.

1. *Demand on a given day is smaller than the customer backlog at the end of the day*. If demand on a given day is smaller than the ending backlog, there must have been a beginning backlog, which has not completely been fulfilled. This also means that no part of the current day's demand has been fulfilled. Therefore, in this situation demand for the current day is added to the cumulative orders not filled on time.
2. *Demand on a given day is larger than the customer backlog at the end of the day*. In this situation, some of the demand for that day was filled, but some units remain in the backlog at the end of the day. This backlog therefore represents those units of the current day's demand that have not yet been received by the customer. The ending backlog is therefore added to the cumulative orders not filled on time.
3. *Demand on a given day is equal to the ending customer backlog*. If demand on a given day is equal to the ending customer backlog this means that the current day's demand has not been delivered to the customer on time, and there are no further delayed orders. This value is therefore added to the cumulative orders not filled on time.

Note that due to the nonlinearity of the production and shipment delays in the model it can happen that an order is filled ahead of time, in which case customer backlog is negative. In the supply chain structure modeled, with customers pulling from a stock of semi-finished products at software flashing, it is possible for a small amount of orders to arrive at the customer before the requested delivery date. However, these amounts are very small, occur independent of the planning approach and their inclusion in the performance measure of delivery performance to customer request would therefore not have added value.

Inventory Turnover. The overall performance measure for inventory levels is inventory turnover, which measures the number of times capital that is invested in components or goods to be sold, i.e. inventory, turns over in the course of the simulation duration. This performance measure, which is used to assess the effectiveness of inventory management, can be improved either by moving the same amount of products through the supply chain with a lower average inventory or by moving more products through the supply chain with the same average inventory. It is therefore a performance measure that allows comparison of average inventory levels even if products, their demand or the supply chain structures are different.[440] Inventory turns are calculated as the total customer demand over the simulation duration divided by the average over the entire simulation duration of the total capital invested in inventory at all supply chain nodes.[441] In practice, inventory turns are normally calculated on a yearly basis; to achieve a single performance measure that allows the comparison over the entire product life cycle, this performance measure is calculated over the entire simulation duration in this work. The inventory turnover performance measure is weighted to ensure that the relative cost of inventory corresponds to the value-added content in the supply chain. These weights are approximations based on a typical mobile phone supply chain, which is a good example for a high-tech electronics product.[442] Actual cost data is not available as it is regarded as highly sensitive. Instead, the relative inventory cost at each stocking location in the supply chain is used as an approximation to measure the system's performance, as shown in Table C-2. The component costs in the high-tech industry reflect between 30 percent and 90 percent of total manufacturing costs[443]. The chosen value of 70 percent is an estimate for the mobile phone industry, and lies within the range of values typically observed. This is equivalent to a 30 percent value-added content of final assembly and software flashing, with the cost of the product at the finished goods inventory stage being weighted at 1 dollar per unit per day.[444] Obsolescence costs and storage costs are not separately measured as

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440 Cf. Speh, Tom: Calculating Warehouse Inventory Turnover, WERC, 2005, pp. 1–2.

441 Total customer demand in this equation is measured in units of finished goods sold, and not as sales in currency terms (cost of goods sold). This calculation is valid to identify the inventory turns in this case as the cost of the products at the different supply chain echelons is also indexed, with finished goods having a cost of 1. Also, this approach avoids inconsistencies in valuation. Finally, the calculation approach used in the simulation is the most accurate approach to determine inventory turns, as it records inventory levels on continuous (daily) basis. See Speh: Calculating Warehouse Inventory Turnover, pp. 1–2.

442 The relative inventory cost data are approximations provided by Andrei Kokoev, associate at McKinsey & Company, Inc., Chicago, personal communication, 7 June 2006.

443 Cf. Helo: Managing agility and productivity in the electronics industry, p. 569.

444 A similar method of weighting inventory levels is used by Holweg *et al.*: Towards responsive vehicle supply, p. 512.

they are included in the relative inventory cost per unit and this measure is sufficient for a comparison of the relative costs of the different supply chain planning approaches.[445]

Table C-2: Relative Inventory Cost per Unit

Inventory Level	*Relative Inventory Cost (dollars/unit/day)*
Software Flashing & Packing	
Inventory FG SWF	1
Inventory WIP SWF	0.9
Inventory RM SWF	0.9
Final Assembly & Testing	
Inventory FG FAT	0.9
Inventory WIP FAT	0.7
Inventory Boards FAT	0.5
Inventory RM FAT	0.2
Board Printing	
Inventory FG BP	0.5
Inventory WIP BP	0.45
Inventory RM BP	0.45
Other Tier 1 Supplier	
Inventory FG Sup	0.2
Inventory WIP Sup	0.2
Inventory RM Sup	0.1

4. *Model Formulation and Testing Process*

In order to provide a helpful tool for decision-making, the simulation model has to provide an adequate representation of underlying real world structures.[446] The first versions of the System Dynamics simulation model were developed by the

445 See Beamon: Measuring supply chain performance, p. 279 and p. 282.
446 Cf. Milling and Maier: Invention, Innovation und Diffusion, p. 187.

author using the Vensim software[447], based on dynamic hypotheses and existing frameworks on modelling a supply chain in the high-tech industry. The author then obtained access to experts in the High-Tech, Supply Chain Management and Manufacturing practices at the consulting firm McKinsey & Company, Inc., as well as direct access to data from OEMs.

A triangulation of methods was perceived to be important, because the appropriate representation of the supply chain system is a prerequisite for the validity of the conclusions drawn from the simulation. Since testing the findings in real-world planning systems was not a realistic option, the author discussed the model with industry experts.[448] Several structured interviews were conducted with high-tech industry experts, followed by a nine-day modelling workshop. During this workshop, the model was presented within an open forum and the author worked extensively with supply chain and industry experts who suggested tests and policies that were run immediately and whose implications were discussed on the spot. The model was refined and revised significantly during the workshop, estimates for the parameters of the model were developed and implemented and the decision-making structures in high-tech firms were discussed, as well as possibilities to realistically represent them in the model.[449] In addition, the author discussed the supply chain models and the simulation results with the members of the System Dynamics Group at MIT and incorporated numerous suggestions for improvements. At the end of this phase, the model was perceived to represent the structure of a typical supply chain in the high-tech industry appropriately. Also, empirical demand and forecast data for representative products was obtained to be used in the model testing phase and for the calibration of appropriate demand patterns to be used in the simulations.

The model developed herein does not attempt to exactly replicate some time behaviour that was observed in the past. Instead, its parameters are flexible enough to allow adaptation to many situations, be it fictitious or real. In order to be able to use the model appropriately it is essential to be aware of its limitations. While the model does capture the dynamics of supply chains well and can answer the research questions, it may be unsuitable for certain tasks. No simulation model can reflect the complexity of a real system perfectly[450], which is why

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447 The modeling software used for the simulation models is Vensim® DSS for Windows Version 5.5d.

448 This approach is common; see, for example, Holweg *et al.*: Towards responsive vehicle supply, p. 522.

449 A similar approach with interviews and several modelling workshops together with industry experts was followed by Sterman, who analyses the dynamics of a company making personal computers. See Sterman: Managing the Supply Chain in a High-Velocity Industry, pp. 10–11.

450 Cf. Sterman: All models are wrong, p. 501and pp. 525–526.

the focus of any modelling effort, including this one, must be to reproduce the structure appropriately such that the dynamic behaviour derived from it can be analyzed. Models are necessarily simplifications; therefore, for example, the model does not attempt to represent every SKU in the product line of a high-tech electronics company. Instead, the focus is on one particular product and on capturing the stock and flow structure of the supply chain at a more aggregate level. The model represents the interdependencies and feedbacks created by the behaviour of the actors, in particular the interactions between the different members of the supply chain. Validation of the model thus refers to the problem that the model is intended to address – a model that was developed for a particular purpose can lead to incorrect conclusions in other contexts.[451]

Throughout its development, attention has been paid to ensure that the structures represented in the model and the time behaviour generated by it are reasonable representations of real world developments. According to Milling, there are three steps in validating a simulation model, which can and in this research were carried out simultaneously: structural validation, parameter validation and behaviour validation.[452] These three overlap, which becomes clear when consulting other literature on model validation.[453]

Structural Validation. This is an important aspect of model validation, since it is essential to ensure that all hypotheses made in the model have a real world counterpart and that the model structure is valid compared to the real world system. Past research has been consulted in the development of the model, as discussed in the previous sections. The representation that is used for physical and information flows in the supply chain, for example, has proved to be a useful representation of reality for more than three decades. Intuition and experience were, of course also important when developing the model. Nevertheless, many if not all of the underlying hypotheses are empirically sound and were verified with industry experts.

Parameter Validation. The supply chain is adaptable to different conditions through various parameters. These include delays in information processing,

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451 Cf. Forrester: Industrial Dynamics, p. 115 and the following other applications to operations management problems: Milling, Peter M.: Der technische Fortschritt beim Produktionsprozeß – Ein dynamisches Modell für innovative Industrieunternehmen, Wiesbaden 1974, p. 208 and Milling and Maier: Invention, Innovation und Diffusion, p. 188.

452 Cf. Milling: Der technische Fortschritt beim Produktionsprozeß, pp. 208–209.

453 For example, see Sterman: Business Dynamics, pp. 843–892 and Shreckengost, Raymond C.: Dynamic Simulation Models: How valid are they?, in: Rouse, B.A., N.J. Kozel and L.G. Richards (Eds.): Self-Report Methods of Estimating Drug Use: Meeting Current Challenges to Validity (NIDA Research Monograph 57), Rockville, MD 1985.

production and shipment delays and resulting lead times, capacity limitations and external shocks to the supply chain that can happen at board printing and at the supplier. Most of these parameters do not differ for comparing different planning approaches, which enables a comparison of performance measures purely based on changes in decision-making policies. The parameters are chosen to be realistic, yet they do not necessarily exactly model the development of a particular product. Instead, they are chosen in order to generate a realistic behaviour. This was confirmed with past research and real world data. The parameters of the System Dynamics model are determined both through analysis of data provided by sample companies and through expert estimations.[454] Inputs into the model include demand patterns, forecast patterns and information about production and ordering policies. For products at different positions on the continuum between innovative and functional products, distinct demand patterns are represented in the model as well as structural differences in supply chain policies. The demand scenarios to reflect different types of products are currently represented in the model as input data read from a spreadsheet document that can be additionally modified using Vensim's capabilities of, for example, random number and table functions. The analysis of simulation results begins with simple scenarios, such as constant demand with no variation, and only later proceeds to more complex product life cycles with random demand. Also, actual customer order data for specific products over their entire product life cycle are used as an input to the model during the model testing phase and were obtained from real world supply chains. This approach bases the analyses on two pillars: firstly, stochastically generated demand and forecast patterns within the model, and secondly, demand and forecast data for the complete product life cycle of different products, obtained from OEMs, to validate the model.

Figure C-2 provides an overview of the lead times that characterise the supply chain in the three planning approaches.[455] The production cycle time, which is the time span from the receipt of raw materials at the first tier supplier until receipt of the product by the customer[456], is 30 days. This was confirmed with industry experts to be realistic and is also the standard throughput time identified by Catalan and Kotzab for a typical mobile phone supply chain as an example.[457] This value is indicated in the second column of Figure C-2 – the first tier

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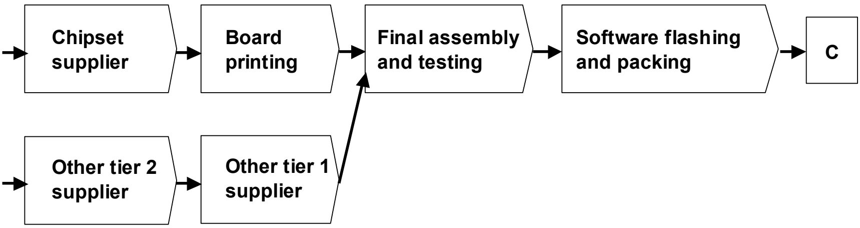
[454] This approach is also, for example, taken by Reiner. See Reiner: Customer-oriented improvement and evaluation of supply chain processes supported by simulation models, p. 5.

[455] All of the delays used for production and shipment processes are third-order exponential delays.

[456] Cf. Milling, Schwellbach and Thun: The Role of Speed in Manufacturing, p. 3.

[457] Cf. Catalan and Kotzab: Assessing the responsiveness in the Danish Mobile phone supply chain, p. 679.

suppliers receives their raw materials 30 days before the delivery date requested by the customer. As shown earlier the transportation lead times depend on the situation and are set to four days for all transportation processes in the model. In addition to the values shown in the figure, the lead time for an emergency supplier of integrated circuits that can be used if backlogs occur at software flashing is 15 days plus five days shipment lead time when no inventory is on stock. Initially, however, the emergency chipset supplier does have 10,000 units of inventory available.



2nd tier supplier LT	1st tier supplier LT	FAT LT	SWF LT
• Chipset supplier: • Receives order –76 • Delivers –30 • 2nd tier supplier • Receives order –36 • Delivers –30	• Board printing: • Receives product –30 • Start processing –29 • Finish processing –25 • Ships –24 • Other FAT supplier • Receives product –30 • Start processing –29 • Finish processing –25 • Ships –24	• Receives product –20 • Start processing –19 • Finish processing –15 • Ship –14	• Receives product –10 • Start processing –9 • Finish processing –5 • Ship –4

Note: The indicated lead times (LT) are the number of days before the delivery date requested by the customer (–x means x days before the customer request date).

Figure C-2: Overview of Lead Times in the Supply Chain Model

The base runs of the different planning approaches build the foundation for all following analyses. A summary of the parameters in the model is provided in Table C-3.[458] Many of these parameters are also explained in the following model description. Note that in the model, each final product at software flashing is composed of one finished good unit received from final assembly. Similarly, each finished good at final assembly is composed of one finished good

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458 This list is not comprehensive. In particular, it excludes switches, the inventory cost parameters and lead times that are listed elsewhere and those parameters that are only relevant in special cases and that therefore are explicitly discussed where they are relevant.

unit from each first tier supplier and each finished component at the first tier suppliers is composed of one unit of components received from the respective second tier supplier.

Table C-3: Further Important Model Parameters

Model Parameter	*Value in Base Case*
All models	
TIME STEP	0.25 days
Correlation time constant for pink noise	4 days
Averaging time for adjustment for difference demand and forecast at SWF/central planning	10 days
Desired Backlog SWF	0 units
Averaging time Backlog SWF for emergency orders	14 days
Adjustment time for emergency orders	36 days
Batch size board printing	5,000 units
Capacity board printing	20,000 units/day
Capacity final assembly and testing	50,000 units/day
Initial value of emergency inventory at IC supplier	10,000 units
Initial values of all other stock variables in the model[459]	0
Cascade only	
Desired days of stock SWF	10 days
Inventory adjustment time SWF	6 days
Inventory adjustment time boards and raw materials FAT	6 days
Inventory adjustment time BP	46 days
Inventory adjustment time Sup	6 days
Desired raw materials inventory FAT (day 81 to 400)	100,000 units
Desired raw materials inventory BP and Sup (day 71 to 400)	100,000 units

[459] The only exception is the market potential, which is set to a high enough value not to affect the dynamics of the simulation and is included to facilitate future development of the model.

Model Parameter	*Value in Base Case*
Push only	
Desired days of stock SWF	10 days
Inventory adjustment time SWF	30 days
Pull only	
Averaging time for adjustment for difference demand and forecast BP/Sup	5 days
Desired days of stock at first tier suppliers	10 days
Inventory adjustment time BP	46 days
Inventory adjustment time Sup	6 days
Averaging time for estimating demand during lead time FAT	5 days
Expected lead time boards and other materials FAT	10 days
Expected lead time from FAT SWF	10 days
Order size SWF	1,000 units
Order size raw materials and boards FAT	1,000 units
Interval for calculation of safety stock at SWF and FAT	10 days
Safety factor z at SWF	1.65
Safety factor z at FAT	1.65

Behaviour Validation. The model behaviour has to reflect reality as well as possible in order to ensure the validity of the conclusions drawn. The assumptions were therefore continuously tested. Throughout the development of the model, in fact, from the very early stages on, plausibility tests and consistency tests were carried out in order to ensure that the model is able to generate a behaviour consistently over several periods, as long as the parameters are reasonable. In order to achieve this, the different parts of the model were often tested independently, without consideration of all other effects. For example, as discussed in the next section, the supply chain models were tested with and without adjustments to the forecasts. Similarly, the whole model was tested with various aspects, such as the calculation of the desired safety stock levels and/or others, set to fixed values in order to observe the sensitivity of model behaviour to these variables. In addition, tests for extreme conditions were carried out; for example, the reaction of the model to a very large one-time order was tested. The results were as expected. A dimensional test was also performed in order to check for possible errors in the units of the model variables. Several runs also showed that there is no time step problem.

This model fulfils the requirements of a thorough validation, even though many of the parameters are estimates. All the hypotheses that are made are plausible and observable in the real world. However, the results obtained should be regarded as relative indices, rather than absolute values.[460]

II. Model Structures and Equations for Different Planning Approaches

In this section, the stock and flow structure, important feedback loops and model equations are described. Each subsystem or key decision is presented in turn, including a structural diagram followed by descriptions of the most important equations. A detailed model listing is provided in the appendix. While it is sometimes argued that representing detail in the model comes at the expense of representing behavioural feedback, primarily due to lack of time and resources, this model balances complexity and simplicity such that the research questions can be answered but no unnecessary complexity is added.

1. Cascade: Cascading Forecasts

The upstream part of a typical supply chain in the high-tech electronics industry is set up as a hybrid planning system that is primarily push-based with forecasts that cascade through the supply chain. In such an approach, a central material requirements planning (MRP) system at software flashing and packing (SWF) sets the framework, while decisions are actually made separately by each echelon. The supply chain members located upstream of SWF use MRP figures only as an indication and take their actual decisions based on personal opinions and other aspects. The product is then pulled by the customer from a stock of semi-finished products at SWF, with the final customization steps being performed only after the order has been received. This hybrid supply chain planning approach is visualized in Figure C-3.

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[460] A similar argument is made by Holweg *et al.*: Towards responsive vehicle supply, p. 512.

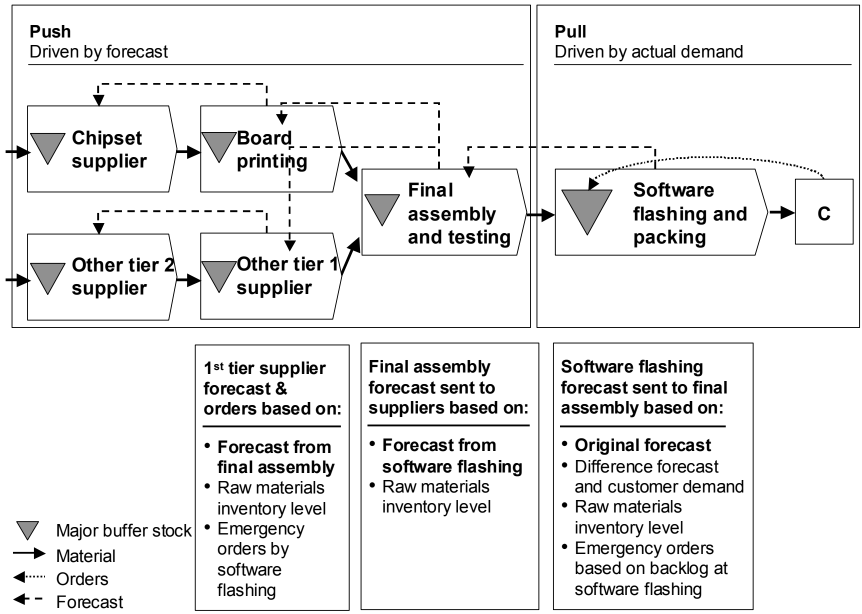

Figure C-3: Push Approach with Cascading Forecasts through Supply Chain

Long supplier lead times for chipsets needed for board printing (e.g., 46 days) require that second tier suppliers base their production and shipments on a forecast. Such a forecast is initially prepared by the Original Equipment Manufacturers (OEMs), which typically run the software flashing part of the supply chain. This initial forecast is based on information from the sales people, who talk directly to customers and then aggregate the forecasts to product groups. The planners at SWF adjust this forecast to keep their raw materials inventory at the desired level. Then they communicate this adjusted forecast to the final assembly and testing stage. Once the product is released to the market, this forecast prepared by SWF is also adjusted based on the difference between the original forecast and actual customer demand to account for forecast errors. The planners at the SWF stage can additionally place emergency orders with the chipset suppliers. The chipset suppliers may be able to supply a limited amount of chipsets faster than usually – and typically at a higher cost. At the same time, the forecasts sent to the other echelons in the chain are adjusted to incorporate these emergency orders such that the components and products flow through the system until the buffer stock at SWF, where they are used to reduce the backlog. This complex situation is visualised in the simplified causal loop diagram in Figure C-4.

The planners at the final assembly and testing stage (FAT) receive the forecast from SWF. They then adjust this forecast to keep their raw materials inventory at final assembly at the desired level, which is typically only a few days of stock.[461] This adjusted forecast is then communicated to their suppliers, such as board printing. Board printing and other suppliers to FAT receive this adjusted forecast and base their supplier orders on this forecast as well as own adjustments for their desired raw materials inventory level.[462] At this stage, the forecast differs significantly from that initially developed by the sales people. There is no central planning, and “nobody is really in charge of the network as a whole”.[463] This complexity is in addition to actual sales volume often fluctuating between 0 percent and 400 percent of the initial forecast developed by the sales people, and sometimes even more.[464]

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461 Cf. Lertpattarapong: Applying system dynamics approach to the supply chain management problem, p. 7 and p. 18.

462 Cf. Catalan and Kotzab: Assessing the responsiveness in the Danish Mobile phone supply chain, p. 670 and p. 673, who describe the development of the forecast at various stages in a mobile phone supply chain.

463 Cf. Akkermans and Dellaert: The rediscovery of industrial dynamics, p. 135.

464 Cf. Jayaram *et al.*: Segmented Approach to Supply Chain Management System Design in High Tech, p. 6. See also Parmar: Supply Chain Architecture in a High Demand Variability Environment, p. 153 and Heikkilä: From supply to demand chain management, p. 757.

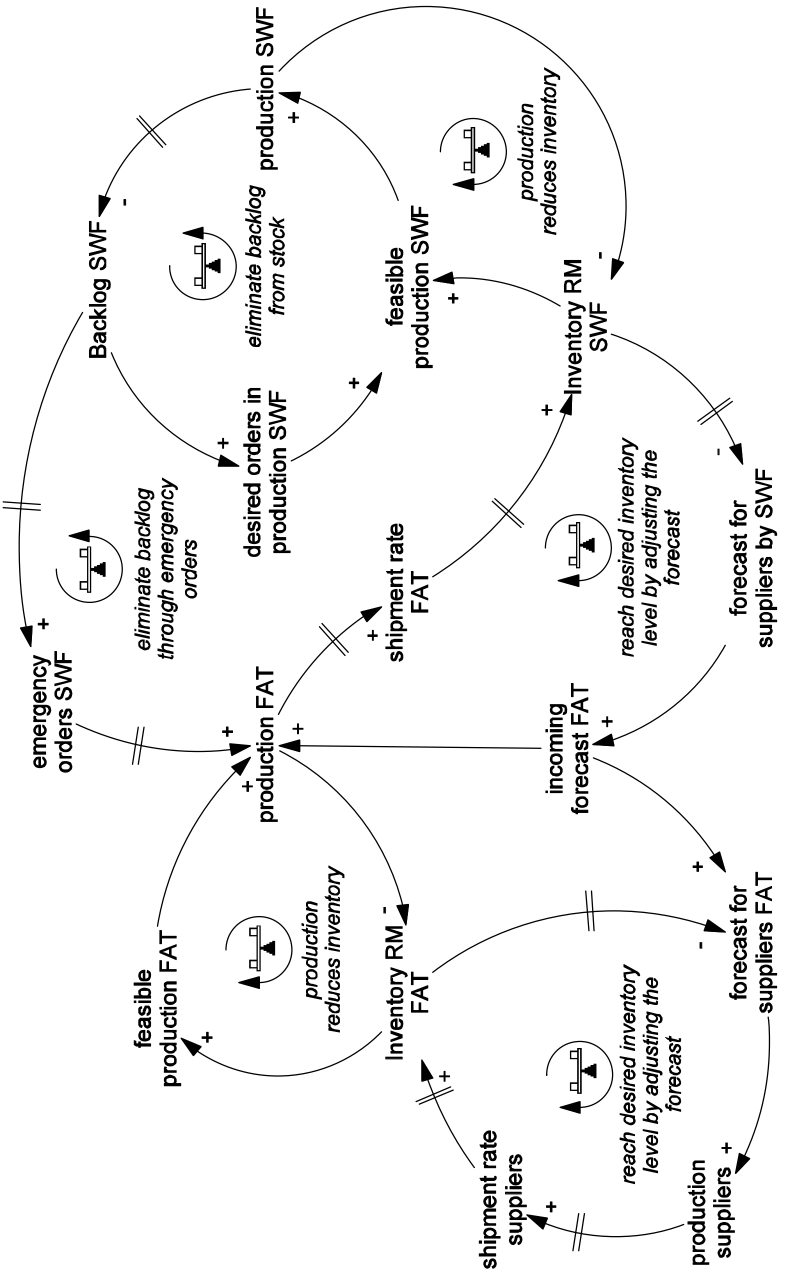

Figure C-4: Partial Causal Loop Diagram of Cascading Forecasts

The adjustments to the plan are typically based on the difference between actual demand as perceived by SWF and the original forecast, as well as on the size of the desired stock levels at each echelon and the desire to keep or reach this desired stock level.[465] There are also other, less tangible factors – in many cases it is not very clear how exactly the process of adjustments is done and there is also empirical data confirming a certain degree of judgment and filtering involved in determining the forecast.[466] However, anchoring the newly generated forecast to that originally produced and then making adjustments is a commonly observed decision rule.[467]

Material orders are based on forecasts with different time horizons for each of the supply chain members. Due to long lead times the board printing echelon will have to order its materials, in particular the chipsets, already several weeks or even months before the finished product eventually reaches the customer. The forecast that is available at this early stage is likely to differ more from actual demand than forecasts that need to cover a shorter time horizon. This increase in forecast errors for forecasts that cover a longer time horizon is also endogenously represented in the model, as information about actual demand influences the long-term forecast only much later than the forecast for a shorter horizon. Each supply chain member adjusts the forecast based on own implicit or explicit decision making policies. For example, deviations of actual inventory levels and desired inventory at each echelon as well as deviations of forecasted demand and actual demand cause adjustments of forecasts and/or material orders to a situation that differs from the expected development. A sudden increase in demand beyond forecast levels therefore causes increases in material orders after some delay. Such decision making policies are specific to each supply chain member, and typically not coordinated with the rest of the supply chain. In the following, the stock and flow structure of the System Dynamics model for the planning approach with cascading forecasts is explained, including a discussion of important model equations.

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465 This was validated in personal communication with Axel Karlsson, partner at McKinsey & Company, Inc., Stockholm, on 5 June 2006. See also Gonçalves, Hines and Sterman: The impact of endogenous demand on push-pull production systems, p. 203 and p. 212.

466 Cf. Gonçalves, Hines and Sterman: The impact of endogenous demand on push-pull production systems, pp. 195–196.

467 Cf. Tversky, Amos and Daniel Kahneman: Judgment under Uncertainty: Heuristics and Biases, in: Science, Vol. 185 (1974), No. 4157, pp. 1128–1130. See also Sterman: Modeling Managerial Behavior, p. 334, who describes anchoring in the case of a desired stock level.

a. Software Flashing and Packing

The processes at the software flashing and packing stage are driven entirely by customer demand. Nine days before the customer desires to receive the finished product, SWF begins processing. To trigger this process, customer demand for any given day is received by SWF nine days ahead of that day. These values, the *demand Cust 9 days ahead variable*, are read from an input file, which in this case is a spreadsheet document. In addition, through the *Input* variable, pink noise can be added to the demand. Pink noise is first-order autocorrelated noise where the next random variation depends in part on the previous variations. This is necessary to represent that one period's demand is not independent of the last but depends to some degree on history, i.e. there is some inertia.[468] The model was built to allow for a future inclusion of a Bass diffusion model to represent the diffusion of products in the market, yet in the current version of the model the market potential is set to a high enough value not to limit the dynamics of the model as customer demand is considered as an exogenous input.[469] This is visualised in Figure C-5 below.

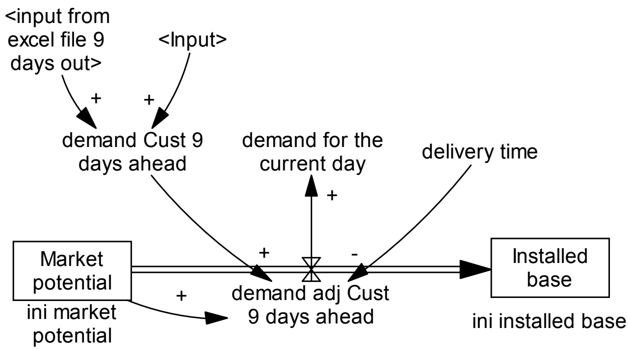

Figure C-5: Cascade: Customer Demand[470]

[468] Cf. Sterman: Business Dynamics, p. 917.

[469] The delivery time variable therefore also does not have any effect on the model dynamics, as the diffusion process is not limited by the market potential. Demand requested for the current day is equivalent to the input data read from the spreadsheet.

[470] In System Dynamics diagrams, rectangles represent stock variables. Arrows with a valve symbol ⌛ represent flows into and out of stocks. Causal relationships between variables are indicated by arrows, with the plus and minus signs representing the link polarity. For further details refer to Sterman: Business Dynamics, pp. 137–141 and pp. 192–195.

SWF begins performing the final software flashing and packing steps nine days before the customer request date (CRD). This corresponds to the time it takes to perform these steps and ship the product to the customer. Figure C-6 visualizes the order fulfilment process at SWF. Orders are received nine days ahead of time as *incoming production requests SWF* and flow into a stock of *Backlog SWF*. This backlog represents the amount of orders waiting to be produced and is depleted by production starts. The number of products whose production begins in a given period is determined by (1) the *desired orders in production SWF*, which are the desired amount of orders that should begin processing at SWF, and (2) the availability of sufficient raw materials inventory (*Inventory RM SWF*). The value of desired orders in production is calculated by taking the new incoming production requests, i.e. the orders that are supposed to begin processing at SWF because of incoming orders in this period, plus any orders that may have accumulated in the *Backlog SWF*. The equation is:

```
desired orders in production SWF =
   MAX
    (0,
     (Backlog SWF/minimum time to start production SWF)
     + incoming production requests SWF)
```

The *feasible FG production SWF* is then defined as either the amount of *desired orders in production SWF* or possible production given the amount of raw materials available[471], whichever is smaller:

```
feasible production SWF =
   MIN
    ( desired orders in production SWF,
      Inventory RM SWF/materials used per FG unit SWF
      /minimum time to start production SWF)
```

Once production at SWF is started, the stock of *Backlog SWF* is reduced by the amount just calculated.

471 The variable *materials used per FG unit SWF* is included to allow possible future modifications of the model with more than one unit of raw materials used per finished good unit, and is set to 1. The *minimum time to start production SWF* is also set to 1.

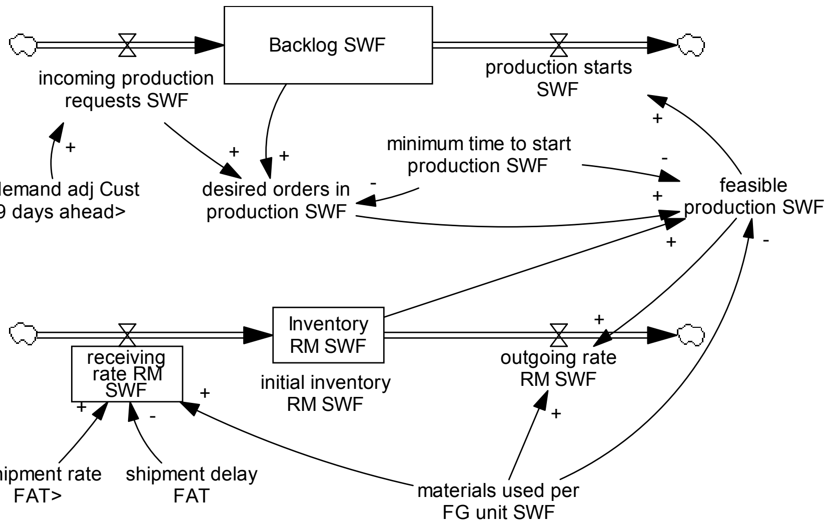

Figure C-6: Cascade: Order Fulfilment at Software Flashing and Packing

The production process at SWF, depicted in Figure C-7, is represented by a third-order exponential delay of the *Feasible production SWF* that converts materials into finished goods, flowing into the stock of *Inventory FG SWF*. The pipeline stock of work in process inventory is also computed to allow inventory cost calculations. As soon as the production process is finished and products reach the finished goods inventory they are shipped to the customer. The customer then receives them after a third-order exponential shipment delay of four days.

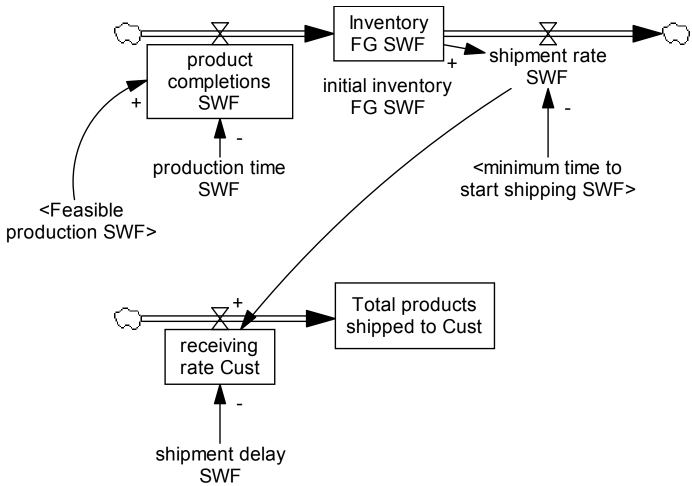

Figure C-7: Cascade: Production at Software Flashing and Packing

In the planning approach with cascading forecasts, the SWF echelon prepares two forecasts that are sent to FAT, the next upstream echelon in the supply chain. Before the product is introduced to the market these forecasts are intended to determine initial staging of components at second tier suppliers, i.e. (1) the supplier to the board printing stage and (2) the supplier to the first tier component supplier. Due to the supplier lead times, which are summarised in Figure C-2, p. 111, the forecast for board printing needs to have a horizon of 76 days, while that for the other supplier has a forecast horizon of 36 days. The original forecasts for customer demand are read as input data from an Excel spreadsheet. This is necessary because before the product is introduced to the market the forecast needs to be based on information that is exogenous to the model. After the product introduction this forecast is adjusted by the planners at software flashing based on two factors, (1) an adjustment to account for the difference between the base forecast and actual demand once the product has been released to the market and (2) an adjustment to the forecast aimed at achieving a specified goal for the desired level of raw materials inventory at SWF. These adjustments can be switched on and off such that their impact on the system can be analysed. The overall structure of the forecast adjustment process at SWF is represented in Figure C-8.

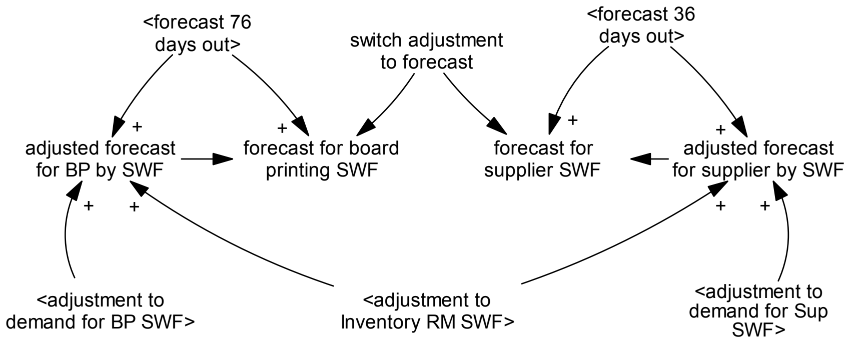

Figure C-8: Cascade: Overview of Forecast Adjustments at Software Flashing

The adjustment for the difference between actual demand and the original forecast is incorporated as a function of their fractional difference, which is multiplied with the base forecast. At the same time, the adjustment for the desired raw materials inventory level at SWF is added to (or subtracted from) from the forecast. The equation for the adjusted forecast for board printing that is prepared by SWF is:

```
adjusted forecast for BP by SWF =
   MAX(0,
   ((forecast 76 days out*adjustment to demand for BP SWF)
    + adjustment to Inventory RM SWF))
```

The variable *forecast for board printing SWF* is the one that is communicated to FAT and is either the adjusted forecast or the original base forecast (*forecast 76 days out*), depending on the switch that can be used to toggle the adjustment on and off for simulation purposes.[472] The forecast for the supplier is calculated in the same way; the rest of the section explains the adjustments using the case of the forecast for board printing that is used to procure chipsets as an example.

The calculation for the adjustment for the difference between actual demand and forecast is performed as follows. First, the original base forecast that is read from the spreadsheet file with the input data is shifted by 76 days, i.e. the forecast horizon, in order to align the forecast data with demand. This is shown in Figure C-9, which represents a forecast of customer demand for 10,000 units per day starting in period 100.

[472] Except where otherwise indicated, this switch is set to 1, indicating that the forecast adjustments are active.

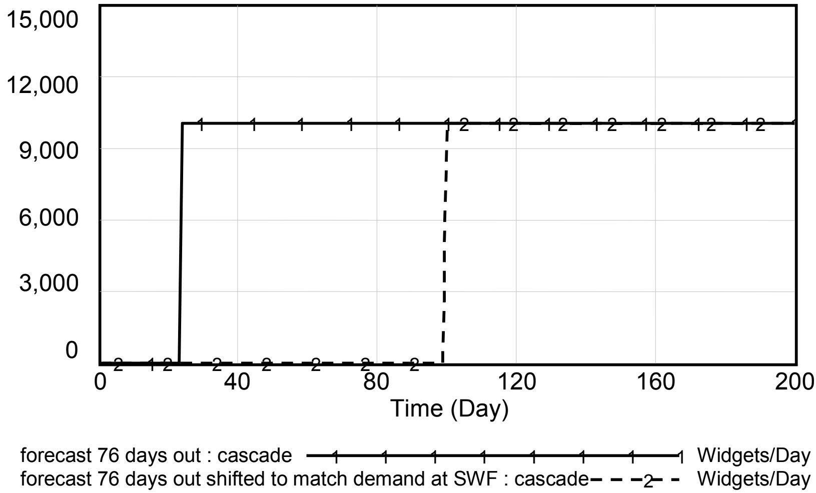

Figure C-9: Cascade: Illustration of Forecast Shift (Forecast for Board Printing)

Then, a first-order exponential smoothing of the shifted forecast is performed. This represents an averaging process that places more weight on more recent observations. Similarly, using the same delay constant, which is 10 days, for the exponential smooth, the actual demand data are smoothed exponentially. Such time delays in reacting to demand changes are in line with observations from actual supply chains, in which changes in customer demand are not immediately communicated to the suppliers.[473] This process therefore generates averages of the original forecast and actual demand, with a first-order delay being appropriate as more recent information on demand is expected to have a larger impact on current decisions than information that is older. As there could be random noise in real-world demand, calculating an average is sensible because adjustments would not be made on a day-to-day basis but only if systematic differences can be observed. Consider a case without such noise, for ease of explanation, in which the original forecast predicts constant customer demand of 10,000 units per day starting in day 100, as visualised in Figure C-9 above. Actual demand turns out to be 12,000 units per day, starting in period 100 as predicted. In addition, there is a one-day pulse in demand of 36,000 units in period 150. The averages using exponential smoothing with a delay time of 10 days for the two variables are as follows:

[473] Cf. Kok *et al.*: Philips Electronics Synchronizes Its Supply Chain to End the Bullwhip Effect, p. 40.

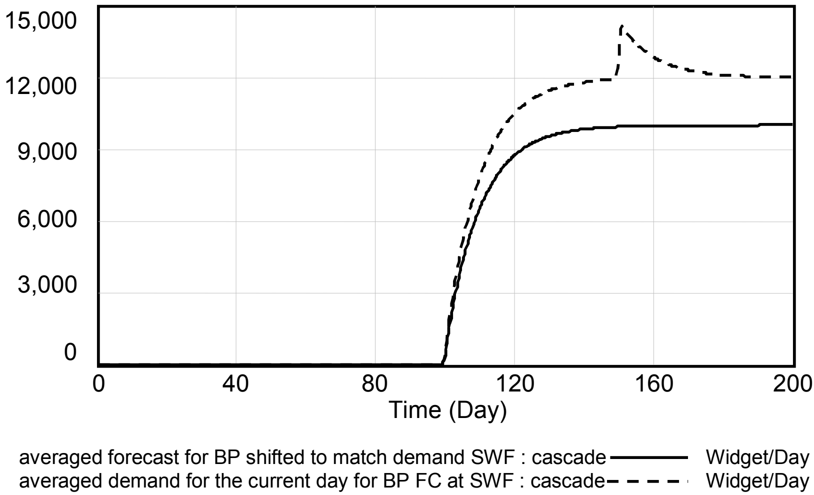

Figure C-10: Cascade: Illustration of Exponential Smoothing of Forecast and Demand (Averaged Forecast for Board Printing and Averaged Demand)

The spike in orders of 36,000 units in period 150 is damped in the forecast adjustment through the averaging process. This means that the forecast is not immediately adjusted to more than three times its original value. Instead, the adjustment happens more slowly while more information about the demand pattern is being evaluated in the exponential smoothing process.

Two further modifications are necessary to compute the final adjustment to demand in the model. First, the fractional difference between demand and forecast can only be computed if the denominator is not zero. Therefore, the XIDZ function is used, which sets the fractional difference to 1 whenever the averaged forecast is equal to zero.

```
fractional difference demand and forecast for BP at SWF
   XIDZ
    (averaged demand for the current day for BP FC at SWF,
     averaged forecast for BP shifted to match demand SWF,
     1)
```

Second, it needs to be ensured that when demand and forecast differ by a very large percentage, e.g. when the forecast is 100 units and actual demand is 10,000, the adjustment to demand should not be 10,000 percent to a forecast for the future of perhaps 10,000 units. Instead, the forecast adjustment should consider the development of average demand in recent periods. It is therefore limited to be no larger than a factor that is calculated as one plus the ratio between average demand and the original forecast for the future. In this example, average demand over the last ten days could be 5,000 and the original forecast for the future (76 days out) is 10,000, so the adjustment would be limited to 50 percent. The adjusted forecast would then be 15,000, and not 1,000,000.

```
adjustment to demand for BP SWF
   MIN
   (fractional difference demand and forecast for BP at SWF,
    1 + XIDZ
     (averaged demand for the current day for BP FC at SWF,
      forecast 76 days out, 0)
   )
```

The final factor that represents the adjustment to the forecast is shown in Figure C-11 below. Also, this model section is reproduced in Figure C-12.

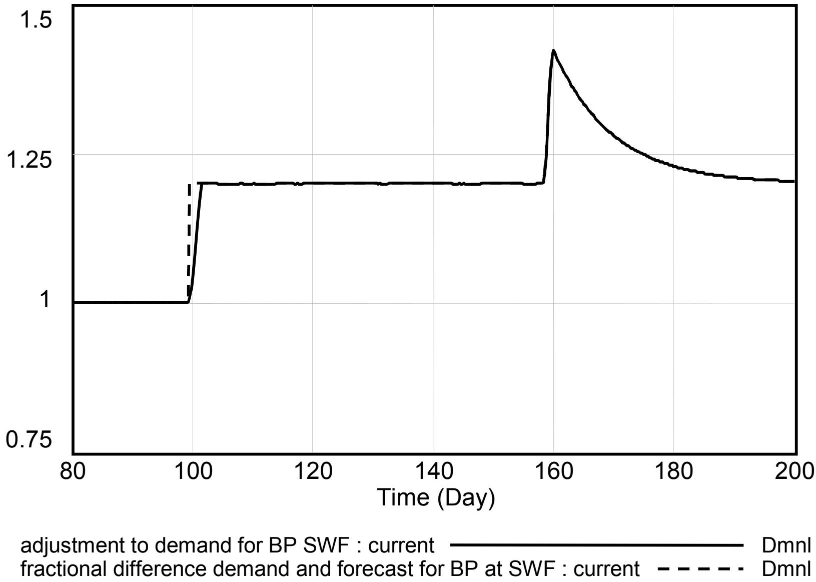

Figure C-11: Cascade: Illustration of Adjustment to Demand (Forecast for Board Printing)

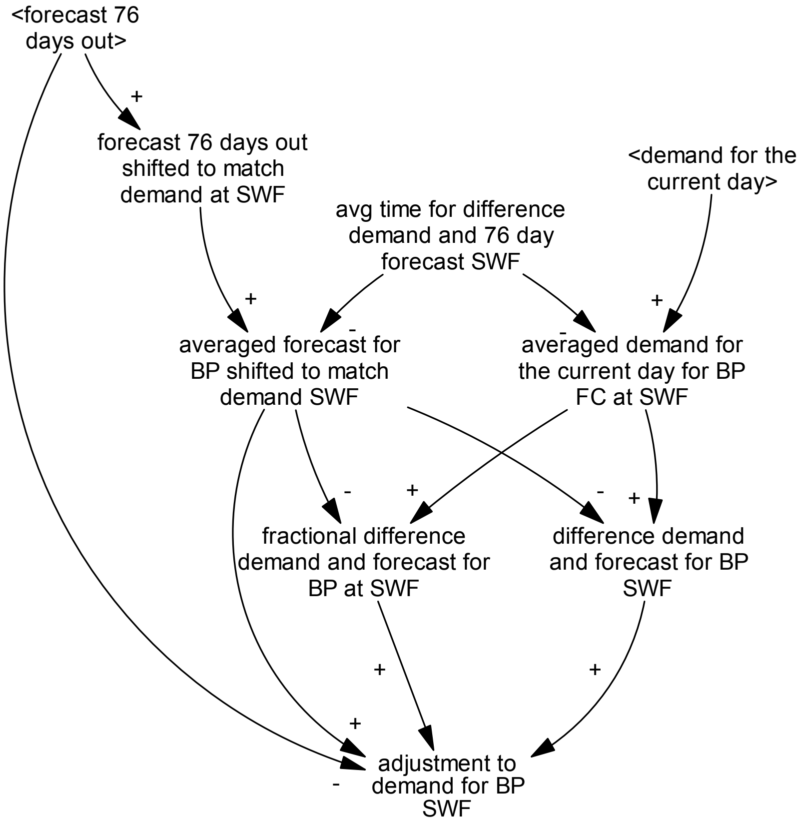

Figure C-12: Cascade: Forecast Adjustment for Difference between Demand and Forecast SWF (76-Day Forecast for Board Printing)

The adjustment for the desired raw materials inventory level at SWF is calculated through a goal-adjustment process as shown in Figure C-13. The average raw material inventory level at SWF is compared to the desired inventory level at SWF, which is the variable *desired Inventory RM SWF*, and the adjustment to the forecast is calculated based on this difference and considering the *inventory adjustment time SWF*, i.e. the time over which the gap between the actual state and the desired state should be closed. Inventory levels are related to the customer service level, which is why it is desirable to correct these discrepancies over time. The inventory adjustment time represents the number of time periods over which the forecast will be modified to adjust for the gap between desired and actual inventory.[474] Due to the delays in the supply chain, this adjustment will be subject to overshoots and undershoots, leading to fluctuations in the forecasts.[475]

Additionally, there is an option for the adjustment process to consider the amount of adjustments that were already made in the past. This corresponds to decision makers taking the supply line of materials already ordered into account. This behaviour can be switched on and off, as in reality the amount of materials already on order is often not considered.[476] In the base case scenario, these adjustments for the supply line are therefore not made. The equation is:

```
adjustment to Inventory RM SWF =
   ((gap desired inventory and average inventory RM SWF
     -(cumulated adjustment to inventory RM SWF
       * switch consider cum adj to inventory RM SWF))
   /inventory adjustment time SWF)
   *switch adjustment to Inventory RM SWF
```

The desired inventory level is determined by multiplying a fixed number of *desired days of stock SWF* with the average customer demand experienced by software flashing. The number of days of stock is typically rather small and determined by the planners at SWF.[477] In this example, it is set to ten days to cover the expected order lead time. Planners at software flashing can observe customer demand directly and use this information to determine which average demand can be expected over the time period to be covered by the raw materials inventory level.

---

474 Cf. Disney, Stephen M., Mohamed M. Naim and Denis R. Towill: Dynamic simulation modelling for lean logistics, in: International Journal of Physical Distribution & Logistics Management, Vol. 27 (1997), No. 3/4, p. 179.

475 Cf. Disney, Naim and Towill: Dynamic simulation modelling for lean logistics, p. 179.

476 See, for example, Sterman: Modeling Managerial Behavior, p. 336.

477 Cf. Lertpattarapong: Applying system dynamics approach to the supply chain management problem, p. 7 and p. 18.

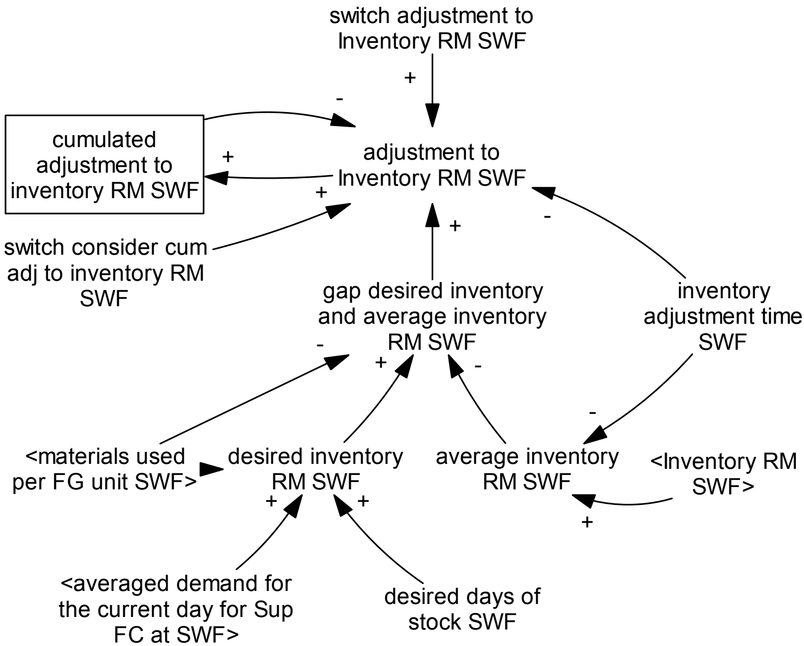

Figure C-13: Cascade: Forecast Adjustment for Desired Raw Materials Inventory at SWF

Finally, the planners at software flashing can place emergency orders with alternative chipset suppliers that have shorter delivery delays. These emergency orders are based on the size of the backlog observed at the software flashing stage. Similarly to the adjustment for inventory, the amount of emergency orders is calculated as a goal-adjustment process, with the goal being a backlog at software flashing of zero units. The structure is shown in Figure C-14. Again, there is an option to consider the amount of emergency orders that were already placed in the past, which can be switched on and off. In the base run, the emergency orders placed in the past are not considered.

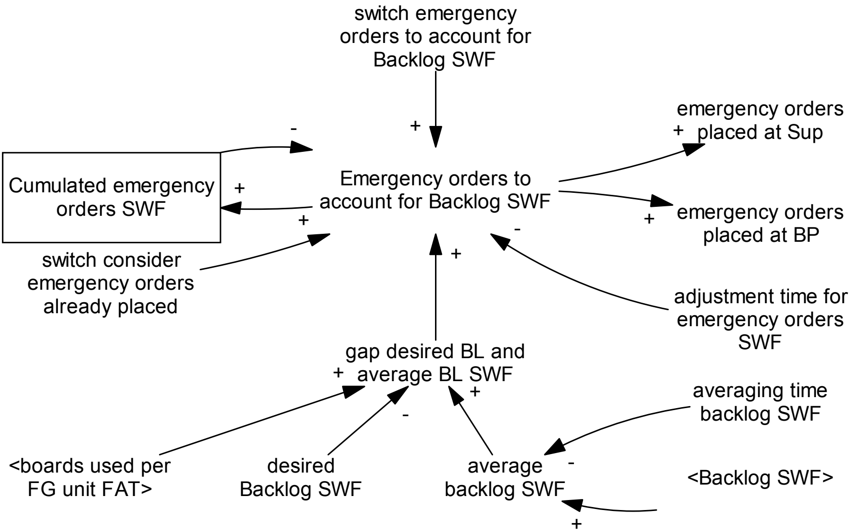

Figure C-14: Cascade: Emergency Order Placement at SWF

b. Final Assembly and Testing

The production process at the final assembly and testing stage is driven by the forecast received from SWF and emergency orders placed by SWF. The forecast sent by software flashing to final assembly is equal to that sent to the first tier supplier (not board printing), as this is the forecast with the shortest forecast horizon prepared by the planners at software flashing and thus the most current. The alternative would be to submit the forecast sent to board printing, which has a longer forecast horizon and therefore a higher forecast uncertainty. Those two variables, the forecast as well as emergency orders, constitute the inflow into the backlog at FAT, called the *incoming forecast FAT*, and represent the quantity of finished goods eventually to be shipped to the SWF, the immediate customer of FAT. This is shown in Figure C-15.

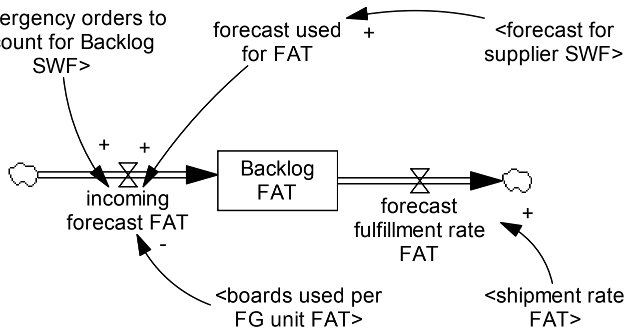

Figure C-15: Cascade: Order Fulfilment FAT

The incoming forecast accumulates in a second stock called *waiting for production FAT*. This stock represents the amount of orders that are awaiting the start of production. This backlog is reduced by the *forecast fulfilment rate FAT*. The amount of orders that can enter the production process is limited by the amount of inputs to the production process that are available in the raw materials inventory levels. This means that sufficient quantities of both boards and other materials need to be available. Also, a capacity limit restricts the maximum throughput through the production process. This is visualised in Figure C-16, which is simplified and for increased clarity does not display the minimum times to start production and shipments, materials used per unit and initial values of stocks. In the model, first, the amount of production that is feasible based on the size of the raw materials inventory levels is calculated as *feasible production based on inventory FAT*.[478]

```
feasible production based on inventory FAT =
   MIN
    (Inventory Boards FAT/boards used per FG unit FAT,
     Inventory RM FAT/materials used per FG unit FAT)
   /minimum time to start production FAT
```

The *capacity limit FAT* is then either the physical capacity of the production process at FAT or the amount just calculated as the feasible production based on inventory, i.e.

```
capacity limit FAT =
   MIN(capacity FAT,
       feasible production based on inventory FAT)
```

[478] The *minimum time to start production FAT* is one day.

The number of production starts at FAT is then either the number of orders waiting to be produced, including those coming in on the day, or the calculated capacity limit, whichever is smaller:

```
Production starts FAT =
   MAX(0,
    MIN
      (waiting for production FAT/minimum time to start
       production FAT+inflow waiting for production FAT,
       capacity limit FAT)
   )
```

The product completion rate is calculated as a pipeline delay of desired production, which allows tracking of the work in process inventory level.

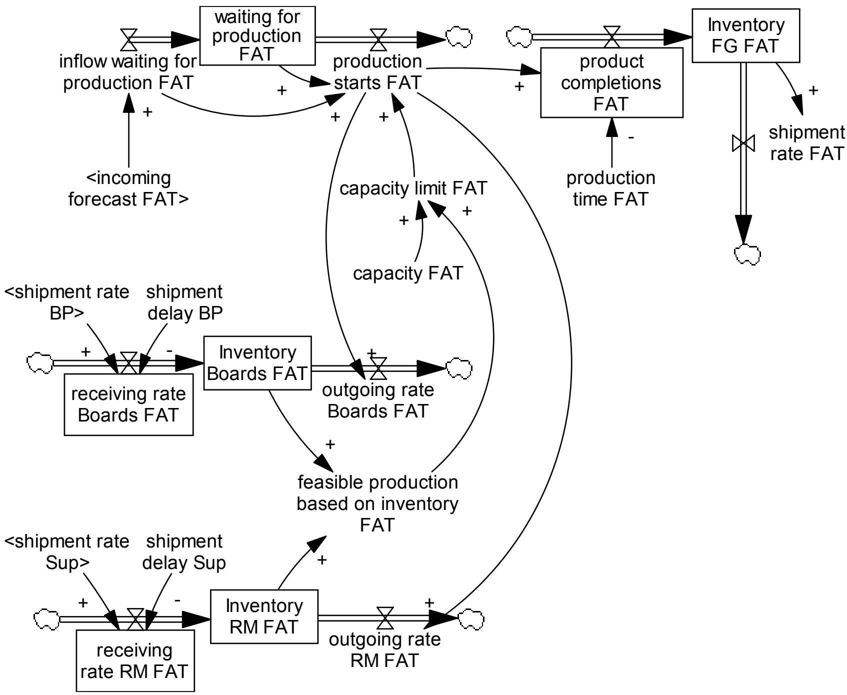

Figure C-16: Cascade: Production at Final Assembly and Testing

With regard to material orders, the planners at final assembly use a similar decision logic as is used as SWF for their forecasting process. One difference is that FAT adjusts the forecasts separately – as shown in Figure C-17, the adjustment for the forecast sent to board printing is based on the actual and desired level of the stock *Inventory Boards FAT*, while the adjustment for the forecast sent to the other supplier is based on the actual and desired level of the stock *Inventory RM FAT*. The second difference is the desired level of stock for raw materials and boards, which for FAT cannot be based on the observed orders. As this is a push production system, FAT does not receive any customer orders. Instead, the desired stock level is predetermined to a fixed level, which in the base scenario is 100,000 units between day 81 and 400[479], corresponding to an estimation of average demand combined with the expected lead time of ten days.

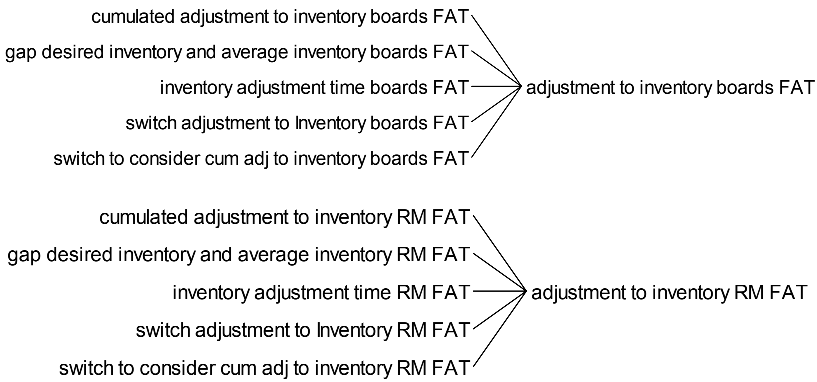

Figure C-17: Cascade: Adjustments to Inventory at Final Assembly and Testing

c. Board Printing

Production at board printing is based on the forecast received from FAT as well as potential emergency orders placed by SWF, as shown in Figure C-18. Its structure is similar to that of production at FAT. In addition to a capacity limit, which constrains production and is fixed during the simulation length of one product life cycle[480], board printing is also subject to a specific batch size. The

[479] The inventory is needed from day 81 as the first unit, according to the forecast, is due to arrive at SWF in period 91. The ten days difference are composed of production and shipment delays. After period 400, no more inventory is needed in the supply chain as the product is scheduled to be taken from the market.

[480] Planning, construction and ramp of a new facility can take four to five years, which implies that capacity cannot be adjusted during a product life cycle. See, for example, Beckman and Sinha: Conducting Academic Research with an Industry Focus, p. 120 and Gonçalves: Demand Bubbles and Phantom Orders in Supply Chains, p. 108.

production process will therefore not be initiated until enough raw materials are available to produce an entire batch, or multiple batches, of products.

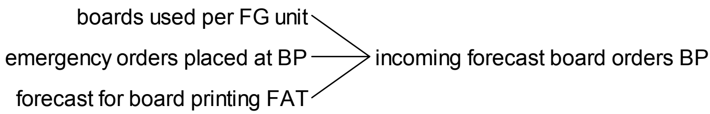

Figure C-18: Cascade: Adjustments to Inventory at Final Assembly and Testing

The process of limiting production based on orders waiting for production, batch size, capacity limitations and the availability of raw materials is visualised in Figure C-19. The *largest possible RM outflow BP* , considering the capacity limit and available raw materials inventory, is calculated as:

```
largest possible RM outflow BP =
   MIN
    (capacity limit BP,
     Inventory RM BP
      /materials used per FG unit BP
      /minimum time to start production BP)
```

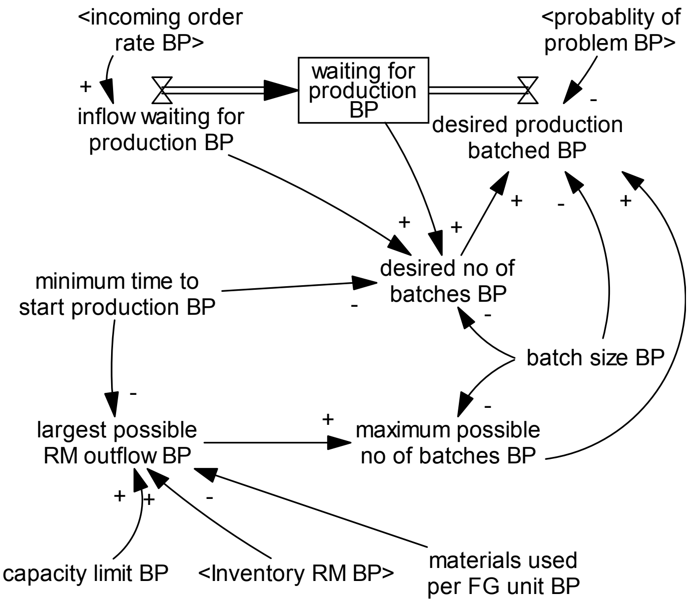

Figure C-19: Cascade: Production at Board Printing

This is used to calculate the *maximum possible no of batches BP*. To calculate this variable, the INTEGER function is used to return the maximum number of batches that can be produced given the largest possible RM outflow just calculated:

```
maximum possible no of batches BP =
   INTEGER(largest possible RM outflow BP/batch size BP)
```

Similarly, the INTEGER function is used to identify the quantity of batches that should be produced given the current order backlog, i.e. what would be produced if there were no constraints other than the batch size.

```
desired no of batches BP =
   INTEGER(
    (waiting for production BP
     / minimum time to start production BP
     + inflow waiting for production BP)
    / batch size BP)
```

Finally, the desired production rate at board printing is calculated similarly as for final assembly using a MAX and a MIN function, i.e.

```
desired production batched BP =
   MAX(0,
    MIN
     (desired no of batches BP * batch size BP,
      maximum possible no of batches BP * batch size BP)
    *(1-probablity of problem BP)
   )
```

The inclusion of a *probability of problem BP*-variable allows to restrain production at BP to simulate additional supplier problems, such as machine failures, that could occur in a real system. This probability can be switched on and off and modified for any scenario. It is zero if not otherwise stated.

The standard processes of material orders at the first tier suppliers are set up such that all orders placed are received by board printing 46 days later. To determine the amount of materials to be ordered through the standard process of material orders, planners at board printing first consider the forecast received from final assembly. They then adjust this forecast with the same logic explained for the planners at SWF and FAT to the desired level of raw materials inventory at board printing, which is also 100,000 units in the base scenario[481].

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[481] In this case, the desired inventory level is set to 100,000 units between periods 71 and 400, which again depends on the production and shipment delays until delivery at SWF and the end of the scheduled product life cycle.

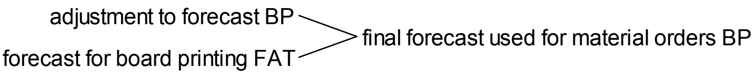

Figure C-20: Cascade: Forecasting at Board Printing

In addition, the planners at software flashing may have placed emergency orders with board printing. Those are handled through a different process, as they need to have a shorter lead time than is the case for regular, forecasted orders. Emergency orders are processed by a different second tier supplier of integrated circuits that has a specified level of emergency inventory on hand. This inventory of 10,000 units can reach BP within four days. Also, the emergency chipset supplier is able to produce additional chipsets within a lead time of 15 days, which is significantly shorter than the 46 days that are assumed for the regular process. There are therefore two possibilities, (1) there is enough emergency inventory available to cover for the emergency orders, in which case they are shipped to BP within 4 days and then processed through the rest of the supply chain, or (2) there is not enough emergency inventory available, in which case the inventory is shipped right away while additional supplies are produced with a production delay of 15 days. Each unit shipped out of inventory triggers a material order by the emergency IC supplier, such that inventory after a one-time order will be back at the level of 10,000 units after around 15 days. At the same time, the forecast for the other first tier supplier to FAT is updated to reflect the increase in scheduled production through the emergency orders.

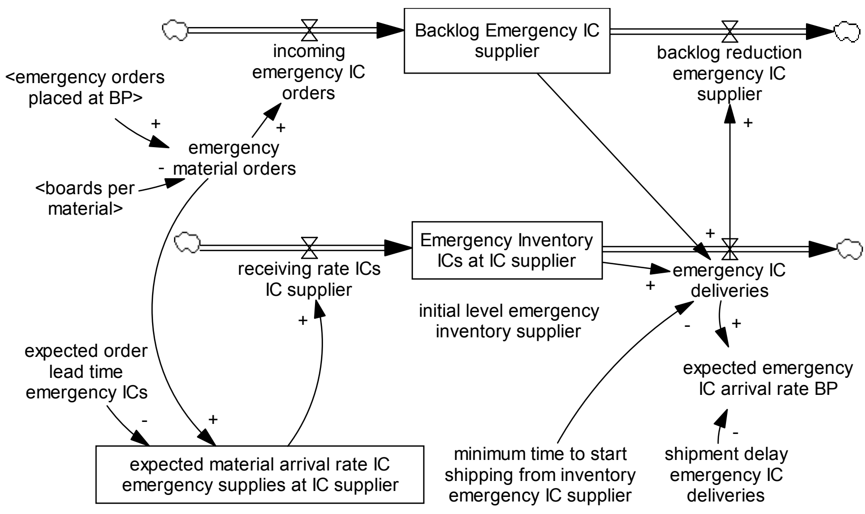

Figure C-21: Cascade: Emergency Orders at Emergency Integrated Circuit Supplier

d. Other First Tier Supplier

The structure of production processes at the other first tier supplier (Sup) is similar to that at BP, except that there are no emergency order structures and no batch sizes in production. The amount of orders waiting for production at the supplier is determined by the forecast received from FAT and by emergency orders placed by SWF, as explained above. The adjustment to the forecast is again based on a desired level of raw materials inventory to be kept by the supplier, and follows the same logic as at the other supply chain members.

e. Impact of Forecast Adjustments if Demand is Known

In summary, the adjustments to the forecast made by the different supply chain members in the planning approach with cascading forecasts are:

- Adjustment for the difference between demand and forecast at SWF
- Adjustment for the desired level of raw materials inventory at SWF
- Emergency orders to account for backlog at SWF
- Adjustment for the desired level of board inventory at FAT
- Adjustment for the desired level of materials inventory at FAT
- Adjustment for the desired level of raw materials at BP
- Adjustment for the desired level of raw materials at Sup

The scenario that is discussed in the following demonstrates the impact of the adjustments as well as their intended rationality. Consider a situation where demand is perfectly known to all parties. Customer demand is constant at 10,000 units from period 100 to 299, and then experiences a step increase to 12,000 units, which is the new value for demand from period 300 to period 399. The original forecasts, shifted appropriately as discussed above, expect exactly this demand pattern, as shown in Figure C-22.

Now, assume that none of the players in the supply chain modify the original forecasts using any of the adjustment policies described above. Instead, the forecast is passed through the supply chain up to the second tier supplier without any changes. This resembles a situation in which customer demand is exactly known to SWF ahead of time, and all players in the supply chain trust that the initial forecast will not change. In such a case, one would expect processes in the supply chain to run smoothly, with no major inventory build-ups anywhere in the chain and also no major incidents of backlog. To evaluate whether this expectation is accurate, and whether the model is performing in the way it is expected to, given the policies that are represented, an evaluation of the behaviour over time of several model variables is necessary.

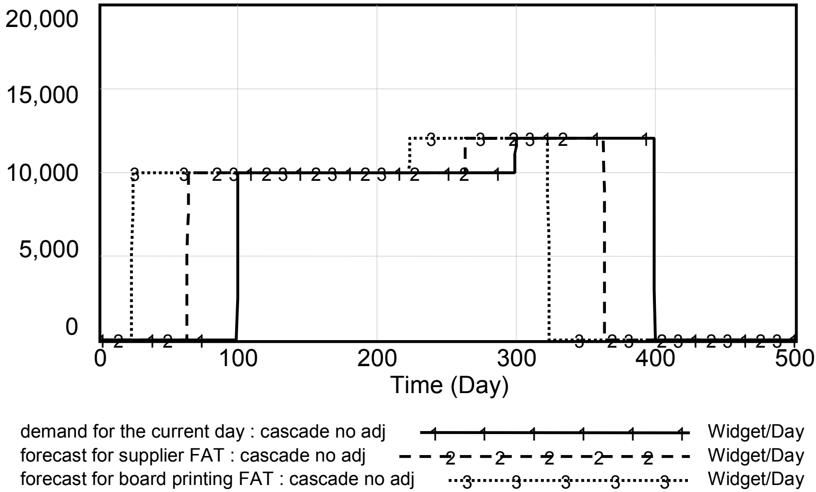

Figure C-22: Cascade: Customer Demand and Forecasts (Example to Illustrate Adjustments to Forecast)

First, consider customer backlog, which measures the extent to which the demand by the customer has been filled. One may have expected customer backlog to remain at zero throughout the simulation. As shown in Figure C-23, this is not the case at all times. However, the variations can be explained by the structural characteristics of the model and do not question its validity.

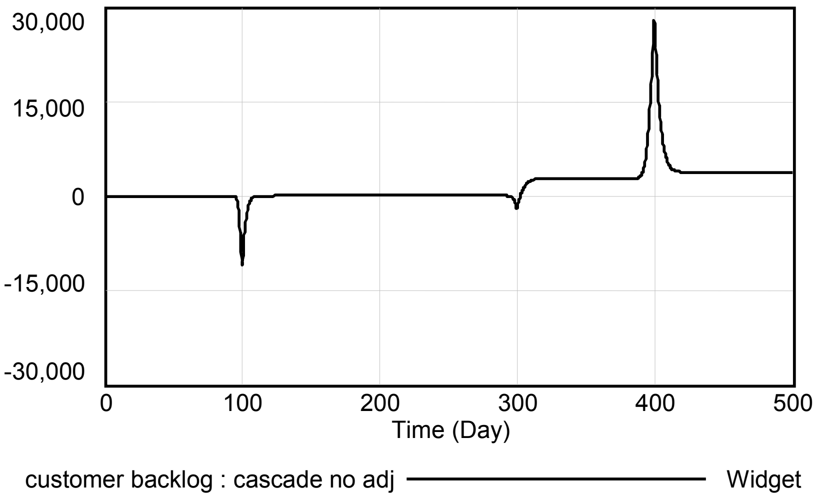

Figure C-23: Cascade: Customer Backlog (Example to Illustrate Adjustments to Forecast)

In period 93, around 7 days before the first delivery is expected by the customer, the customer backlog has a negative value for the first time. This means that products are received by the customer that were not yet expected to arrive – they arrived earlier than scheduled. This can also be seen in Figure C-24, which shows customer demand for any given day as well as the rate at which products are received by the customer. The explanation for this behaviour lies in the nature of the delay types used for the production process and shipments at SWF. In a third-order exponential material delay, the output does not react immediately to a change in the input. For example, when desired shipments rise from zero to 10,000 they do not reach this value on the next day, but rise slowly at first, then more quickly until a point of inflection until they approach the target value of 10,000.[482] This behaviour can be observed in Figure C-24 around periods 100, 300 and 400. For example, by period 98 the customer received 4,957 units (cumulative), by period 99 8,949 and by period 100 the customer received 10,538 units of the product. This situation balances as the system reaches equilibrium and the receiving rate approaches the ideal rate of 10,000 units per day.

[482] See, for example, Sterman: Business Dynamics, pp. 417–421 and Milling, Peter M.: Verzögerungsglieder in der Simulationssoftware Vensim, 1997, Arbeitspapier der Fakultät für Betriebswirtschaftslehre der Universität Mannheim, http://is.bwl.uni-mannheim.de/Forschung/Publikationen/delays.pdf, retrieved on: 17 March 2006, p. 11.

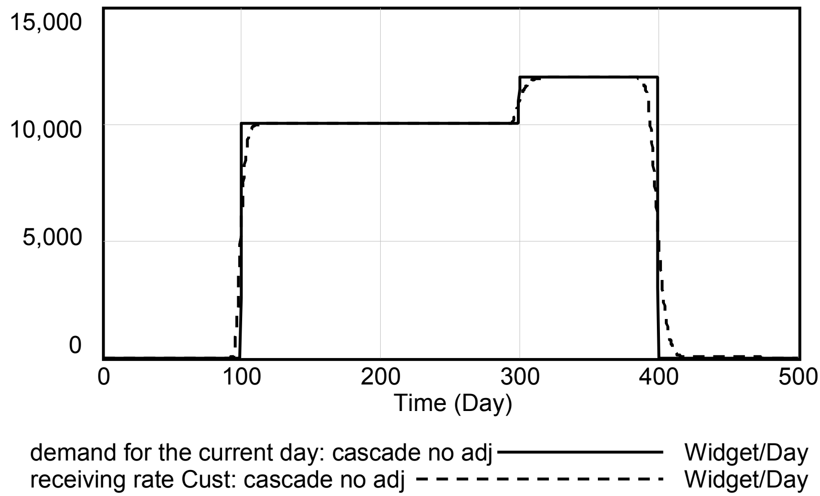

Figure C-24: Cascade: Customer Demand and Receiving Rate at Customer (Example to Illustrate Adjustments to Forecast)

These delayed responses to changes in the system are the explanation for the cases of customer backlog even in a situation where demand is known to all parties. Also, the magnitude of the customer backlog is minor compared to the magnitude of daily orders. However, in the example case a customer backlog of between 2,500 and 4,000 units remains in the backlog stock for the entire time period where the increase in demand occurs, i.e. starting in period 300. This backlog is equivalent to less than half of a day's customer demand. Nonetheless, with no adjustments to the forecast occurring and no emergency orders placed to adjust for the backlog at SWF, the inability of the system to recover the backlog has a negative impact on delivery performance to customer request. Delivery performance at the end of the simulation and product life cycle is 90 percent even in this scenario with steady demand and perfect forecasts. If the forecasts are incorrect and there are changes in demand, such a system would fail to react, resulting in constant misalignment of demand and supply.[483] In this model, this effect is related to a misalignment of the overall production volume of the modelled product with demand. In reality, as noted by Holweg et al., such misalignment can happen on many layers, particularly when there are different product variants. Even if overall production volume is aligned to demand for a model, it

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[483] See also Holweg *et al.*: Towards responsive vehicle supply, p. 617, who describes a similar problem for a supply chain model of an automotive supply chain.

might be the case that the majority produced variants are blue, or have Japanese keypads, whereas customer demand may be much stronger for yellow devices with English keypads.[484] The system therefore needs to respond to such changes and ensure rapid recovery of backlogs.

Before analysing the impact of adjustments to the forecasts, consider the efficiency of such a supply chain system. In the simulation, the inventory turns over the duration of the simulation are 36, which is relatively high. As examples, Figure C-25 shows the raw materials inventory levels at SWF, FAT and Sup. The time behaviour is as expected, with the peaks as well as the small amount of materials inventory left at FAT after the simulation, which represents around one third of average daily demand, caused by the behaviour of the delays discussed above. The inventory levels for boards at FAT and for raw materials at BP behave in a similar way, as do all the other inventory levels. There are no major inventory build-ups in the system. While this high level of efficiency is positive, in a real system it is unrealistic that no adjustments would be made to the forecast if, for example, a backlog is observed.

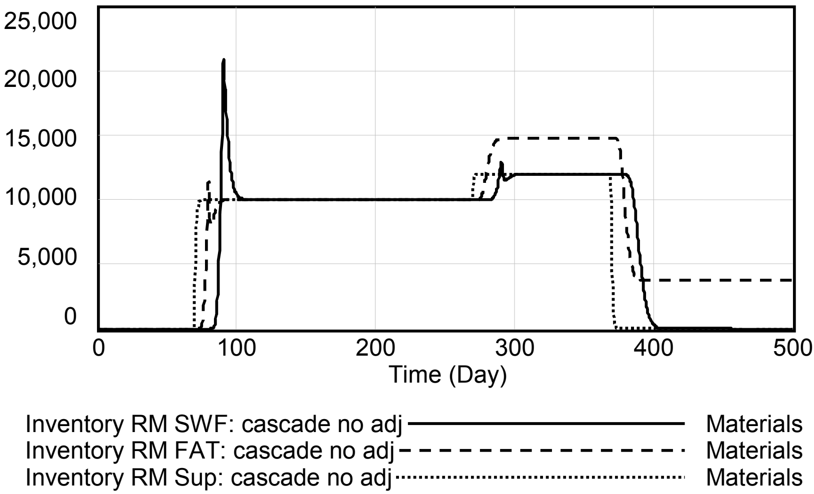

Figure C-25: Cascade: Raw Materials Inventory Levels (Example to Illustrate Adjustments to Forecast)

Now, consider the same scenario allowing for only one adjustment, i.e. emergency orders being placed by SWF. Recall that the amount of emergency orders placed by SWF depends on the size of the backlog observed by SWF. In

484 Cf. Holweg *et al.*: Towards responsive vehicle supply, p. 517.

determining the amount of emergency orders placed, the cumulated emergency orders already placed (i.e., the supply line) are not considered in this example. The backlog considered by the planners at SWF in determining the amount of emergency orders is different from the customer backlog, as they do not know when the product actually reaches the customer. Their backlog is represented by the model variable *Backlog SWF*, which is the stock variable that is increased by *incoming production requests SWF* and decreased by *production starts SWF*. For them, the backlog thus cannot become negative. Figure C-26 shows the time behaviour of the backlog at SWF. In the simulation run without emergency orders, the backlog persists until the end of the simulation (line 1). In the simulation run that allows emergency orders, the backlog is eventually reduced to zero due to the additional orders placed by the planners at SWF (line 2). In total, the planners ordered 7,632 additional units through the channel of emergency orders. This increased delivery performance to customer request from 90 percent to 93 percent, with inventory turns remaining at 36.

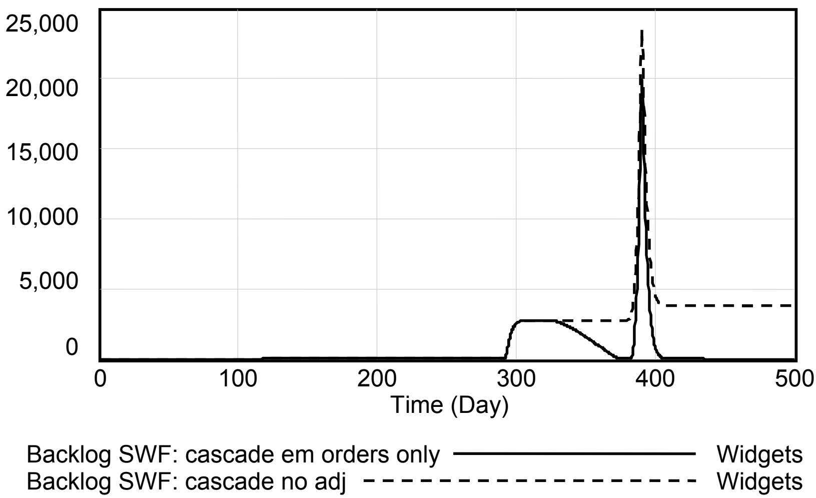

Figure C-26: Cascade: Backlog at Software Flashing (Example to Illustrate Adjustments to Forecast)

Now consider a situation where all the discussed adjustments listed at the beginning of this section are made by all supply chain members. SWF may place emergency orders and in addition adjusts the forecast for their desired inventory level of 10 days of stock (i.e. around 100,000 units if demand is on average 10,000 units) as well as for the difference between the forecast and actual demand, and SWF, FAT, Sup and BP each adjust the forecast based on their desired raw materials inventory levels of 100,000 units, respectively. None of the players take into account the supply line of materials already ordered, which is in line with empirical observations.[485] In this simulation run, delivery performance is at 80 percent, and inventory turns are down to 4.7. Figure C-27 and Figure C-28 show the original forecast from the input spreadsheet as well as the modified forecasts prepared by SWF and FAT in the simulation with all adjustments active. The forecast prepared by FAT is sent to the second tier suppliers. In the previous simulations, the forecast prepared by SWF was equal to that prepared by FAT since there were no adjustments, but now significant variation around the original forecast can be observed, originating in the attempts of the various supply chain members to adjust the forecasts according to their individual decision rules. The comparison between the forecasts for board printing and the forecast for the supplier show that there is higher fluctuation in the final forecast for the supplier prepared by FAT than in the forecast for board printing prepared by FAT. This is in line with the reference framework model for material flow in electronic product supply chains developed by Berry et al. Their model suggests smaller, more frequent oscillations downstream electronics supply chains and larger oscillations with lower frequency upstream in the chain.[486] Even in this straightforward scenario, decisions are made by the different members of the supply chain that are introducing significant volatility, upstream amplification and oscillation into the supply chain. Such decisions are, for example, the desire by the planners at final assembly to achieve a certain desired level of raw materials inventory, causing significant adjustments to the forecast even before the product is introduced to the market. These decision rules are intendedly rational, as the implicit assumptions made by the decision makers about their decisions are sensible (e.g., adjusting the forecast upwards when demand is higher than expected) and would produce reasonable and sensible results "if the actual environment were as simple as the decision maker presumes it to be".[487] However, the decisions made have consequences that could not be expected by the decision makers due to their cognitive limitations and the feedback complexity inherent in the system.

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485 For example, Sterman finds that "even a perfect forecast will not prevent a manager who ignores the supply line from overordering". Cf. Sterman: Modeling Managerial Behavior, p. 336.

486 Cf. Berry, Danny, Denis R. Towill and Nick Wadsley: Supply Chain Management in the Electronics Products Industry, in: International Journal of Physical Distribution & Logistics Management, Vol. 24 (1994), No. 10, p. 22.

487 Cf. Sterman: Business Dynamics, p. 603.

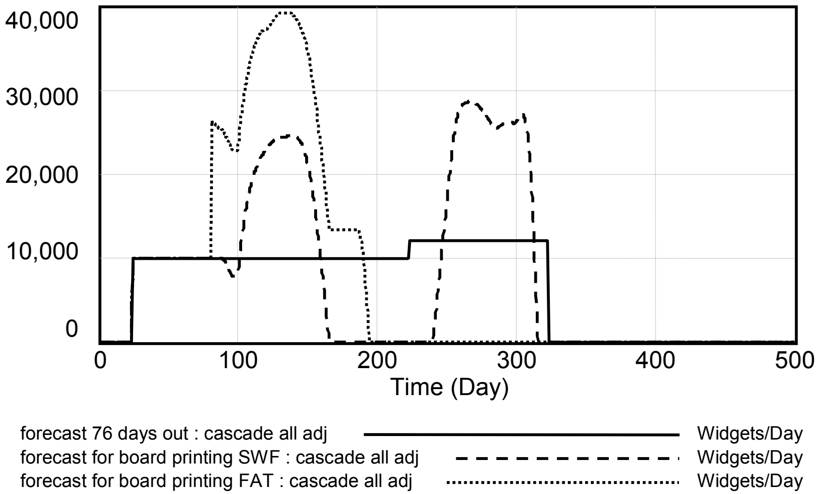

Figure C-27: Cascade: Forecasts for Board Printing (Example to Illustrate Adjustments to Forecast)

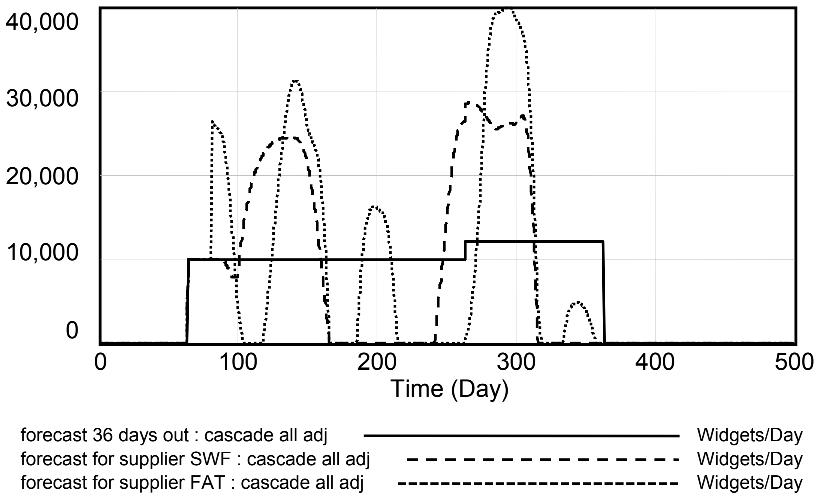

Figure C-28: Cascade: Forecasts for Other 2nd Tier Supplier(Example to Illustrate Adjustments to Forecast)

2. Push: Central Planning for Push Structures

In an approach that is primarily based on push principles with central planning up to the software flashing production step, the different players in the supply chain do not adjust the forecast provided by the central planning unit. There is one global plan driving production at the upstream suppliers. This reduces confusion in the supply chain as the original forecasts are not adjusted by each member of the supply chain. Anything that is produced by the suppliers based on the global plan is then pushed through the other production steps, board printing and final assembly, until the products reach the buffer stock at the SWF stage. This approach is visualized in Figure C-29. As in the planning approach with cascading forecasts, the central plan is adjusted based on the difference between the original forecast and actual customer demand. Also, it accounts for the desired raw material level at the SWF stage. In addition, there is again the possibility for emergency orders with the chipset suppliers.

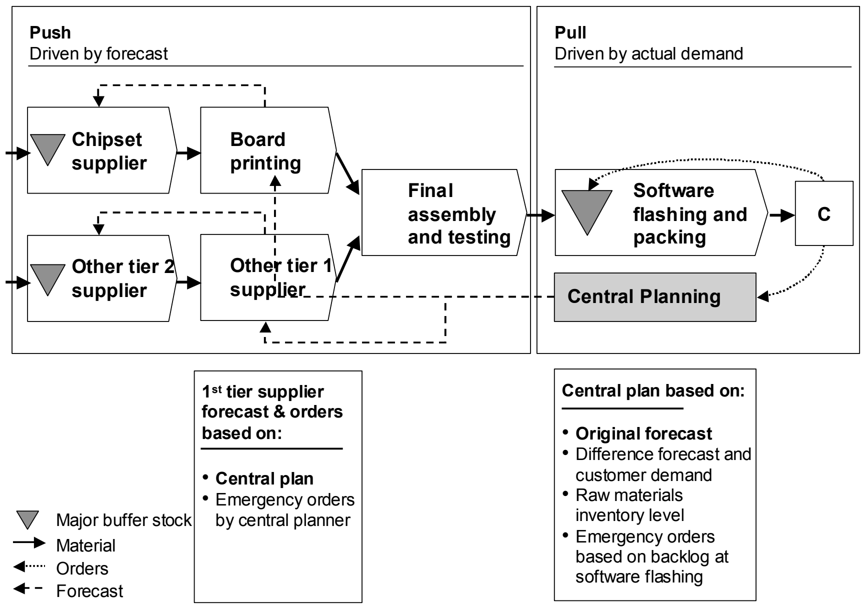

Figure C-29: Push Approach with Central Planning until SWF Stage

a. Software Flashing and Packing

As in the Cascade-planning approach, the processes at the software flashing and packing stage are driven by customer demand only. The distinction of these two planning approaches is the preparation of the forecasts. In the approach with central planning, a single central plan is prepared and communicated to the first tier suppliers that is based on the original forecast, the difference between that forecast and actual customer demand and the desired raw materials inventory level at software flashing. This plan is prepared by the central planners that are based at the software flashing and planning stage, which corresponds to the OEMs. The central plan is therefore developed in the same way as the forecast prepared by SWF in the planning approach with cascading forecast, considering both an adjustment to inventory based on a desired number of days of stock to be kept and an adjustment for the difference between actual demand and the original forecast. Emergency orders can also be placed. The model structure in this sector is equal to that in the Cascade-approach, which ensures comparability of the models.

b. Final Assembly and Testing

In the push-based planning approach with central planning the production process at the final assembly and testing stage is driven by the amount of production that is feasible based on the raw materials that are available, i.e. there is no forecast that drives production and production continues as long as enough raw materials, i.e. both boards and other supplies, are available. This is visualised in Figure C-30 and corresponds to pushing the parts through the supply chain, following the central plan that drives production at the suppliers.

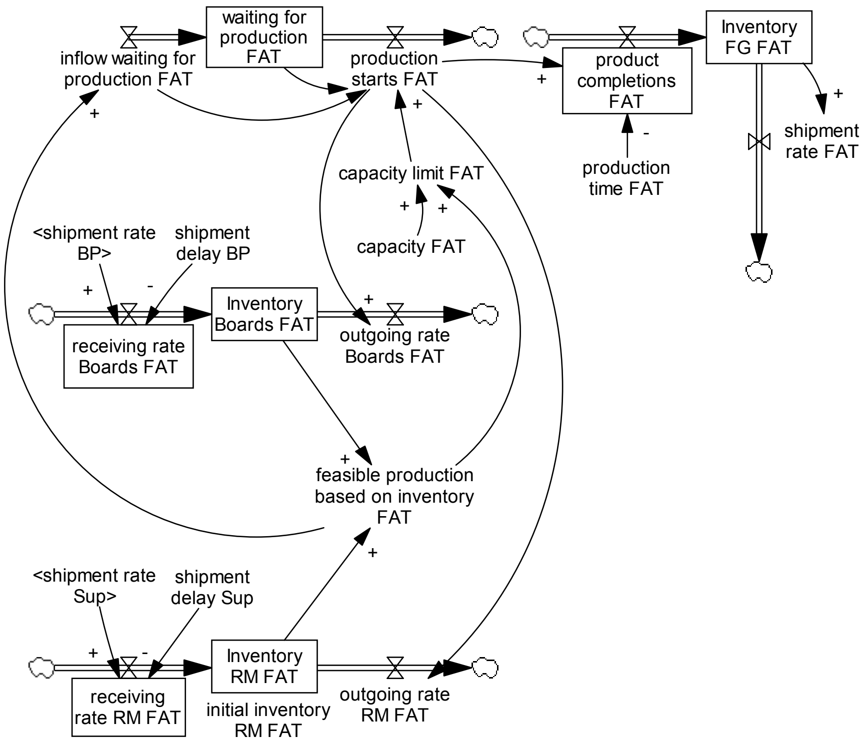

Figure C-30: Push: Production at Final Assembly and Testing

c. First Tier Suppliers

In the push approach with central planning, the first tier suppliers, i.e. board printing and the other supplier to final assembly, receive the central plan and order the materials from their raw materials suppliers based on exactly this plan. Board printing orders the forecast through the standard channel and considers emergency orders separately, as in the Cascade-approach, while the supplier orders the forecast as well as the emergency orders from the same second tier supplier. This is shown in Figure C-31. Production at the first tier suppliers is then, similarly to that at final assembly, driven by the amount of materials they receive from their suppliers.

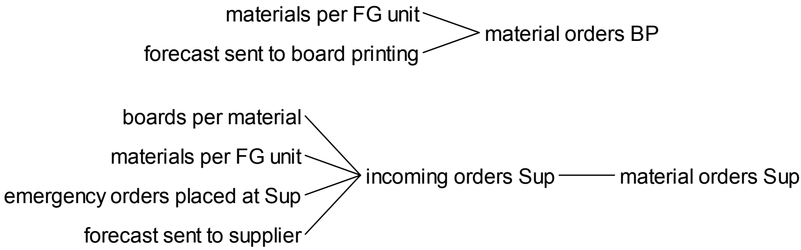

Figure C-31: Push: First Tier Supplier Orders

3. Pull: Planning with Pull Loops

In a pull-based planning approach, material orders at each supply chain echelon are based on actual demand and on changes to safety stock levels, as opposed to being based on a forecast, as in the push-based planning approaches. Such a pull-based supply chain planning system is suggested by Mason-Jones et al. for electronics supply chains, as it may enable a better combination of efficiency and responsiveness of the system than current approaches.[488] Specifically, in each period a supply chain member orders materials to fulfil demand of a period, as well as a potential additional adjustment to achieve the desired safety stock level.[489] This approach is visualized in Figure C-32. For the different supply chain tiers modelled, i.e. software flashing and packing, final assembly and testing, and the first tier suppliers, details of the decision rules in the pull-based planning system are explained in the following.

[488] Cf. Mason-Jones, Rachel, J. Ben Naylor and Denis R. Towill: Engineering the leagile supply chain, in: International Journal of Agile Management Systems, Vol. 2 (2000), No. 1, p. 58–61.

[489] Cf. Reiner: Customer-oriented improvement and evaluation of supply chain processes supported by simulation models, p. 407.

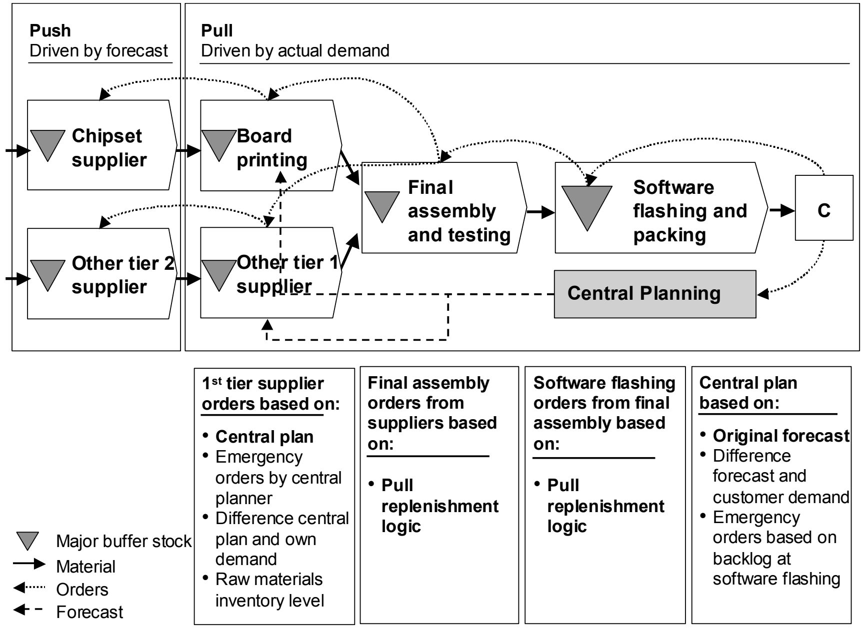

Figure C-32: Pull Loops

a. Software Flashing and Packing

The production and shipment processes at software flashing and packing as well as the preparation of the central plan are identical to those in the other two planning approaches. A central plan is necessary even in a pull approach since the first tier suppliers need to place orders with their suppliers according to a long-term forecast. The difference of the pull approach lies in the policies regulating the receipt of materials from final assembly. In contrast to the push approaches, the pull approach triggers a shipment from final assembly to software flashing only when an order by software flashing has been placed. This ordering logic is based on a pull replenishment logic that is explained in the following.

First, the number of orders to be placed with a specified order size is calculated. This number is then multiplied with the order size resulting in the amount of materials to be ordered each day. This value is accumulated in the stock *Materials on order SWF* that itself is reduced by the material arrival rate at software flashing.

The number of orders to be placed is calculated as follows. The material orders consist of several factors that are summed up. First, the *incoming production requests SWF*, which represents customer demand in the current period, are part of material orders. Considering new incoming orders is, however, not sufficient for driving the ordering process. Therefore the forecasted demand during the lead time until any orders are received from FAT also becomes part of the calculation, since this period needs to be covered with materials on order. This forecast for demand during the expected lead time fluctuates if demand is different from the original forecast, as the forecasts used for the calculation are the adjusted forecasts. Then, the safety stock size is added to the material orders. Also, the backlog at SWF is considered since orders need to be placed to consider any orders that could not yet be fulfilled. From the sum of these values, the inventory position, i.e. the amount of materials on order plus the current inventory level at SWF, is deducted. The inventory position represents the amount of materials already ordered or received, and creates a limit to the amount of orders that are in the system.[490] The INTEGER function is finally used to identify the number of orders to be placed in each period when dividing the desired orders through the order size. This order size can also be limited to a maximum value; in the base case, the maximum order size is set to a high enough value not to limit the dynamics of the system.

```
no of orders SWF =
   INTEGER
   (
    (
     (incoming production requests SWF
      * materials used per FG unit SWF
      * time to place an order SWF)
     + forecast demand in materials LT SWF
     + safety stock size SWF
     + initial stock SWF
     + (Backlog SWF * materials used per FG unit SWF)
     - Materials on order SWF
     - Inventory RM SWF
    )
    /order size SWF
   )
   /time to place an order SWF
```

The safety stock size at SWF is calculated as the standard deviation of demand over the material lead time, which is 10 days, multiplied with a service level factor *z*, representing the number of standard deviations of demand to be covered by the safety stock level. In the base scenario this safety factor is set to 1.65, which corresponds to a service level of 95 percent. The standard deviation of demand is calculated every 10 days using an algorithm developed by John D.

[490] See Hopp and Spearman: To Pull or Not to Pull: What Is the Question?, pp. 142–143.

Sterman.[491] Figure C-33 displays the time behaviour of the desired safety stock levels at SWF for three simulation runs. The first one represents a demand pattern with constant demand of 10,000 units between day 100 and day 400, the second run represents a demand pattern with mean demand of 10,000 units but low noise in that demand pattern, i.e. variations with a standard deviation of the noise 0.1, and the third simulation run represents a demand pattern with a mean demand of 10,000 units and high noise with a standard deviation of 0.8. The safety stock level is zero in the no noise scenario, as no deviations in demand need to be covered. In the low noise scenario, the safety stock level fluctuates at a relatively low level and in the high noise scenario the safety stock size is the highest, as expected. One can also observe the recalculations of the safety stock level every 10 days based on the standard deviation of demand over the last 10 days.

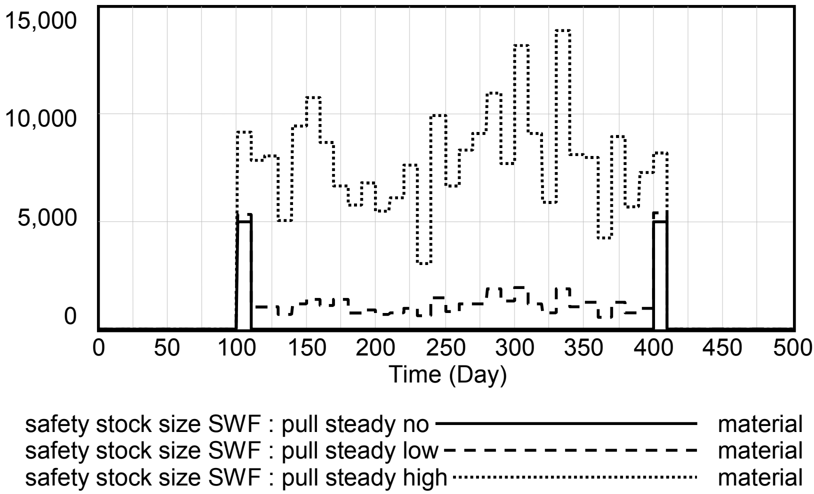

Figure C-33: Pull: Safety Stock at Software Flashing and Packing

In addition to the *safety stock size SWF* variable there is also the possibility to include an additional *initial stock SWF*. This initial stock can incorporate

491 Cf. Sterman, John D.: Appropriate Summary Statistics for Evaluating the Historical Fit of System Dynamics Models, in: Dynamica, Vol. 10 (1984), Winter, pp. 51–66 and Sterman: Business Dynamics, p. 874–880. The time interval of ten days is a reasonable estimate for real-world pull-based planning systems, where safety stock levels may be calculated even more frequently, such as daily or weekly. In other supply chains, however, this interval may also be longer.

planned safety stocks in the model even when currently no demand is observed, i.e. before the product introduction. Except where otherwise indicated, to simulate a pure pull-based system this initial stock is zero.

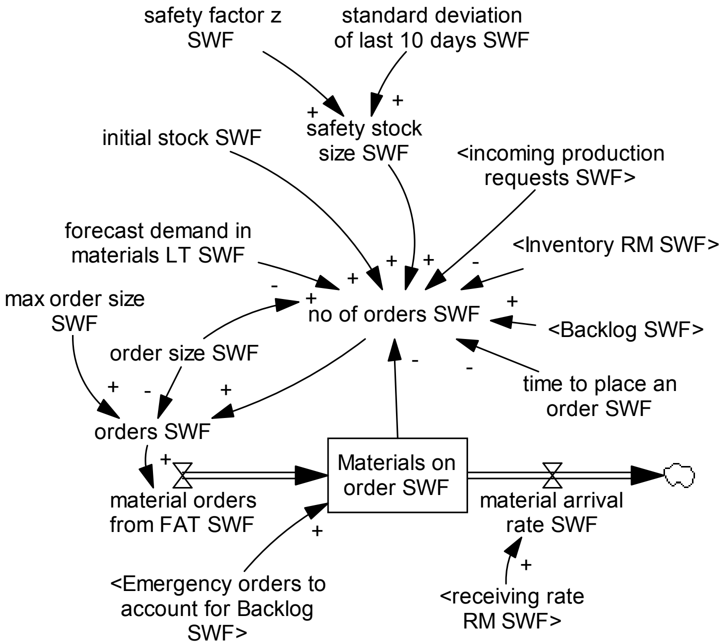

Figure C-34: Pull: Material Orders at Software Flashing and Packing

b. Final Assembly and Testing

Production and shipment processes at final assembly in the pull planning approach begin only after orders from software flashing have been received. Material orders by final assembly are placed following similar policies as at software flashing. The incoming orders, i.e. current period demand, are the *incoming order rate FAT*. This variable represents the sum of normal material orders placed by SWF at FAT and emergency orders. The only difference to the decision rule at the software flashing is that the expected demand in the materials lead time to be covered by materials on order is not based on a forecast, but on the five-day average of demand from software flashing that is observed by the planners at final assembly and testing.

c. First Tier Suppliers

Production and shipment processes at board printing in the pull planning approach begin only after orders from FAT have been received. Standard material orders, however, are placed according to a forecast prepared by central planning. The orders are adjusted to account for the difference between that forecast and actually experienced demand, i.e. orders placed by FAT, and for a desired inventory level at BP. This desired stock level is determined by a desired number of days of stock based on average demand observed from final assembly. Emergency orders by SWF are placed separately as in the other two planning approaches. In the pull approach, additionally, if the initial staging of the supply chain is simulated these one-time orders are added to the material orders from second tier suppliers in their first forecasting period, respectively. This ensures that the supplies arrive on time in order to ensure that they can flow through the supply chain before the product life cycle begins.

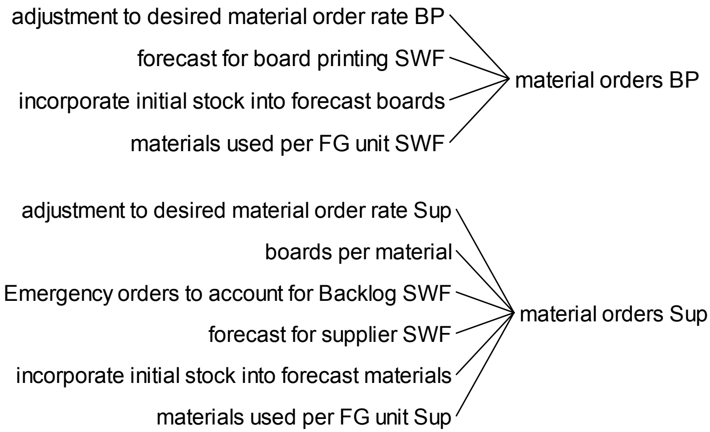

Figure C-35: Pull: First Tier Supplier Orders

Similarly to board printing, production and shipment processes at the other first tier supplier in the pull planning approach begin only after orders from FAT have been received. Material orders, including emergency orders, are placed according to a forecast prepared by central planning. This forecast is adjusted to account for the difference between that forecast and actually experienced demand, i.e. orders placed by FAT, and for a desired inventory level at the first tier supplier. The desired inventory level is determined by a desired number of days of stock based on average demand from FAT.

D. Evaluation of Planning Policies to Achieve Responsiveness and Efficiency

The planning processes in a supply chain for functional products should be designed primarily to deliver at the lowest possible cost. Innovative products require processes that respond quickly to changes in demand in order to minimize stockouts and obsolete inventory.[492] Even though high-tech products are generally considered to be innovative, even within the high-tech sector there are significant differences in demand patterns and forecast stability. Using a System Dynamics simulation model to represent the supply chain structure in the high-tech electronics industry, the impact of external effects, such as a strike at a supplier causing a component shortage, is analysed, as well as the consequences of internal changes in the supply chain structures and policies. Typically, demand is most predictable during the maturity stage of the product life cycle, and rapid changes in demand can be observed during a product's introductory, growth and decline stage.[493] There are also structural differences in the demand patterns, such as demand volatility, which make forecasting extremely difficult and unstable. Therefore, a number of different order patterns are used as input data for the model, based on different products that are characterised by, for example, relatively stable or highly variable demand. Demand volatility is used here as a criterion for segmentation of the products because it is a major factor impacting supply chain performance.

I. Dynamics of Tailoring Supply Chains to Product Requirements

Products with different characteristics pose different challenges to supply chains. For example, higher demand volatility makes forecasting and the achievement of high delivery performance more challenging, increasing the need for responsiveness of the supply chain. While products with predictable demand require less responsiveness to changes in customer demand, there may be supply chain disruptions that require reactions to ensure on-time deliveries. In the following, the System Dynamics model is used to analyse how capable the three different planning approaches are in achieving high responsiveness and efficiency when confronted with a number of challenges, such as high demand volatility or low forecast accuracy. For each demand scenario discussed, the

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[492] Cf. Huang, Uppal and Shi: A product driven approach to manufacturing supply chain selection, p. 194.

[493] Cf. Chopra, Sunil and Peter Meindl: Supply Chain Management, Upper Saddle River, NJ 2004, p. 42.

simulation model provides insights on the extent of responsiveness and efficiency achieved with the different planning approaches.

1. Scenario 1: Steady Demand

In the first demand scenario analysed with the simulation model customer demand is constant at 10,000 units per day between the product introduction at day 100 and market exit at day 400, as shown in Figure D-1. This corresponds to a cumulative demand of 3,000,000 units over the life cycle of the product. The initial forecasts are perfect, i.e. both the exogenous initial forecast for the supplier and the forecast for board printing predict a demand of 10,000 units per day between day 100 and 400. In the base case, this scenario corresponds to one in which demand is stable and highly predictable.

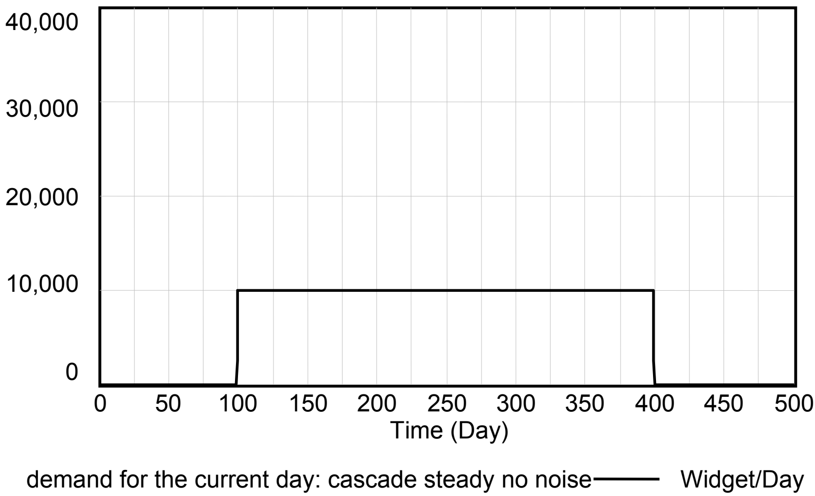

Figure D-1: Demand for the Current Day: Steady, No Noise

In such a situation, it should be relatively simple for a supply chain to achieve efficiency and responsiveness, at least compared to scenarios where demand is highly volatile and unpredictable. Nonetheless backlog situations occur in all of the three different planning approaches even though these forecasts are perfect. As shown in Figure D-2, the maximum backlog is equal to more than 10 days of demand for each planning approach, while the timing of these backlog incidents is different. In the pull-based planning approach, a period with a large backlog occurs as soon as the product is introduced to the market. This backlog is caused by the time delays inherent in a pull-based planning system that relies on forecasts only for the orders of materials from second-tier suppliers. Unless a forecast is made and products are being manufactured before the product introduction (i.e., pushed through the supply chain) such a backlog is unavoidable, but also very harmful as the initial sales are often an important determinant of the financial success of a product.[494] In the simulation of pull-based planning, the first units are delivered on time starting only about 75 days after the product introduction. At this point in time, it I likely that competitors will have captured parts of the market share. If the first product is delivered on time several months after the product introduction, it is more difficult to ensure the financial success of the product. Therefore, in practice, to avoid such initial backlogs pull-based systems rely on a forecast for the product introduction phase. The impact of such a plan for the product introduction phase is analysed later in this section. However, the pure pull approach is not the only planning approach in which backlog builds up as orders cannot be fulfilled. At later stages of the product life cycle, backlogs also occur in the push approaches with cascading forecasts and with central planning.

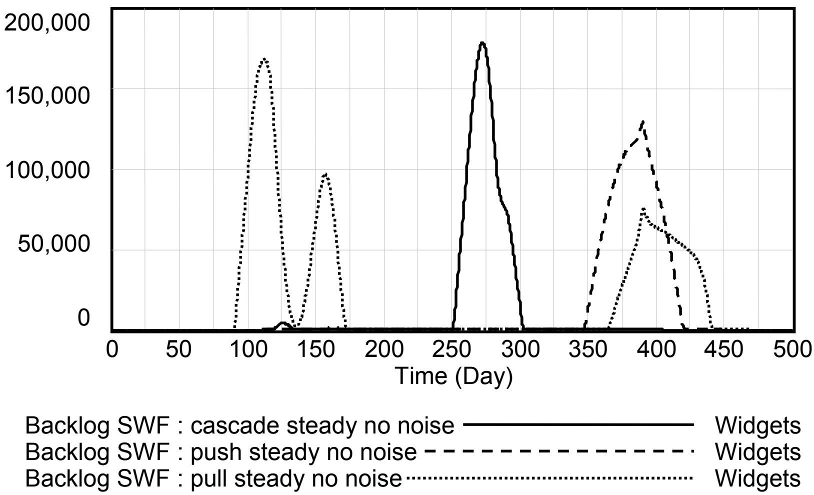

Figure D-2: Backlog at Software Flashing

The backlog incidents, except for the initial backlog in the pull-based planning approach, are caused by adjustments to the forecast that are perfectly rational for the decision makers at the different supply chain echelons but lead to

494 Cf. Milling and Maier: Invention, Innovation und Diffusion, pp. 95–96. and pp. 202–208. How such initial backlog situations can be avoided in the pull-based planning approach is analyzed in section D.I.1.f starting on page 163.

unintended consequences for the supply chain as a whole.[495] In the push approach with central planning, for example, the planners at software flashing intend to reach a level of raw materials inventory that represents 10 days of average demand as a safety buffer. Initially, the raw materials inventory level at software flashing is below that level, which is why the forecast is adjusted upwards, as shown in Figure D-3, which compares the initial forecast for board printing with the adjusted forecast actually sent to board printing. After the delay involved in receiving the ordered materials, the inventory at software flashing starts to build up, but in period 235 average inventory exceeds the desired level because the supply line of materials already on order is not considered by the planners in their decision making process for forecast adjustments (see Figure D-4, which shows the raw material inventory level at SWF). Therefore, the forecast is then adjusted downwards with the intention to counteract the inventory build-up. This downward adjustment, which leads to lower levels of material orders from the second tier suppliers, is the cause for the backlog that begins to appear around period 350 (see Figure D-2).

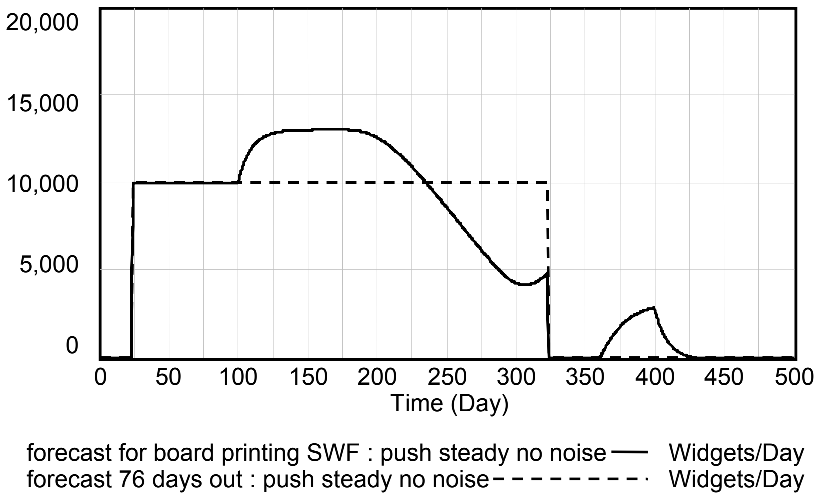

Figure D-3: Push: Forecasts for Board Printing

In the base case, while backlogs occur in all of the three different planning approaches modelled there are also periods with significant inventory build-ups at software flashing in each of the planning approaches, which can also be explained by the forecast adjustments. Again, as can be seen in Figure D-4, the

495 See also section C.I.1, where this common phenomenon is discussed in more detail.

timing and magnitude of these inventory build-ups is different. The fluctuations in the raw materials inventory level at SWF are highest in the Cascade planning approach, which results from the multiple forecast adjustments in the supply chain. With average demand at 10,000 units per day during the product life cycle a maximum inventory level of nearly 800,000 units corresponds to 80 days of demand, or eight times the desired average inventory level. Such an inventory pile-up can easily cause space problems in the warehouse at software flashing and is an additional concern because of the potential for product obsolescence. Therefore, such high inventory levels are highly undesirable. In all planning approaches, there are also stock levels at the end of the product life cycle, which cannot be sold to customers as there is no further demand. These inventory build-ups can also be explained by adjustments to the forecasts that are made over time. In the pull-based planning approach, for example, an inventory build-up at board printing in the middle of the product life cycle causes a reduction of chipset orders by the planners at board printing. This adjustment, in turn, causes a shortage of boards near the end of the product life cycle. This shortage creates a backlog of orders at software flashing and as a consequence leads to the placement of emergency orders, which are delivered to software flashing and help to reduce the backlog. Eventually, as the backlog has been reduced to zero and there is no further demand, these emergency orders remain in the stock of semi-finished products at software flashing.

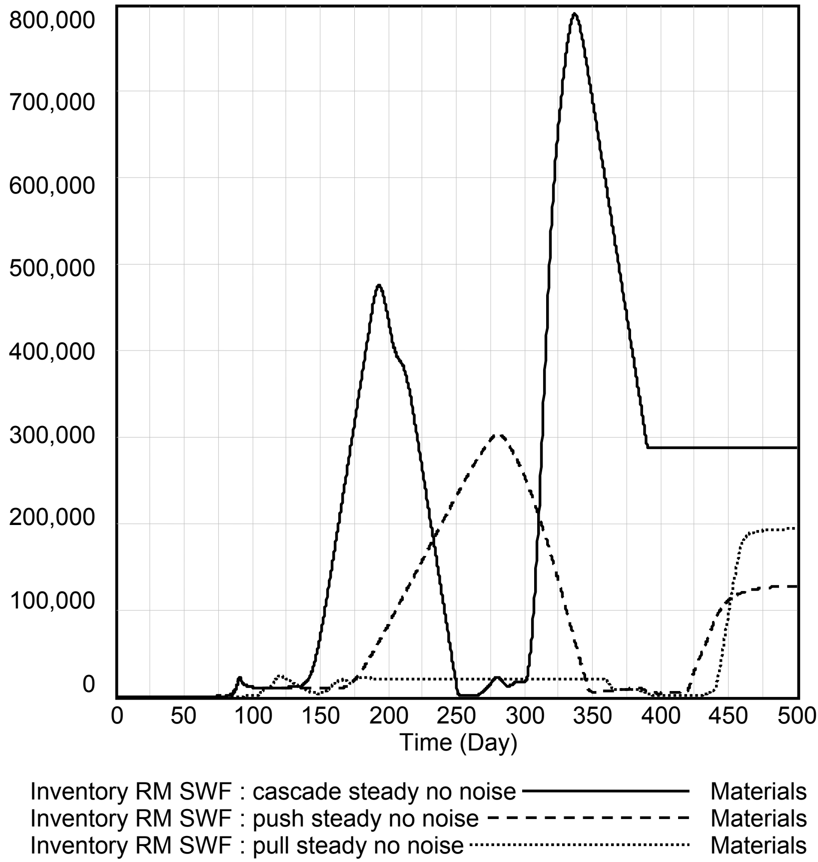

Figure D-4: Raw Materials Inventory at Software Flashing

With regard to the responsiveness and efficiency of the supply chain in this scenario without demand volatility, delivery performance ranges between 64 percent and 85 percent in the three planning approaches with equally significant differences in inventory turns, which evaluate inventory levels across the supply chain and not only at software flashing and packing. In the Cascade planning approach, inventory turns are only 4.7 compared to 16.8 in the Push approach and 16.2 in the Pull approach. The order of magnitude of these figures for inventory turns is in line with values from actual high-tech electronics companies, such as IBM with inventory turns of 16.7, Nokia with inventory turns of

12.7, Motorola with 7.9 and Cisco Systems with 4.7 in 2005.[496] For the supply chain as a whole, the average total inventory levels in the entire supply chain are equivalent to 106 days of stock for the planning approach with cascading forecasts, 30 days of stock in the push-based planning approach with central planning and 31 days for the pull-based planning approach.[497] Average delivery performance reaches 80 percent in the planning approach with cascading forecasts, 85 percent in the push approach with central planning and 64 percent in the pull approach. Even in this simple demand scenario, none of the planning approaches achieves a delivery performance of close to 100 percent. This is due to the individual decision-making policies of the different supply chain members.

Capacity utilization at board printing also differs in the three planning approaches. In both the cascade and the push planning approach, production is ramped up around 25 days before the product is introduced to the market and soon reaches a level of 10,000 units per day. In the cascade approach, this production level rises to 20,000 units, the maximum capacity at board printing, around day 130, i.e. 30 days after the market introduction of the end product. This level is kept until day 280 and then rapidly drops to a production volume significantly below average demand. In the push planning approach there are less fluctuations, with production first slowly rising above the average end customer demand level due to the forecast adjustments by SWF and then slowly falling again. In the pull approach, there are large fluctuations in production shortly after the introduction of the product to the market and production at board printing remains constant at 10,000 units only from around day 200 on, with some more fluctuation near the end of the life cycle. Nonetheless, the correlation between the incoming order rate at BP and the production rate at BP is 0,65, indicating that board printing in this scenario has a relatively high capability to produce what was demanded in the pull-based planning approach.[498]

In summary, the predictability of production when considering the initial forecasts and the demand pattern at board printing in this scenario is largest in the push-based planning approach, which is an important consideration for the initial planning of the supply chain set-up and capacity requirements. While the pull approach is similarly predictable later in the product life cycle in this demand scenario, the production rate at board printing experiences a large amount of fluctuations at the beginning of the product life cycle. The planning approach

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496 Cf. Kozik, Cathie: Motorola: Integrated Supply Chain (ISC) - Creating Sustainable Transformation, Motorola, 2007, p. 10. Dell, in contrast, achieves inventory turns of 86.8 with its direct-sales model.

497 Days of stock for the supply chain are calculated as the average aggregate value of inventory in the supply chain divided by the average customer demand over the simulation duration.

498 See also Holweg *et al.*: Towards responsive vehicle supply, p. 514.

with cascading forecasts uses up the full capacity at board printing of 20,000 units per day while demand is only 10,000 units per day. Both the push approach with central planning and the pull approach therefore manage to keep production at board printing at a rate close to the actual customer demand, even though in the pull approach significant fluctuations are experienced at the beginning of the product life cycle. In contrast, the production rate at board printing in the planning approach with cascading forecasts exceeds the level of customer demand by far during an extended period of time, even when demand is constant at 10,000 units per day.

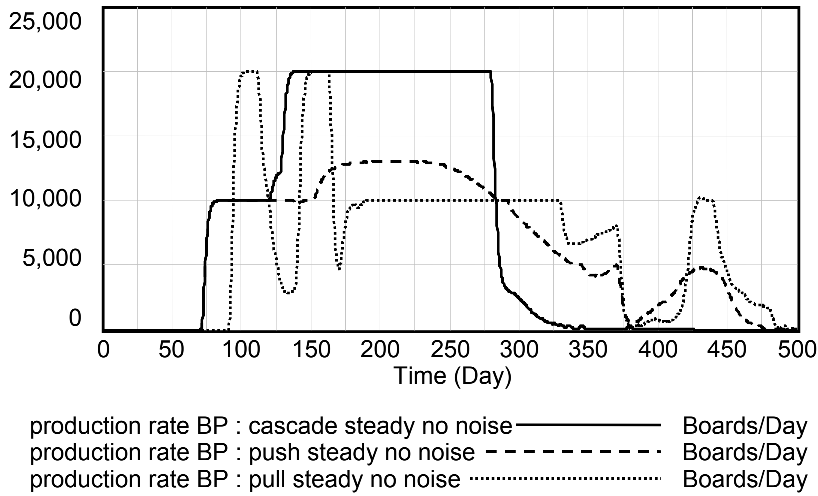

Figure D-5: Production Rate at Board Printing

a. Increasing Desired Inventory Levels

The desired raw materials inventory levels at the different echelons in the supply chain, whose calculation, as described earlier, depends on the planning approach, are the most important determinant of forecast adjustments in this scenario with steady demand and perfect forecasts. Therefore, a sensitivity test is performed to identify the impact of increasing these desired safety stock levels on responsiveness and efficiency. In the cascade planning approach, delivery performance is 80 percent given the standard base case parameters. A sensitivity analysis that increases the desired days of stock at software flashing as well as the desired raw materials inventory levels at each echelon by a factor of up to two leads to a maximum delivery performance of 89%. At the same time, however, inventory turns fall from 4.7 to 1.9. The increase of desired days of stock at software flashing by a factor of up to two in the push planning approach leads to a new level of inventory turns of 10.7, while delivery performance could only be improved by two percentage points. In the pull approach, the effect of increasing the safety factors at SWF and FAT as well as the desired days of stock at board printing and the other first tier supplier is an increase in delivery performance by five percentage points and a reduction in inventory turns from 16.2 to 13.1. These results indicate for the theoretical scenario with constant demand and perfect forecasts that even with a significant increase in the safety stock levels it is not possible to achieve close to 100% delivery performance in all of the planning approaches. The push approach with central planning experiences the lowest relative improvement in delivery performance, but the performance of this planning approach has already been superior to the other two planning approaches in terms of responsiveness and efficiency in the base case scenario.

Table D-1: Sensitivity to Increases in Desired Inventory Levels

		Steady Demand with Perfect Forecasts			
		Base Case		Increased Inventory[499]	
		Delivery Performance	Inventory Turns	Delivery Performance	Inventory Turns
Supply Chain Planning Approach	Cascade	80%	4.7	Mean: 87% Max: 89% Min: 81%	Mean: 2.8 Max: 4.3 Min: 1.9
	Push	85%	16.8	Mean: 85% Max: 87% Min: 85%	Mean: 13.3 Max: 16.8 Min: 10.7
	Pull	64%	16.2	Mean: 67% Max: 69% Min: 64%	Mean: 14.5 Max: 16.1 Min: 13.1

499 Multivariate sensitivity analysis over 500 simulations with the following variations: Cascade: desired days of stock SWF=RANDOM_UNIFORM(10,20), inventory size boards FAT, RM FAT, BP and Sup=RANDOM_UNIFORM(100000,200000); Push: desired days of stock SWF=RANDOM_UNIFORM(10,20); Pull: safety factors z at SWF and FAT=RANDOM_UNIFORM(1.65,2.33), desired days of stock BP and Sup=RANDOM_UNIFORM(10,20).

b. Simulating Forecast Error

Forecasts are rarely as perfect as assumed in the preceding discussion. For example, to analyse how the system reacts to a single unexpected perturbation of the input, consider a demand scenario in which customer demand is constant at 10,000 units per day between the product introduction at day 100 and the middle of the intended product life cycle, i.e. day 249. From day 250, demand is constant at 12,000 units, i.e. demand experiences an unexpected step increase. The initial forecasts are no longer perfect, as they predict a demand of 10,000 units per day between periods 100 and 400, as in the previous analyses. This corresponds to a cumulative demand of 3,000,000 units, which in total is 300,000 more than expected. The increase in demand is unexpected for each member of the supply chain, including the planners preparing the forecasts sent to the suppliers before the product is introduced to the market. There will be therefore be adjustments to the forecasts and/or material orders, depending on the planning approach.

Figure D-6 provides an overview of the performance of the different planning approaches. In the base case scenario with demand of 10,000 units per day, the push planning approach again outperforms the pull and cascade planning approaches on both dimensions, responsiveness and efficiency. The most striking result of this simulation run is that the push approach in the scenario with an unexpected increase in demand outperforms the push planning approach in the scenario with steady, perfectly predictable demand, on both responsiveness and efficiency. This means that in this demand scenario the push-based planning approach is best able to handle small day-to-day deviations in demand as well as an unexpected 20 percent increased in demand.

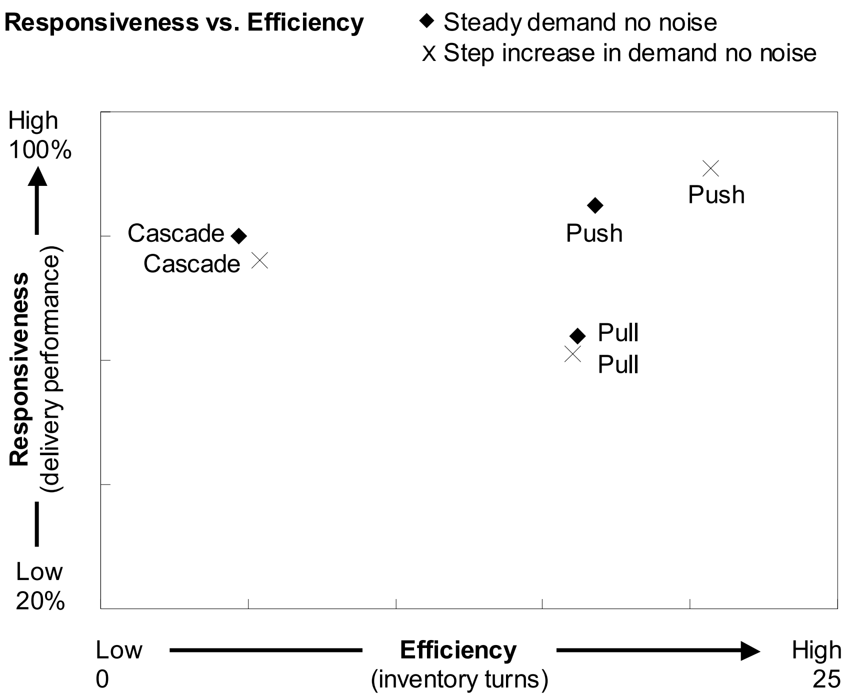

Figure D-6: Sensitivity of Responsiveness and Efficiency to an Unexpected Step Increase in Demand

Compared to the base case scenario with steady demand and perfect forecasts, a few observations can be made in the scenario with an unexpected step increase in demand. Firstly, the inventory turnover for the push approach with cascading forecasts and for the push approach with central planning is significantly higher in the simulation with imperfect forecasts and a step increase in demand, independent of demand volatility. This increased efficiency can be explained by some of the excess inventory that has accumulated in the push approach being consumed by the step increase in demand. At the same time delivery performance for the planning approach with cascading forecasts is only slightly lower in the scenario with the step increase compared to steady demand. This small difference can be explained by the higher overall level of inventory throughout the supply chain in the cascade approach, which allows compensating for the increase in demand. Compared to the steady demand case, with central planning the delivery performance in the step increase scenario is higher. This can be explained by an upward adjustment of the forecasts for the first tier suppliers after perception of the step increase in demand (see Figure D-7).

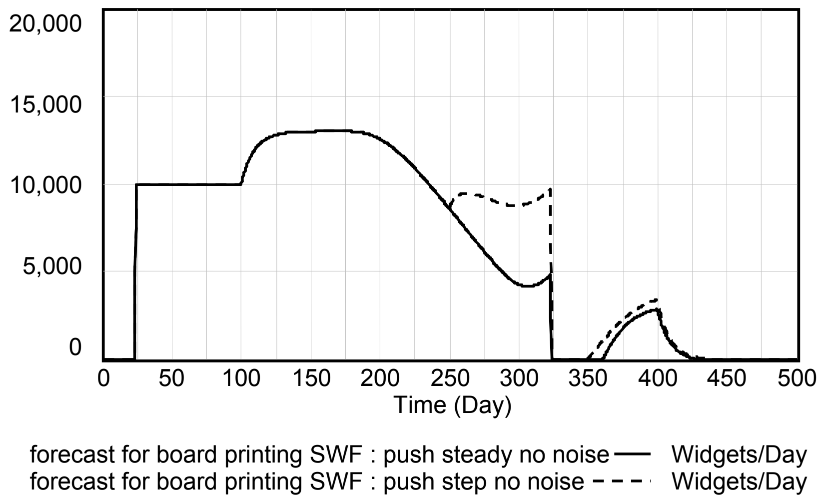

Figure D-7: Push: Adjustment of Forecast for Board Printing after a Step Increase in Demand

Regarding the pull approach, in the step increase scenario this planning approach performs worse than in the steady demand case on both dimensions, delivery performance and inventory turns. This is explicable since no excess inventory is kept to cover this unpredicted major and permanent increase in demand.

Now, consider a scenario in which the planners preparing the initial forecast underestimate demand by 20%. The forecasts initially prepared thus assume a demand of 8,000 units per day, and not 10,000. All other conditions are unchanged, including actual demand of 10,000 units per day and the length of the product life cycle. There is no unexpected step increase in demand. While backlog situations occur in the scenario with perfect forecasts as well, the backlog situations in this scenario with incorrect forecasts are to some extent caused by the initial underestimation of demand. Therefore the first backlog occurs much earlier, i.e. as soon as the product is introduced to the market (see Figure D-8, which displays the backlog in the planning approach with cascading forecasts in the underforecast scenario compared to the scenario with accurate forecasts).

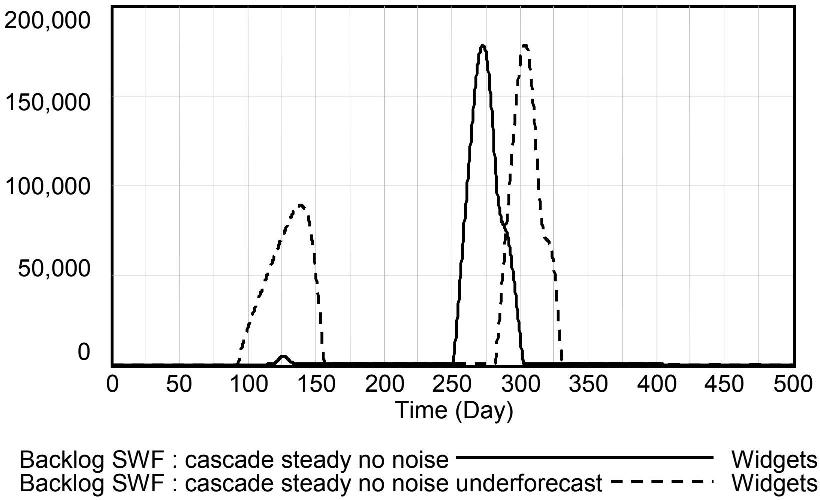

Figure D-8: Underforecast: Backlog at Software Flashing

In a planning approach with no adjustments to the initial plan, the backlog would never disappear. Therefore, the response of the system to the demand change is that while the forecasts are adjusted to represent the higher demand level, supply chain planners also place emergency orders as they attempt to recover the backlog as quickly as possible. These emergency orders are placed as long as a backlog occurs and, combined with the failure to adjust the other forecasts for the emergency orders that were placed, eventually cause an even larger inventory build-up near the end of the product life cycle than in the scenario with perfect forecasts, as shown in Figure D-9.

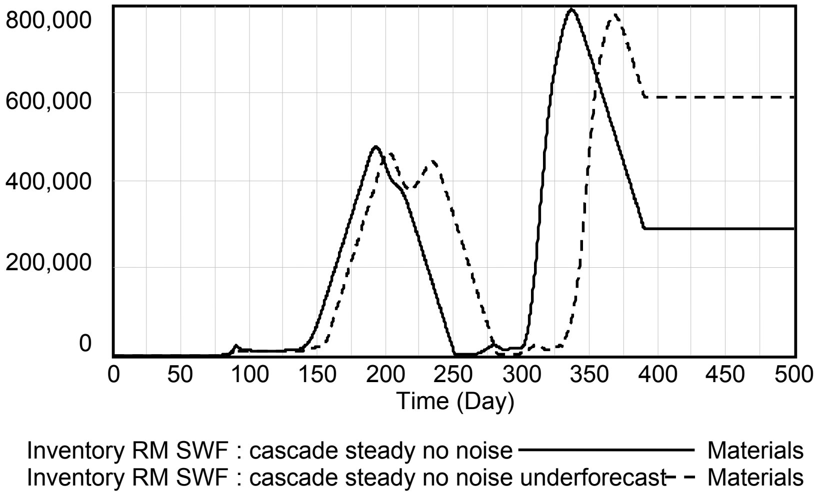

Figure D-9: Underforecast: Raw Materials Inventory at Software Flashing

While the original forecast is adjusted downwards to consider the actual raw materials inventory level at software flashing that begins to exceed the desired inventory level shortly before day 350, the adjustment as shown in Figure D-10 is too little, too late, as demand for the product ceases at day 400. Taken together, these factors cause a major inventory build-up at the end of the product life cycle.

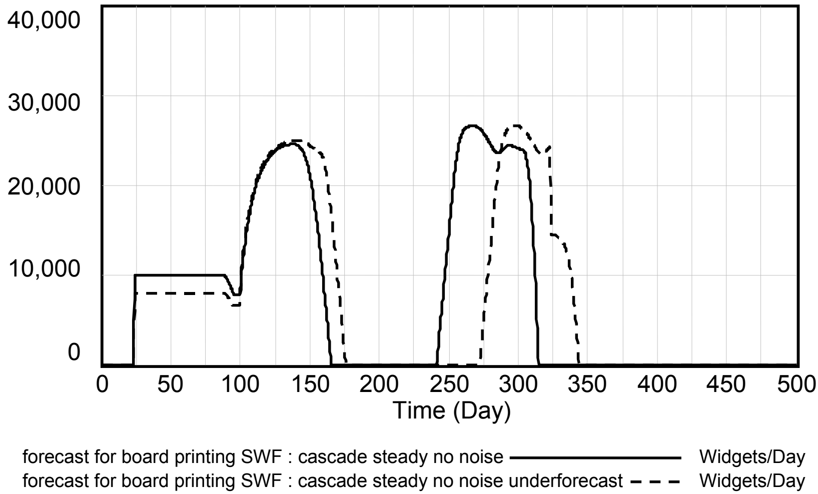

Figure D-10: Underforecast: Forecast for Board Printing Prepared by Software Flashing

The consequences of the incorrect forecasts are reductions in supply chain responsiveness and efficiency in all three planning approaches. The pull planning approach suffers the lowest reduction in inventory turns and delivery performance compared to the scenario with perfect forecasts and therefore shows the least sensitivity to an underestimation of demand in this scenario. The push approach, whose performance on these dimensions was best in the base case with perfect forecasts with slightly higher efficiency and significantly lower delivery performance compared to the pull approach, now performs slightly worse than the pull approach in terms of delivery performance and slightly better in terms of inventory turns, as shown in Figure D-11. The cascade planning approach performs worst on efficiency but achieves a slightly higher delivery performance than both other planning approaches. This is primarily caused by the higher inventory levels throughout the supply chain that allow a quicker elimination of backlog situations.

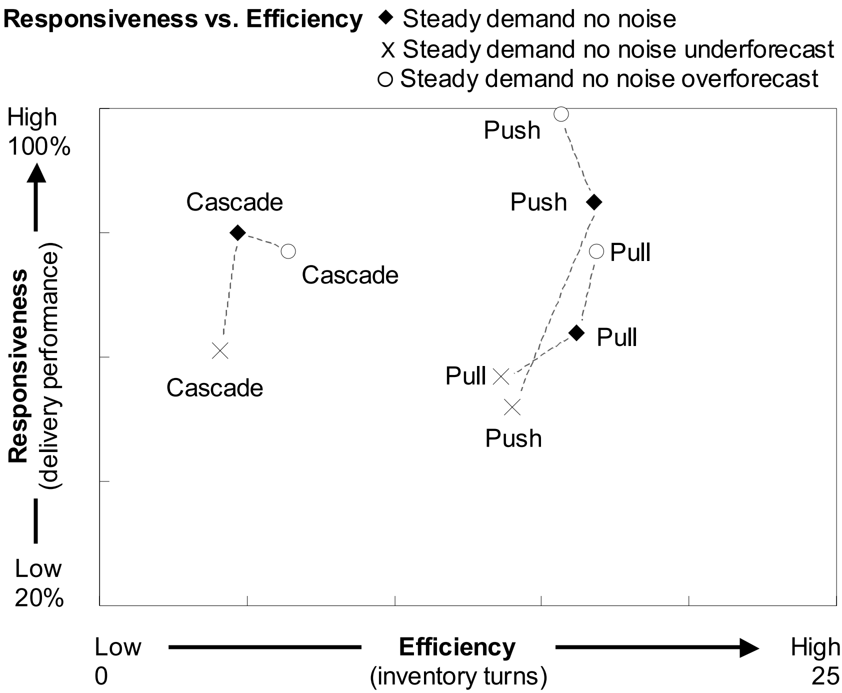

Figure D-11: Underforecast and Overforecast: Responsiveness vs. Efficiency

The initial forecast could also err in the other direction, i.e. overestimate demand. This could be either due to an incorrect estimation of demand, or due to a purposeful inflation of the forecast. Inflating the forecast by, for example, 20 percent is frequently done when actual demand is uncertain and product life cycles are short in order to ensure availability and increase delivery performance during the initial phase of the product life cycle.[500] In the no noise scenario with steady demand, the results are surprisingly different for the three planning approaches. In the push-based planning approach with forecasts cascading through the supply chain, efficiency as measured by inventory turns increases from 4.7 to 6.4, while delivery performance is reduced from 80 percent to 77 percent due to the overforecast and resulting adjustments within the supply chain. The push-based planning approach with central planning achieves a delivery performance of 99 percent in the overforecast scenario, with a reduction in inventory turns

[500] See, for example, the case of a product transition at Intel described in Erhun, Gonçalves and Hopman: Moving from Risks to Opportunities, pp. 16–18. See also Wendin: Electronics Manufacturing: EMS at a Crossroads, p. 13.

from 16.8 to 15.7. In the pull-based planning approach, an overforecast improves both performance measures as inventory turns increase from 16.2 to 16.9 and delivery performance increases from 64 percent to 77 percent. The primary explanation is that the reduction of the initial backlog through the overforecast avoids the need for emergency orders, which reduces inventory accumulations near the end of the product life cycle and therefore improves responsiveness of the supply chain as well as its efficiency.

c. Effect of Random Demand Deviations

In the base case scenario, demand is constant at 10,000 units per day throughout the product life cycle. In reality, however, demand is subject to variation over time. This demand volatility is now introduced in order to analyse its impact on the performance of the different planning approaches. The forecasts remain at 10,000 units per day, and also mean demand is 10,000 units per day. Noise is added to the previously constant demand through a pink noise process, which is first-order autocorrelated noise where the next random variation depends in part on the previous variations. Using pink noise and not white noise, where all variation is independent, is necessary to represent that one period's demand is not independent of the last but depends to some degree on history. This means that customer demand is subject to some inertia.[501] In the simulations with random noise, the supply chain performance measures discussed refer to the mean values obtained from a sensitivity analysis with 200 different random demand patterns. The values indicated for inventory turns and delivery performance to customer request are the mean values at the end of over 200 simulations with different noise seeds, i.e. 200 demand patterns with different noise patterns, each with a mean demand of 10,000 units per day. The standard deviation of the pink noise remains constant over these 200 simulations and is 0.1 in the low noise scenario and 0.8 in the high noise scenario. The high noise scenario may appear to assume a relatively large degree of variation. However, a comparison with the demand pattern for a real mobile phone shown in Figure B-5, page 47, reveals that in reality demand may be even more volatile than assumed in the simulations. The standard deviation of the real-world demand pattern for the sample mobile phone is 13,388 (when normalized to the same average demand level as in the simulation, i.e. 10,000 units per day) with a difference between the maximum and minimum demand of 96,822 units, while the simulated high noise demand pattern shown below, as an example, has a standard deviation of 6,500 and a range of 30,805 units.

[501] Cf. Sterman: Business Dynamics, p. 917.

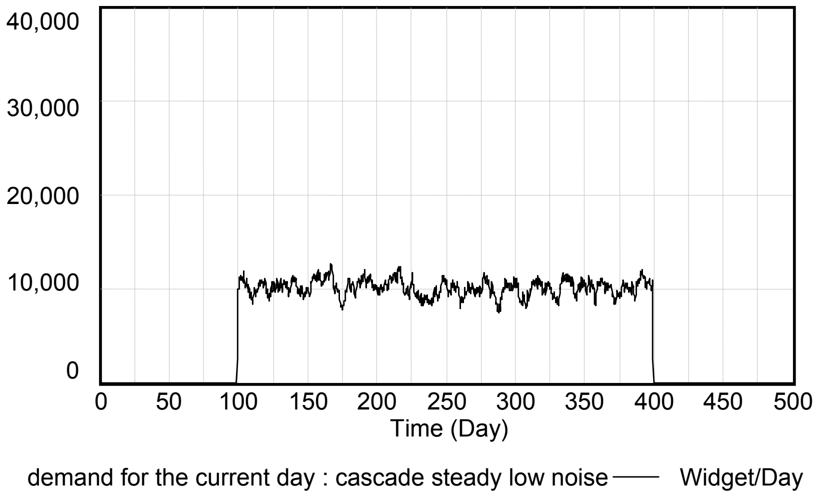

Figure D-12: Demand for the Current Day: Low Noise (example)

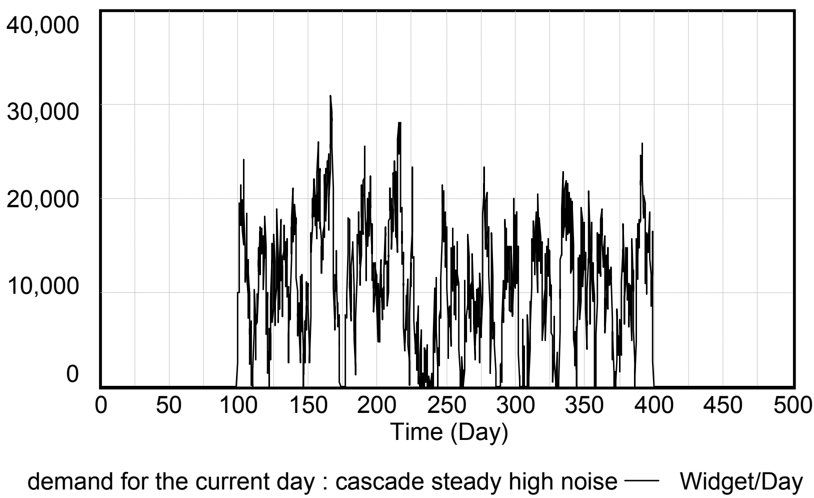

Figure D-13: Demand for the Current Day: High Noise (example)

Driven by the variation in demand the planners in all planning approaches are confronted with the same problem – how to satisfy customer demand on time considering that the raw material receipts are unlikely to constantly coincide with the requirements during a particular period. If demand is below the forecast for a few days, inventory will build up, and if demand is higher than the forecast, the inventory levels will decline until eventually a backlog situation arises as demand can no longer be fulfilled.

In each of the represented planning approaches the initial forecasts are modified to reflect differences between the original forecasts and actual demand as well as the desired level of inventory at software flashing. In the push approach and in the pull approach, these are the only changes to the forecast for the first tier suppliers that are made, while in the cascade scenario an additional adjustment to that forecast is made by the planners at final assembly. Considering only the forecast adjustment made by software flashing, differences between the three scenarios can be observed, as shown in Figure D-14. In the two primarily push-based planning approaches, the structure of the adjustments to the forecast done by software flashing is exactly the same, while in the pull-based planning approach no adjustment to the desired level of inventory at software flashing is made. The major cause for the forecast deviations are differences in the development of the level of raw materials inventory at software flashing, which is an important input for the determination of the adjustment for the desired level of raw materials inventory (see Figure D-15). For example, as the raw materials inventory level at SWF in the planning approach with cascading forecasts begins to quickly rise above the desired level from shortly after day 150, the forecast for board printing is adjusted downwards. As a consequence, the forecasts of future demand are not independent of current orders. If current orders are higher than the average forecast, inventory levels deplete and the forecast is adjusted upwards. Similarly, if current orders are lower than the average forecast, inventory builds up and the forecast is adjusted downwards. Forecasts therefore respond strongly to recent events, even if the results of the change in the forecast will only have an impact on incoming materials several months in the future.[502] Since such an adjustment for the desired inventory level is not made in the pull-based planning approach, the forecast stability is higher, which is beneficial for the upstream echelons in the supply chain.

502 This phenomenon is described for a company in the semiconductor industry in Sterman: Business Dynamics, pp. 449–462.

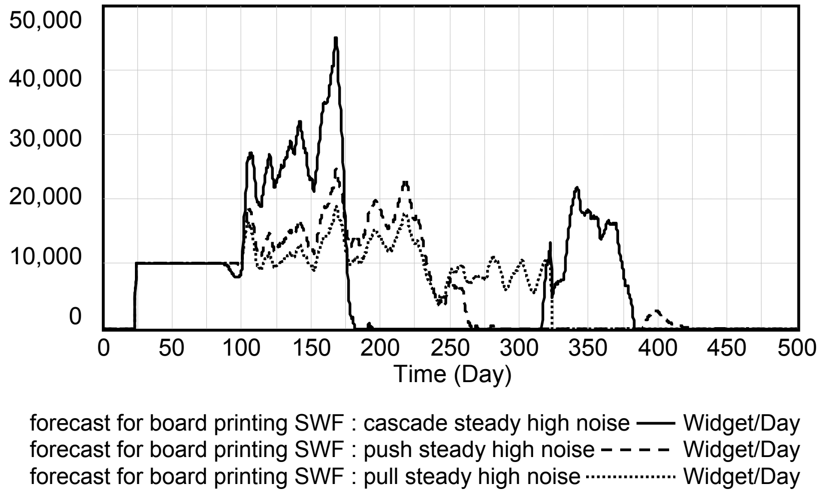

Figure D-14: Forecast for Board Printing prepared by Software Flashing (example, not averaged)

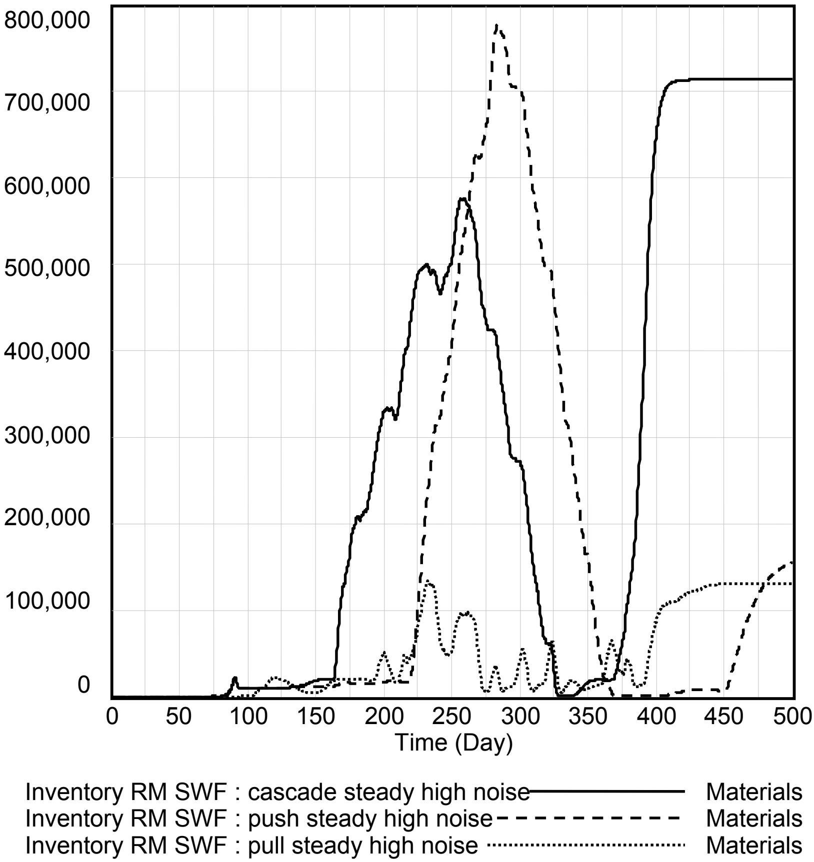

Figure D-15: Raw Materials Inventory at Software Flashing (example, not averaged)

In the pull planning scenario, variations in demand influence the material orders by software flashing and final assembly in several ways. Firstly, demand variations are passed on immediately through newly placed orders. Except for the smoothing caused by the minimum order size in the pull logic the material orders placed therefore have a similar level of volatility as the demand from that echelon's customer.[503] Secondly, the changes in the forecast by the central planners cause changes in the forecast for demand expected during the materials lead time, which affect the order size either positively or negatively. If actual demand is higher than the forecast, the forecast will be adjusted upwards by the

[503] See also the analysis in section D.I.1.d.

central planners, and vice versa. This change then traverses through the supply chain as material orders are also adjusted in the same direction to cover the expected higher level of demand during the materials lead time. This is shown for one sample simulation in Figure D-16. Finally, the desired safety stock level depends directly on the variation in demand observed by SWF or FAT, respectively. Every ten days, which corresponds to the lead time after which ordered materials are expected to be received, the volatility of demand is recalculated and the desired level of safety stock is adjusted. This is shown in Figure D-17.

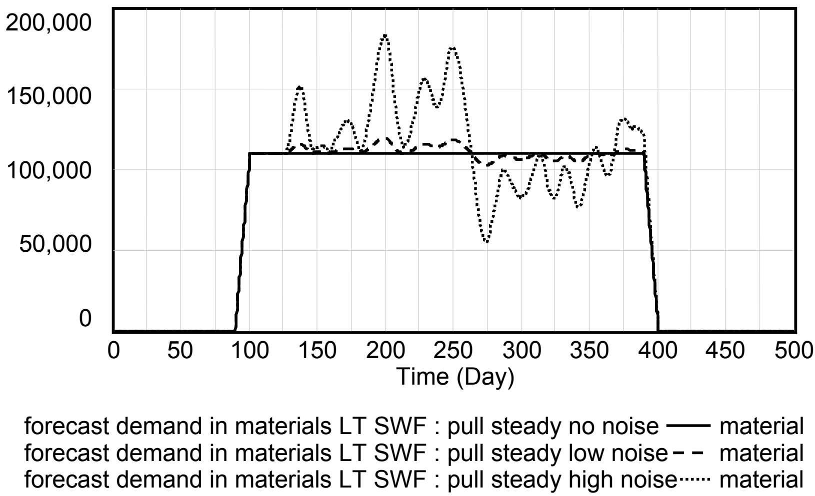

Figure D-16: Pull: Forecasted Demand During the Expected Materials Lead Time at Software Flashing (example, not averaged)

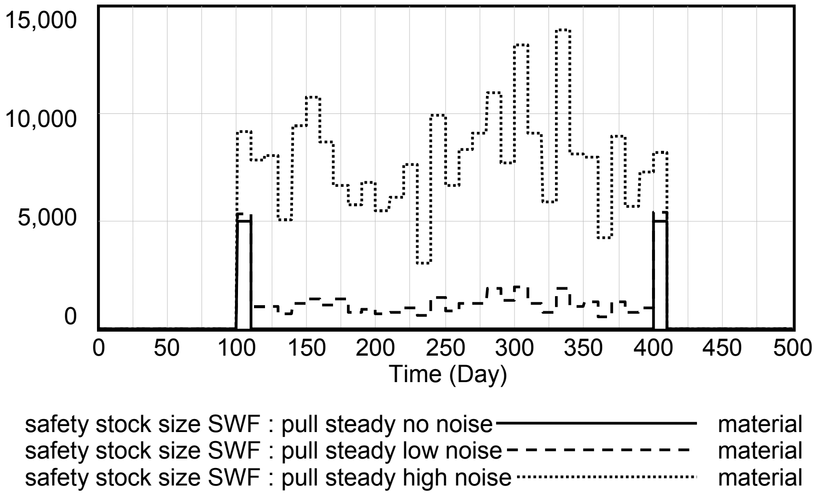

Figure D-17: Safety Stock Size at Software Flashing (example, not averaged)

In the low noise scenario, delivery performance is five to 14 percentage points lower than in the base case scenario and reaches 72 percent in the push approach with cascading forecasts, 71 percent in the push approach with central planning and 59 percent in the pull approach. Inventory turns in the simulation with low noise are almost the same as in the scenario with no noise for each of the planning approaches, i.e. no significant reduction in the level of efficiency could be observed. The only major impact of the small amount of noise in demand was therefore a reduction in the delivery performance, with little impact on the efficiency of the supply chains. One reason for this observation is that the averages of demand used in decision making and forecasting smooth out small changes in demand such that the adjustments made to react to the changes in demand are relatively small. The push-based planning approach with central planning adapts best to this small amount of day-to-day variation in demand. While its delivery performance is only one percentage point lower than that in the planning approach with cascading forecasts, it achieves the highest efficiency when comparing the three planning approaches. In the high noise scenario, the changes in demand are much larger and not entirely smoothed out by the forecasting processes as both extended periods with significantly above average demand and significantly below average demand can occur, which is shown for a sample demand pattern in Figure D-12 and Figure D-13. Figure D-18 and Figure D-19 illustrate the resulting forecast adjustments. The dashed lines in each figure are the forecast sent to board printing in the scenario without noise. The drawn through line represents the mean forecast averaged over 200 sensitivity simulations in the scenarios with low noise and high noise, respectively. While the forecast in the low noise scenario is very similar to the forecast in the no noise scenario, the discrepancy between the two is significant in the high noise scenario, which can be explained by the higher fluctuations in demand and resulting inventory fluctuations.

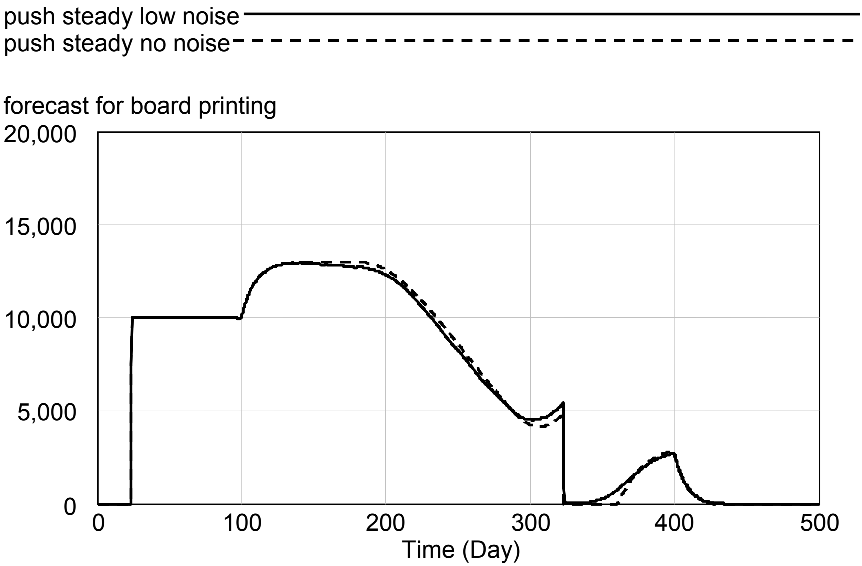

Figure D-18: Push, Low Noise: Average Forecast Adjustments

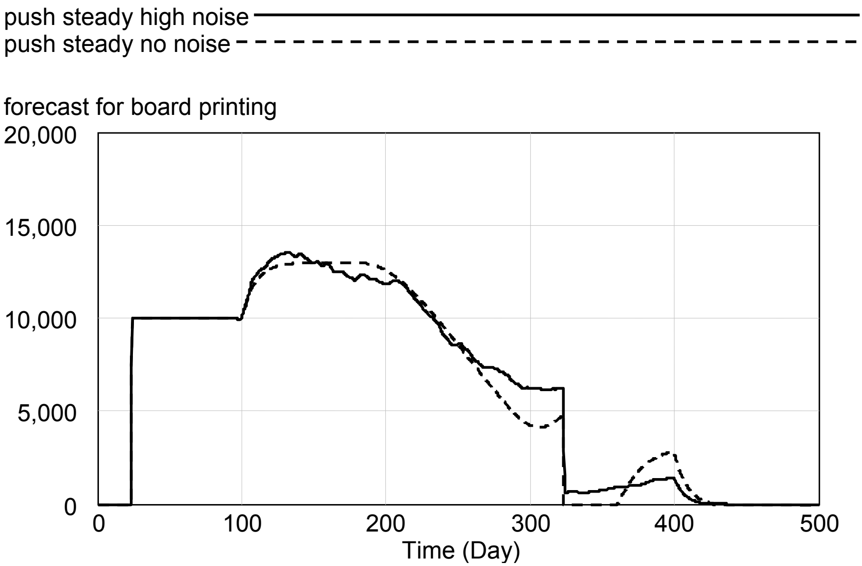

Figure D-19: Push, High Noise: Average Forecast Adjustments

In the high noise scenario, because of the larger variation in demand, delivery performance is at 50 percent in the cascade approach and thus 22 percentage points lower than in the low noise scenario. Delivery performance is 43 percent in the push approach (27 percentage points lower) and 26 percent in the pull approach (33 percentage points lower). With its higher average inventory levels throughout the supply chain and resulting lower efficiency, the cascade planning approach allows this result of a higher delivery performance than the other planning approaches could achieve. This is also visible in the behaviour over time graph of the backlog level at software flashing, reproduced in Figure D-21. The performance of pull in the high noise scenario is the worst of the three planning approaches, with customers having to face particularly long delivery delays in the initial phase of the product life cycle. This inability to deliver of the pure pull-based planning approach in the first phase of the product life cycle is almost unavoidable due to the pure pull nature of the system. In a later analysis, planning for the product introduction through initial staging of the supply chain is analysed. Even though the push approach outperforms the other planning approaches on efficiency in the high noise scenario, this approach achieves only 43 percent delivery performance.

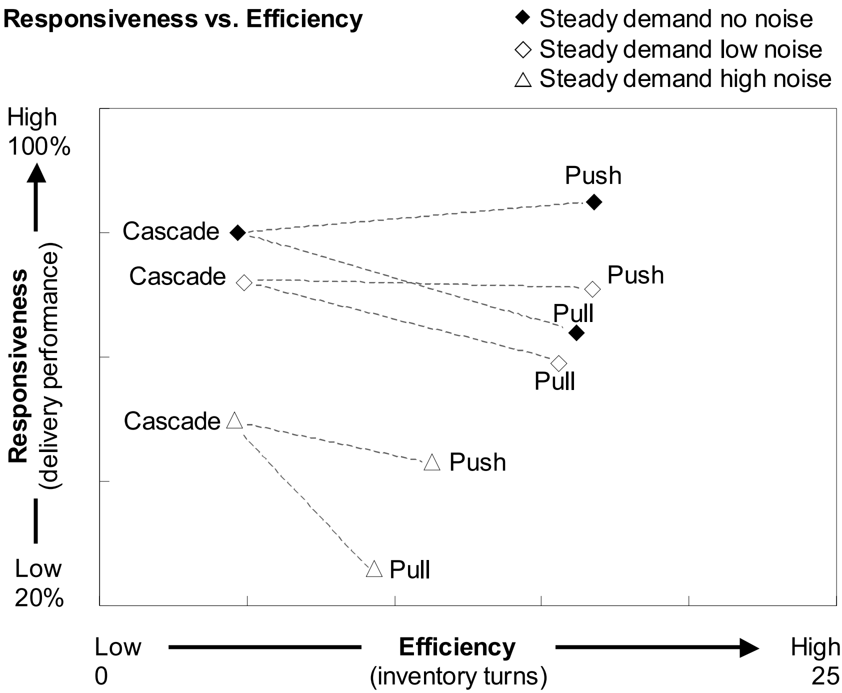

Figure D-20: Steady Demand: Sensitivity of Responsiveness and Efficiency to Randomness in the Demand Pattern

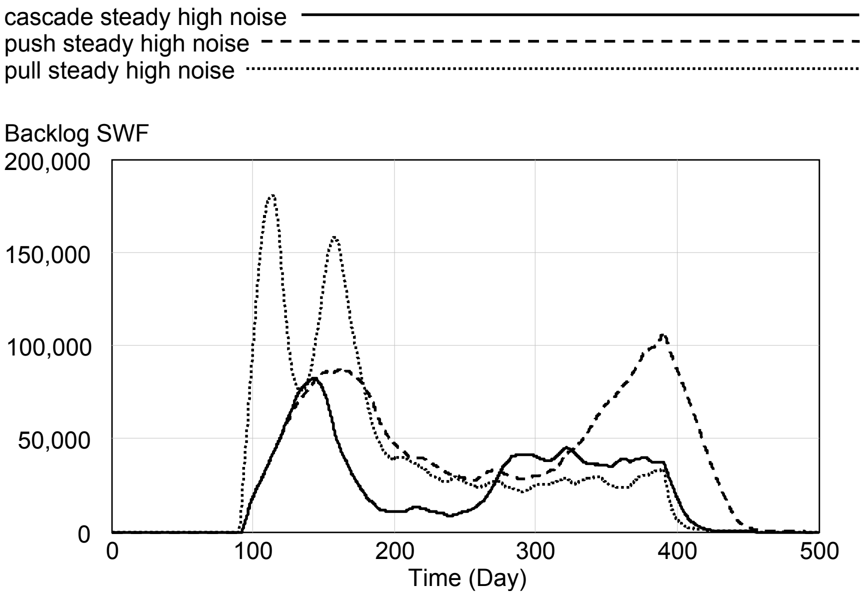

Figure D-21: Steady Demand: Average Backlog at Software Flashing[504]

504 The plotted values are the average values over 200 simulations with different noise seeds, i.e. the average values for 200 different demand patterns with variation in the noise that is added to the base product life cycle.

Table D-2: Sensitivity of Responsiveness and Efficiency to Randomness in the Demand Pattern

Steady Demand with Perfect Forecasts

Planning Approach	Base Case		Low Noise[505]		High Noise[506]	
	Delivery Perf.	Inventory Turns	Delivery Perf.	Inventory Turns	Delivery Perf.	Inventory Turns
Cascade	80%	4.7	72%	4.9	50%	4.6
Push	85%	16.8	71%	16.7	43%	11.3
Pull	64%	16.2	59%	15.6	26%	9.3

d. Changing Pull Parameters

One critical question is whether the performance of the pull-based planning approach is affected by a modification of various order parameters, such as the frequency of updating the safety stock level, the minimum order size, and the maximum order size.[507] These parameters may need to be adjusted when a fundamental demand change is experienced, since otherwise stockouts could occur.[508] Changing these parameters, however, creates additional upstream demand variability and thus may also cause disruptions in the supply chain. Disney and Towill and also Forrester, for example, find that continuously recalculating these inventory control parameters according to the demand signal causes fluctuations in production quantities. They suggest that slow reactions to

505 Mean values over 200 simulations with different noise seeds; standard deviation of white noise used for pink noise process is 0.1; this noise is added to the constant demand. Pink noise is first-order autocorrelated noise where the next random shock depends in part on the previous shocks.

506 Mean values over 200 simulations with different noise seeds; standard deviation of white noise used for pink noise process is 0.8.

507 See Krupp, James A.G.: Some Thoughts on Implementing "Pull" Systems, in: Production and Inventory Management Journal, Vol. 40 (1999), No. 4, p. 36. See also Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, pp. 107–110, who discuss a related complication with regard to vendor managed inventory.

508 Cf. Krupp: Some Thoughts on Implementing "Pull" Systems, p. 36.

changes in the demand signal reduce variability by creating more stable inventory levels and less fluctuation in production volumes.[509] To test the impact of such parameter changes on the simulated pull-based planning approach, the demand scenario with high variation in demand is selected, since it relies most on safety stock and generates the largest fluctuations in material orders. Three possible adjustments to the pull parameters are identified, which are

4. *Minimum order size*. The minimum order size represents the smallest size of an order that can be placed at the supplier. A reduction of the minimum order size leads to smaller and more frequent orders, which is one of the objectives of pull-based planning systems.
5. *Maximum order size*. The maximum order size represents an upper limit to the amount of orders that can be placed at the supplier. Such a limit can be useful if capacity is limited upstream in the supply chain, in which case orders beyond that limit cannot be fulfilled in any case.
6. *Frequency of updating desired size of safety stock levels*. The frequency of updating the desired size of safety stock levels could also have an impact on the performance of the supply chain as it reflects changes in the variability of demand.

These adjustments are tested with the model. As Table D-3 shows, however, none of the adjustments cause a significant improvement of either responsiveness of efficiency, suggesting that their importance in determining responsiveness and efficiency in the pull-based planning approach is secondary compared to other factors. Nonetheless, the aspect of forecast stability is an important determinant of supply chain responsiveness[510], but this stability is already higher in the pull-based planning approach than in the other planning approaches.

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[509] Cf. Disney, Stephen M. and Denis R. Towill: A procedure for the optimization of the dynamic response of a Vendor Managed Inventory system, in: Computers & Industrial Engineering, Vol. 43 (2002), No. 1–2, p. 42; Forrester: Industrial Dynamics, p. 186 and Kaipia, Korhonen and Hartiala: Planning nervousness in a demand supply network, p. 100.

[510] See Harrison: An Investigation of the Impact of Schedule Stability on Supplier Responsiveness, p. 90.

Table D-3: Responsiveness vs. Efficiency: Modifying Pull Parameters

Supply Chain Planning Approach	*Steady Demand with Perfect Forecasts* High Noise: Delivery Performance	*Steady Demand with Perfect Forecasts* High Noise: Inventory Turns
Pull	26%	9.3
Minimum order size reduced from 1,000 to 100	26%	9.3
Maximum order size limited to 20,000	25%	10
Safety stock size update interval increased from 10 days to 20 days	26%	9.3
Safety stock size update interval decreased from 10 days to 5 days	25%	9.4
Combination of the above changes[511]	25%	10.0

e. Comparing Responsiveness at the Same Level of Efficiency

Since the push planning approach performs best on efficiency in the high noise scenario, one could modify some of the parameters, such as desired inventory levels, to attempt an improvement of the delivery performance. To allow an easier comparison of the three planning approaches, the parameters in the push and pull planning approaches were adjusted to reach the same level of inventory turns as the cascade planning approach. This analysis is done for the high noise demand scenario only. A level of inventory turns of 4.6 corresponds to an aver-

511 Sensitivity analysis over 200 simulations incorporating all of the indicated changes. For the safety stock size update interval, the increase of the interval from 10 days to 20 days is simulated.

age total inventory level that represents 106 days of stock in the supply chain, which is very high. In this scenario, the cascade planning approach achieves 50 percent delivery performance at inventory turns of 4.6. If the desired days of stock for raw materials inventory at software flashing in the push approach with central planning are increased from 10 to 39, inventory turns of 4.6 are achieved. At the same time, delivery performance increases to 59 percent. For the pull approach, two different possibilities are explored. Firstly, the calculated safety stock levels only at software flashing are increased by a factor of 39, which leads to inventory turns of 4.6 and delivery performance of 54 percent. This represents an increase in the days of stock covered by safety stock from approximately from less than one day to approximately 30 days, which is much higher than what would typically be found in a pull system. Second, the safety stock levels at SWF are increased not only at SWF but also at FAT, by a factor 19, respectively. With inventory turns again at 4.6, delivery performance is also 54 percent. In this demand scenario, therefore, with relatively high inventories across the supply chain the cascade planning approach performs worst in terms of delivery performance. At the same level of efficiency as in the cascade planning approach, the push approach achieves a significantly higher delivery performance. The pull approach with higher inventories throughout the supply chain and the pull scenario with higher inventories close to the market only, i.e. at SWF, perform only slightly worse than Push, but still better than cascade. Both push and pull, therefore, can be viable alternatives to the cascade planning approach.

Table D-4: Comparing Responsiveness at the Same Level of Efficiency

Supply Chain Planning Approach	*Steady Demand with Perfect Forecasts* High Noise: Delivery Performance	*Steady Demand with Perfect Forecasts* High Noise: Inventory Turns
Cascade	50%	4.6
Push – increased desired days of stock at SWF from 10 to 39	59%	4.6
Pull – increased safety stock at SWF by a factor of 40	54%	4.6
Pull – increased safety stock at SWF and FAT by a factor of 19	54%	4.6

f. Planning the Product Introduction in the Pull Approach

While the pull approach does, on average, not perform as well as the push-based planning approach in the different cases tested above, one major problem of the pull-based approach is the low delivery performance in the initial phase of the product life cycle. In the push approach, the long term forecasts are used to produce materials before the introduction of the product in order to achieve availability of raw materials at all stages of the supply chain.[512] Planning for this introduction phase by initialising production before customer demand is observed could make the pull approach equally attractive as the push approach, with its simplicity making it particularly attractive.

The software flashing and final assembly and testing stages therefore each order materials with the objective of having an initial stock of 100,000 units of components available when the product is introduced to the market. This intention of the two supply chain members is also known to the suppliers at the beginning of the simulation, allowing them to begin production early enough. The value of 100,000 units corresponds to a rough estimation of the demand during the order lead time from the next upstream supply chain echelon. In period 120,

[512] Cf. Sterman: Managing the Supply Chain in a High-Velocity Industry, p. 13.

i.e. 20 days after the product introduction, the desired amount of materials in stock to cover for the product introduction phase is reset to zero.

In the demand scenario with steady demand and no noise, delivery performance in the pure pull-based planning approach was 64 percent with inventory turns at 16.2. The modification of planning for the product introduction increases delivery performance to 66 percent, with inventory turns falling to 12.3. A small improvement in delivery performance is accompanies by a significant reduction of inventory turnover. However, delivery performance is at 100 percent for two thirds of the product life cycle, as shown in Figure D-22. The reason for this is that board printing experiences an inventory build-up in the initial phase of the product life cycle and consequently adjusts the material orders from second tier suppliers downwards. This effect eventually leads to a shortage of chipsets starting on around day 250, as shown in Figure D-23. The push-based planning approach is less affected by such effects, which allows it to achieve a higher level of average delivery performance (85 percent).

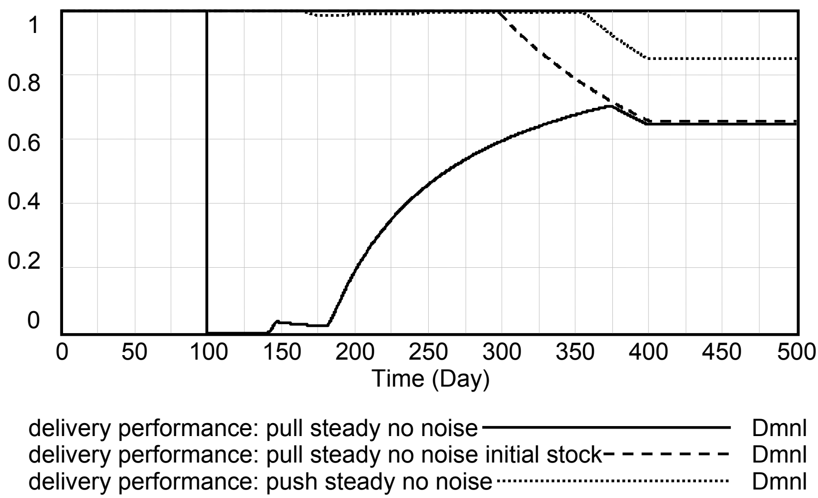

Figure D-22: Delivery Performance to Customer Request: Planning the Product Introduction

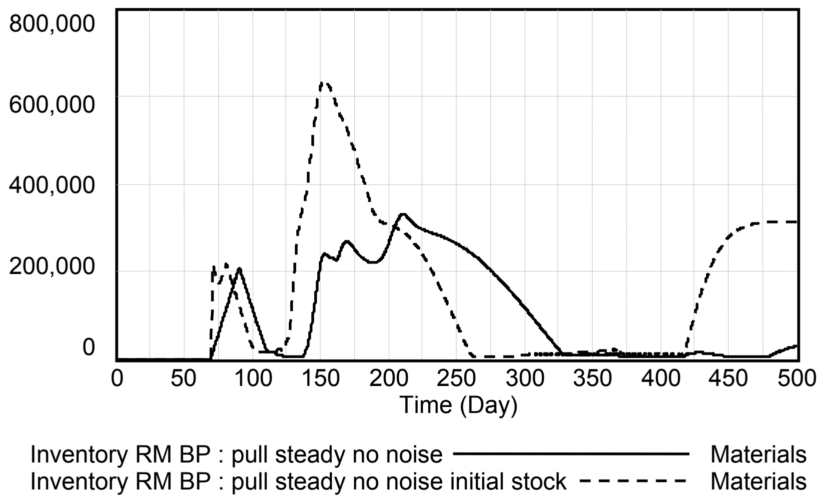

Figure D-23: Raw Materials Inventory at Board Printing: Planning the Product Introduction

The observations for the demand scenario with low noise are similar to those in the demand scenario with no noise. In the scenario with high noise, however, there is no reduction in efficiency but an improvement of average delivery performance to 38 percent. Nevertheless, this average level of delivery performance is lower than that achieved, for example, by the push-based planning approach with central planning (43 percent). When considering the time behaviour of delivery performance, however, the pull-based planning approach with initial stock achieves higher delivery performance in the initial phase of the product life cycle, which then declines during the product life cycle to a level that in the end is lower than that of the push approach. In contrast, delivery performance of the push approach falls more quickly initially and is therefore lower than that of the pull approach in the initial phase of the product life cycle. This is shown in Figure D-24. Therefore, if initial sales are prioritized over later sales it may make sense to use such an initialized pull-based planning approach when demand volatility is expected to be high. The pull-approach can therefore be a suitable planning approach when demand is highly volatile, as long as the initial product introduction phase is pre-planned through certain amounts of safety stock.

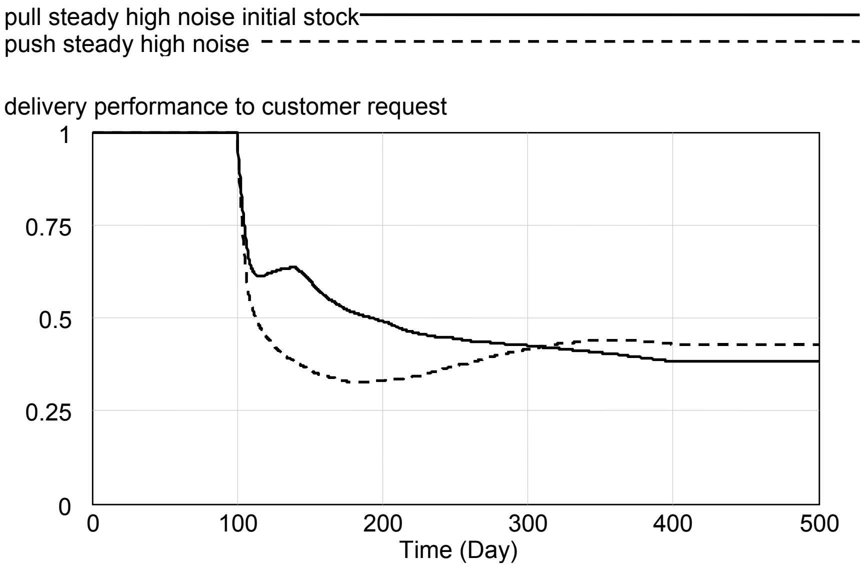

Figure D-24: Steady: Average Delivery Performance to Customer Request[513]

[513] The plotted values are the average values over 200 simulations with different noise seeds, i.e. the average values for 200 different demand patterns with variation in the noise that is added to the base product life cycle.

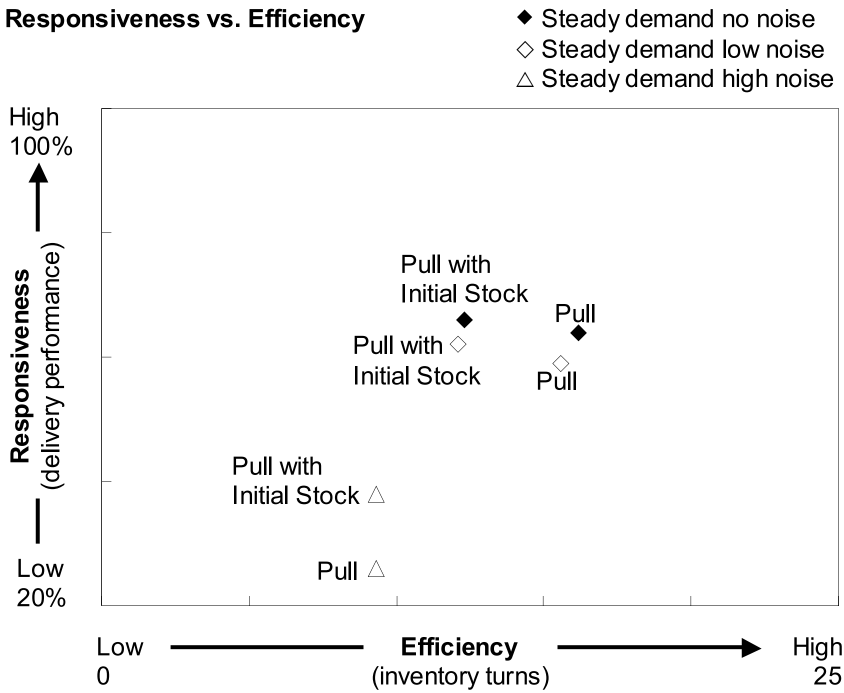

Figure D-25: Steady Demand: Planning the Product Introduction

Table D-5: Responsiveness vs. Efficiency: Planning for the Product Introduction (Steady Demand)

Steady Demand with Perfect Forecasts (incl. Initialisation Stock)

	Base Case		Low Noise[514]		High Noise[515]	
	Delivery Perf.	Inventory Turns	Delivery Perf.	Inventory Turns	Delivery Perf.	Inventory Turns
Pull with Initial Stock	66%	12.3	62%	12.1	38%	9.3
Pure Pull	64%	16.2	59%	15.6	26%	9.3

g. Overforecasting to Increase Responsiveness

In section D.I.1.b, it has been shown that in a scenario with no noise, inflating the forecast increased the responsiveness in the push-based planning approach with central planning and in the pull-based planning approach. While this result has theoretical value, it remains to be analysed how such an inflation of the initial forecasts affects the performance of the supply chains if demand is subject to random variation.

When demand is random and the initial forecast is 20 percent higher than average demand (10,000 units), delivery performance in both the low noise and the high noise scenario increases for all three planning approaches compared to the base case without such an overforecast.[516] This is shown in Figure D-26 and Figure D-27. In the demand scenario with low noise, the highest average delivery performance is achieved by the push approach (88 percent), and in the high noise scenario the planning approach with cascading forecasts achieves the highest delivery performance (51 percent). For efficiency, as measured by inventory turns, the situation is less clear. In the both the low noise and the high

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514 Mean values over 200 simulations with different noise seeds; standard deviation of white noise used for pink noise process is 0.1; this noise is added to the constant demand. Pink noise is first-order autocorrelated noise where the next random shock depends in part on the previous shocks.

515 Mean values over 200 simulations with different noise seeds; standard deviation of white noise used for pink noise process is 0.8.

516 The only case in which delivery performance is not improved is the demand scenario with no noise in the planning approach with cascading forecasts, where delivery performance decreases slightly from 80 percent to 77 percent.

noise scenario, the planning approach with cascading forecasts as well as the pull approach also achieve higher efficiency in the overforecast scenario compared to the case with perfect forecasts. In these cases, therefore, an inflation of the forecast leads to simultaneous improvements of both responsiveness and efficiency of the supply chain. The push-based planning approach with central planning, however, achieves a lower inventory turnover in the low noise scenario (15.5; 16.7 with perfect forecasts). In the high noise scenario, the push approach achieves the same inventory turnover compared to the case with perfect forecasts (11.3). This indicates that an overforecast in this planning approach leads to improved delivery performance, but can come at the expense of a reduction in efficiency.

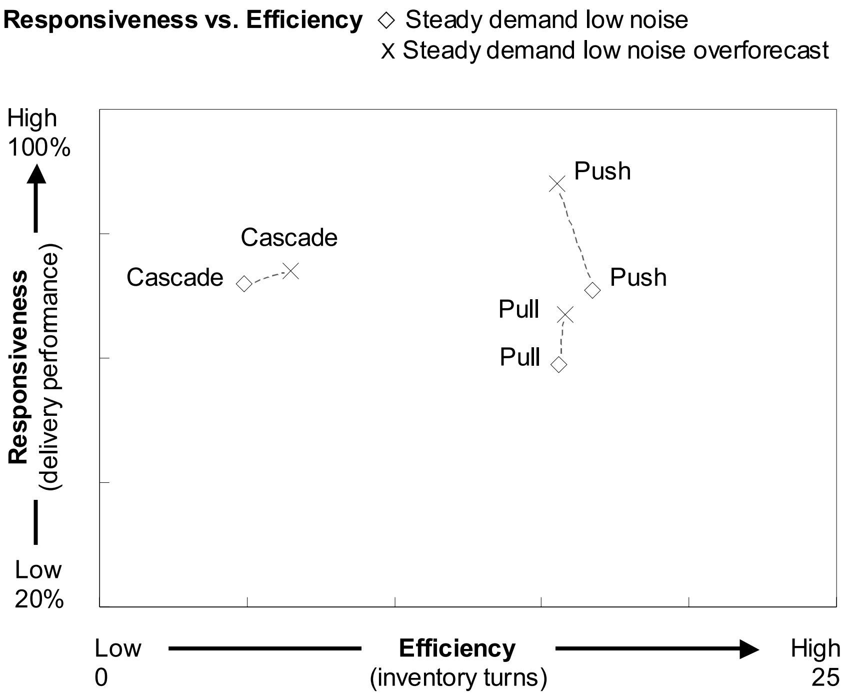

Figure D-26: Responsiveness vs. Efficiency: Overforecasting with Random Demand (Low Noise)

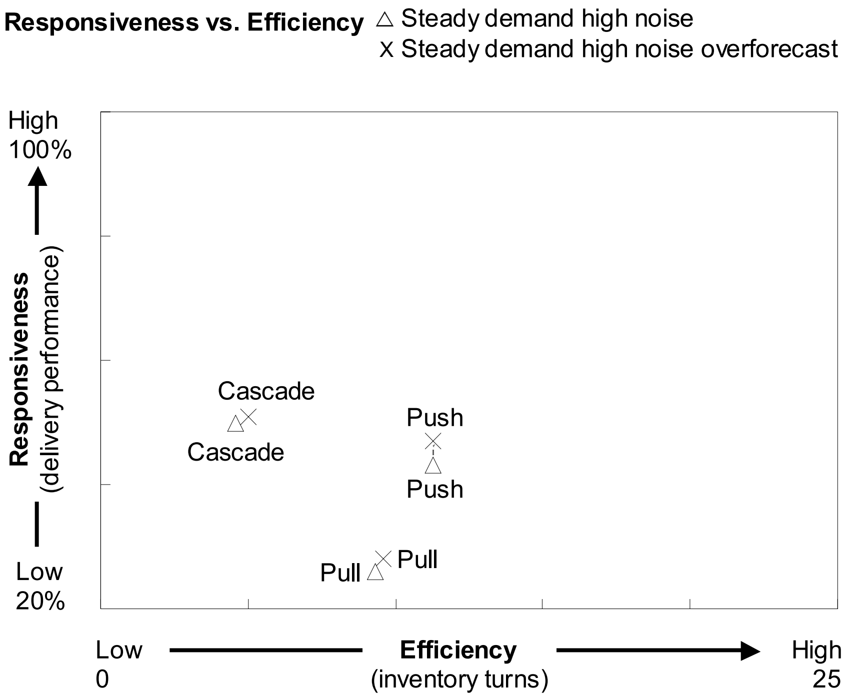

Figure D-27: Responsiveness vs. Efficiency: Overforecasting with Random Demand (High Noise)

Table D-6: Responsiveness vs. Efficiency: Overforecasting with Random Demand

Steady Demand with Inflated Forecasts (20 percent overforecast)

Planning Approach	Base Case		Low Noise[517]		High Noise[518]	
	Delivery Perf.	Inventory Turns	Delivery Perf.	Inventory Turns	Delivery Perf.	Inventory Turns
Cascade	77%	6.4	74%	6.5	51%	5.0
Push	99%	15.7	88%	15.5	47%	11.3
Pull	77%	16.9	67%	15.8	28%	9.6

2. *Scenario 2: Different Product Life Cycles*

In the preceding analyses the main challenges to supply chains represented in the simulation runs are demand uncertainty and demand volatility. As a second source of demand dynamics, in the next demand scenarios customer demand follows a standard product life cycle pattern, as shown in Figure D-28. It is important to consider such product life cycles because the conclusions drawn from simple demand patterns may lead to misjudgements regarding the required responsiveness, particularly if forecasts are inaccurate.[519] The product is introduced at day 100 and demand is back at zero in period 400, as in the other scenarios. Also, mean demand over the total product life cycle is 10,000 units per day, leading to cumulative sales of 3,000,000 units, which is comparable to the other scenarios. In the first product life cycle represented (PLC1), sales increase slowly at first, then faster, up to a peak of slightly over 17,000 units around pe-

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[517] Mean values over 200 simulations with different noise seeds; standard deviation of white noise used for pink noise process is 0.1; this noise is added to the constant demand. Pink noise is first-order autocorrelated noise where the next random shock depends in part on the previous shocks.

[518] Mean values over 200 simulations with different noise seeds; standard deviation of white noise used for pink noise process is 0.8.

[519] Cf. Francas, David *et al.*: Strategic Process Flexibility under Lifecycle Demand, 2006, Mannheim Business School: Department of Logistics, http://minner.bwl.uni-mannheim.de/hp/_files/forschung/reports/tr-2006-01.pdf, retrieved on: 5 September 2006, pp. 4–5 and p. 27.

riod 250 and then start to decline again. The other product life cycle represented (PLC2) is similar to that shown in Figure B-3, with an initial sales peak of close to 17,000 units on day 130 followed by a gradual downward trend in demand and a steep drop at the end of the product life cycle. The initial forecasts predict exactly these product life cycles.

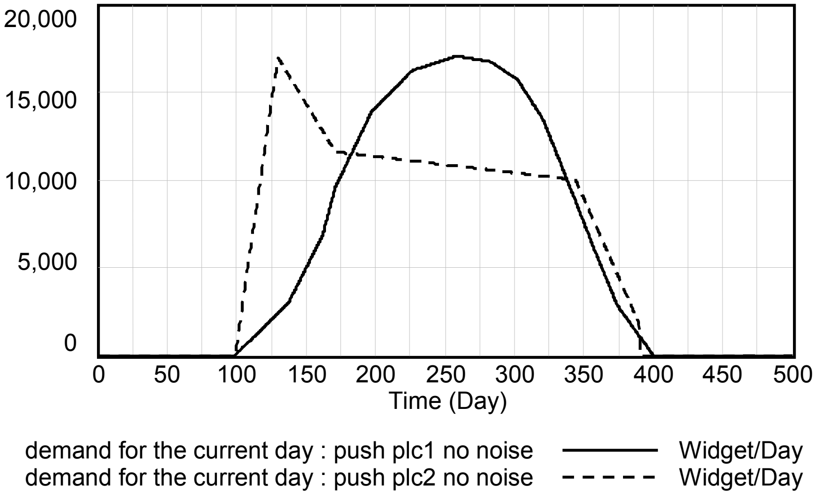

Figure D-28: Product Life Cycle 1 and 2: Demand Patterns

a. Effect of Random Demand Deviations

As in the previous demand scenarios, analyses are performed with demand that is not subject to random variations and that is therefore perfectly predictable in the base case with perfect forecasts, demand that is subject to a low degree of random variation with a standard deviation of the noise of 0.1 and with demand that is subject to a high degree of such variation with a standard deviation of the noise of 0.8.[520] The performance of the different planning approaches under these conditions is discussed in the following.

520 To provide an indication of the standard deviation of the actual demand patterns, for the first product life cycle, a sample low noise demand pattern has a standard deviation of 5,937 and a sample high noise demand pattern has a standard deviation of 9,450. For the second product life cycle, a sample low noise demand pattern has a standard deviation of 3,754 and a sample high noise demand pattern has a standard deviation of 8,180.

Product Life Cycle 1

For the first product life cycle, the performance of the planning approach that is based on cascading forecasts through the supply chain is similar to that in the previously analysed demand scenarios. This planning approach therefore seems to be relatively robust to changes in demand, as long as they are predicted correctly, but at the same time can only achieve a relatively low level of efficiency, lower than that of both other planning approaches in all scenarios. The first product life cycle modelled is best handled in terms of efficiency by the pull approach in the no noise and low noise scenario and by the push approach in the high noise scenario, while maximum responsiveness is achieved by the push approach in the no noise and low noise scenario and by the cascade approach in the high noise scenario. If average delivery performance is prioritized over efficiency, then the push approach is the optimal choice for this demand scenario as long as there is only a low level of demand volatility. The planning approach with cascading forecasts achieves the highest level of average delivery performance if demand volatility is high.

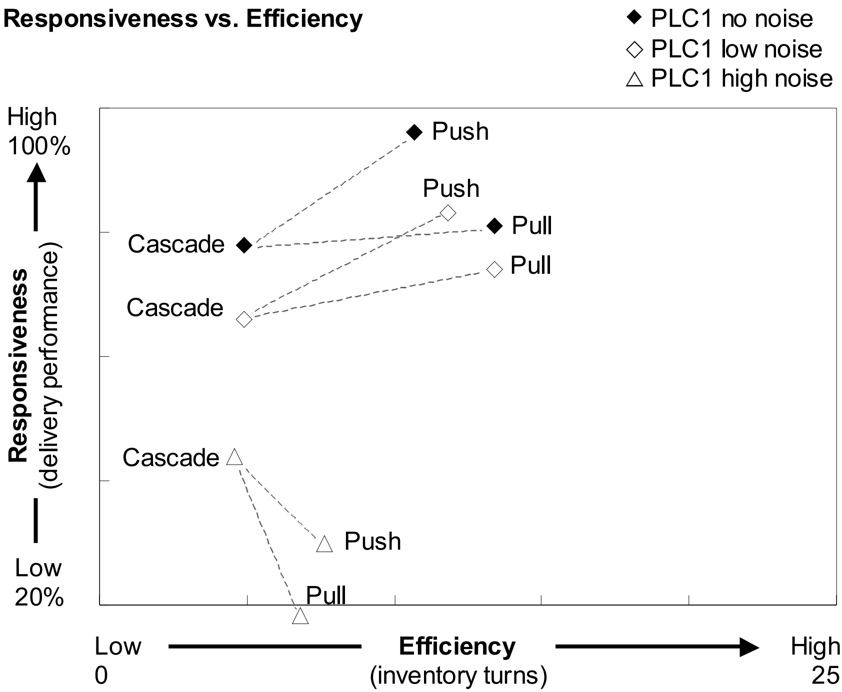

Figure D-29: PLC1: Sensitivity of Responsiveness and Efficiency to Randomness in the Demand Pattern

In a scenario with large demand fluctuations, achieving high delivery performance is intrinsically difficult due to the nonlinear delays of production and shipment processes at software flashing. As Figure D-29 shows for a sample simulation run in which the initial raw materials inventory at software flashing is high enough to cover the entire customer demand, matching customer demand for a given day with the receiving rate at the customer is difficult even if the products are in stock. In other words, the receiving rate at the customer in this ideal case with abundant demand is a smoothed flow in which the extreme values, such as demand spikes or zero demand, in customer demand for a given day are not matched to their full extent. Over 200 simulations with different noise seeds, average delivery performance is 75 percent, as units that are delivered late reduce delivery performance to values below 100 percent and such delays are to some degree unavoidable within the structure of the system.

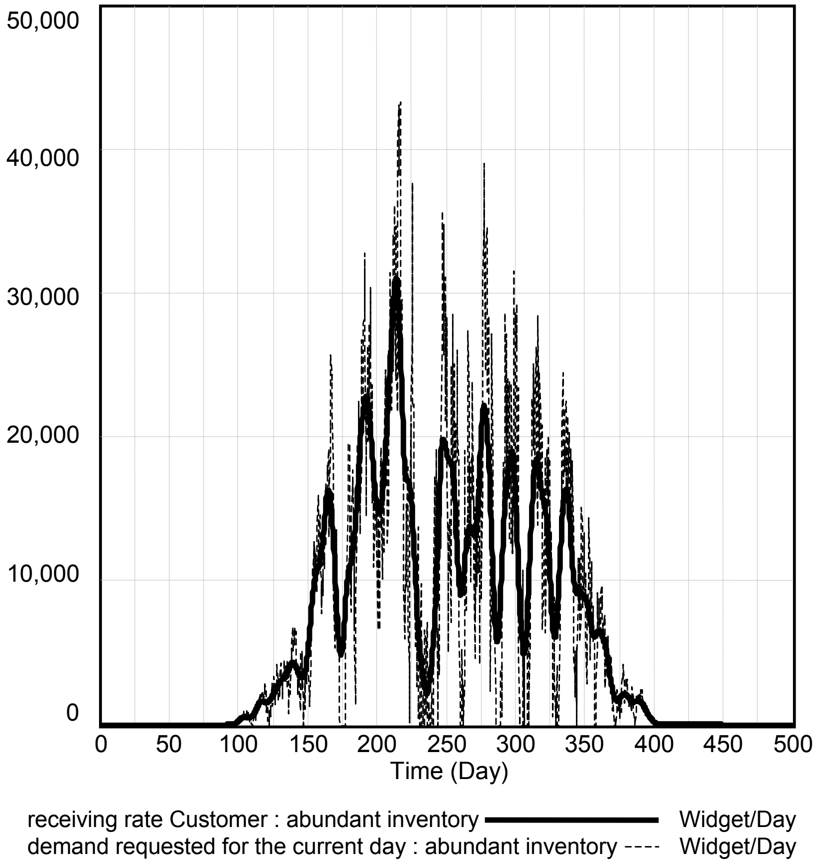

Figure D-30: Demand vs. Receiving Rate at the Customer: PLC1, Simulation with Abundant Inventory at Software Flashing

Table D-7: PLC1: Sensitivity of Responsiveness and Efficiency to Randomness in the Demand Pattern

Product Life Cycle 1

Planning Approach	Base Case		Low Noise[521]		High Noise[522]	
	Delivery Perf.	Inventory Turns	Delivery Perf.	Inventory Turns	Delivery Perf.	Inventory Turns
Cascade	78%	4.9	66%	4.6	44%	4.6
Push	96%	10.7	83%	11.8	30%	7.6
Pull	81%	13.4	74%	13.4	18%	6.8

Product Life Cycle 2

In the case of the product life cycle PLC2, the planning approach with cascading forecasts is again characterised by the lowest level of inventory turns, independent of the demand variation. The push approach achieves the highest level of delivery performance in the scenarios with no noise and low noise, but is outperformed by the planning approach with cascading forecasts in the scenario with high noise. The push-based planning approach achieves 86 percent delivery performance to customer request in the demand scenario without noise, 74 percent in the low noise scenario, and 41 percent in the high noise scenario. While the pull-based planning approach outperforms the other planning approaches on efficiency in the scenarios with low noise and no noise, its delivery performance is consistently lower than that achieved by the alternative planning approaches. Delivery performance in the pull-based planning approach is 60 percent in the no noise scenario, 56 percent in the low noise scenario, and 24 percent in the high noise scenario. This is shown in Figure D-31. Depending on the objectives of the organisation, the lack of planning for the initial strong increase in demand and consequential high initial backlog makes the pure pull-based planning approach unattractive. Both the push approach with central

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[521] Mean values over 200 simulations with different noise seeds; standard deviation of white noise used for pink noise process is 0.1; this noise is added to the demand.

[522] Mean values over 200 simulations with different noise seeds; standard deviation of white noise used for pink noise process is 0.8.

planning and that with cascading forecasts outperform the pull approach on delivery performance, with the approach with central planning being better than that with cascading forecasts on both performance dimensions except when demand volatility is high.

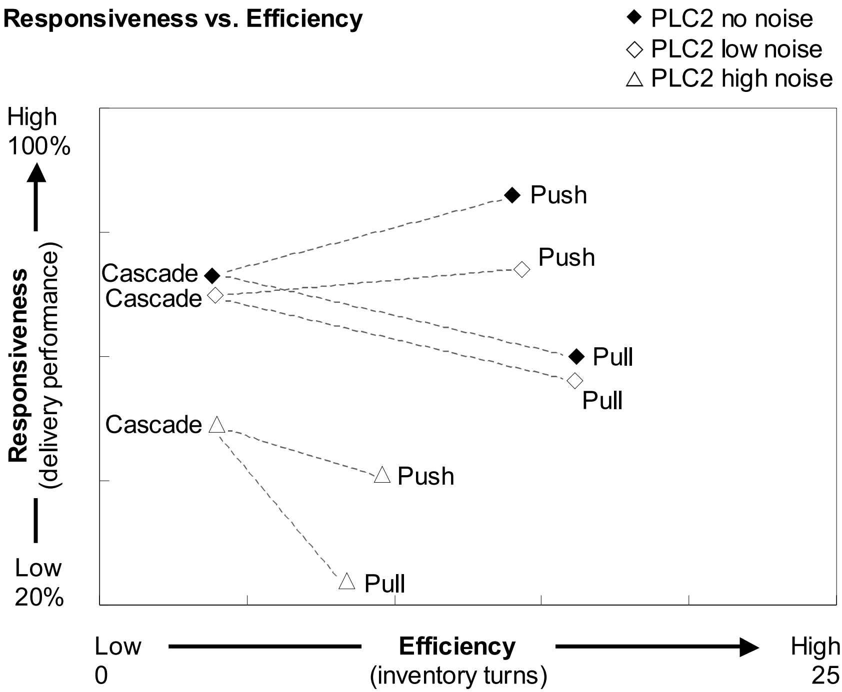

Figure D-31: PLC2: Sensitivity of Responsiveness and Efficiency to Randomness in the Demand Pattern

Table D-8: PLC2: Sensitivity of Responsiveness and Efficiency to Randomness in the Demand Pattern

		Product Life Cycle 2					
		Base Case		Low Noise[523]		High Noise[524]	
		Delivery Perf.	Inventory Turns	Delivery Perf.	Inventory Turns	Delivery Perf.	Inventory Turns
Planning Approach	Cascade	73%	3.8	70%	3.9	49%	4.0
	Push	86%	14.0	74%	14.3	41%	9.6
	Pull	60%	16.2	56%	16.1	24%	8.4

b. Planning the Product Introduction in the Pull Approach

As identified previously, a major problem of the pull-based approach is the low delivery performance in the initial phase of the product life cycle. In order to accommodate this difficulty, as in the previous analysis of a planned product introduction, the product introduction is planned for by initialising production before customer demand is observed. Such adjustments can also be expected in real pull-based planning systems, where the product introduction phase requires intervention by the planners. The initial stock of components ordered by software flashing and final assembly to cover for the first phase of the product life cycle is 100,000 units. This desired initial component inventory level is reduced to zero at day 120.

Product Life Cycle 1

As in the similar analyses for a mean demand of 10,000 units per day, the only scenario in which planning for the product introduction improves average delivery performance is the demand scenario with high demand uncertainty, as shown in Figure D-32. For the first product life cycle scenario with high demand uncertainty, introducing an initial stock at SWF and FAT increases aver-

523 Mean values over 200 simulations with different noise seeds; standard deviation of white noise used for pink noise process is 0.1; this noise is added to the demand.

524 Mean values over 200 simulations with different noise seeds; standard deviation of white noise used for pink noise process is 0.8.

age delivery performance to 26 percent (from 18 percent) and increases inventory turns to 7.3 (from 6.8). Therefore, in this case the introduction of such an initial stock is beneficial for responsiveness and efficiency.

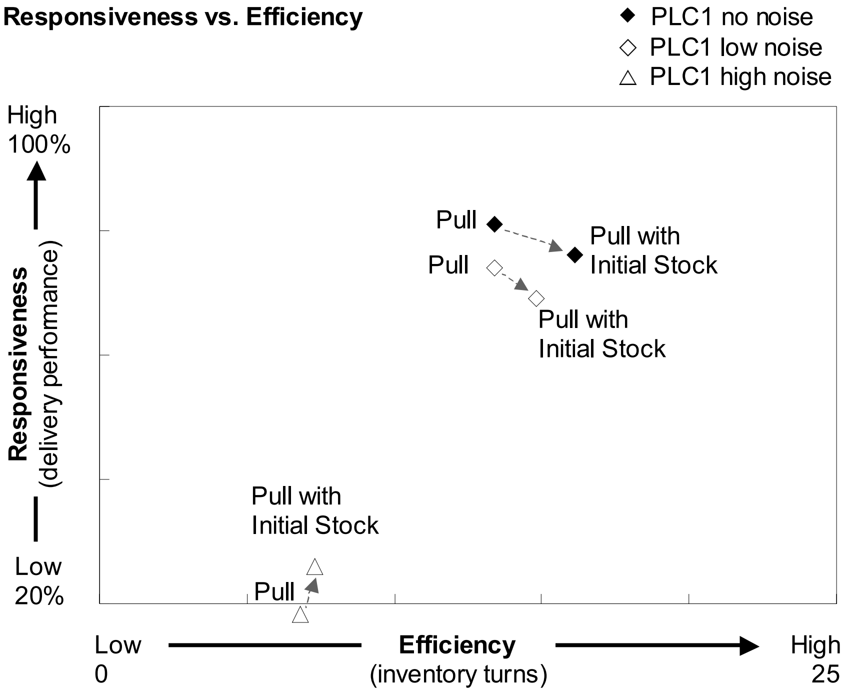

Figure D-32: PLC1: Improvements of Responsiveness and/or Efficiency through Introduction of Initial Stock in Pull Approach

When considering the time behaviour of average delivery performance, as in the previous analysis, the pull approach with initial stock is also superior to the push approach in the demand scenario with high noise, especially in the initial phase of the product life cycle. Even though average delivery performance of the pull approach with initial stock is lower than in the push approach, as shown in Figure D-33, the strong performance during the product introduction phase makes the pull approach the more attractive choice in this regard. Note that demand at the beginning of the first product life cycle is very low and only exceeds average demand of 10,000 units per day after day 175. This means that deviations from the customer request date for a small number of orders have a relatively large negative impact on delivery performance.

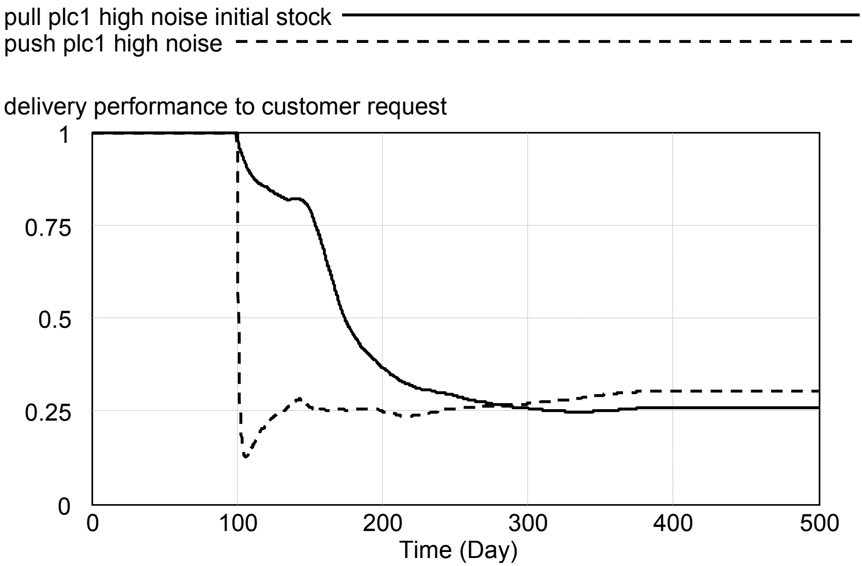

Figure D-33: PLC1: Average Delivery Performance to Customer Request[525]

Product Life Cycle 2

As for the first product life cycle, planning for the product introduction in the pull planning approach does not improve average delivery performance or inventory turns for the second product life cycle in the demand scenarios with no noise and low noise, respectively. In the demand scenario with high noise, the initial staging of the supply chain through pre-production of components and stocking these at software flashing and final assembly increases average delivery performance to 40 percent (from 24 percent) and increases inventory turns to 9.0 (from 8.4). The average value of delivery performance is almost equal to that in the push-based planning approach, with a difference of only one percentage point. Efficiency as measured by inventory turnover is slightly lower. However, as in the preceding discussion, the delivery performance in the initial phase of the product life cycle is higher in the pull planning approach.

This can also be seen in Figure D-35, which compares the backlog at software flashing in the push approaches and in the pull approach with initial stock. Also, it can be seen that the average backlog is higher in both push approaches, indicating that customers need to wait longer for their products than in the pull

[525] The plotted values are the average values over 200 simulations with different noise seeds, i.e. the average values for 200 different demand patterns with variation in the noise that is added to the base product life cycle.

approach with initial stock. This means that customers in a pull approach experience delivery delays slightly more often than in a push approach, i.e. more orders are delayed, but these delays are significantly shorter. With average sales of 10,000 units per day, the backlog at software flashing is four days of demand at the most, while in the push approaches with central planning and cascading forecasts the backlog can reach 13 days of demand at the most. These are average values over all simulations, which means that for a specific product these values could be even higher.

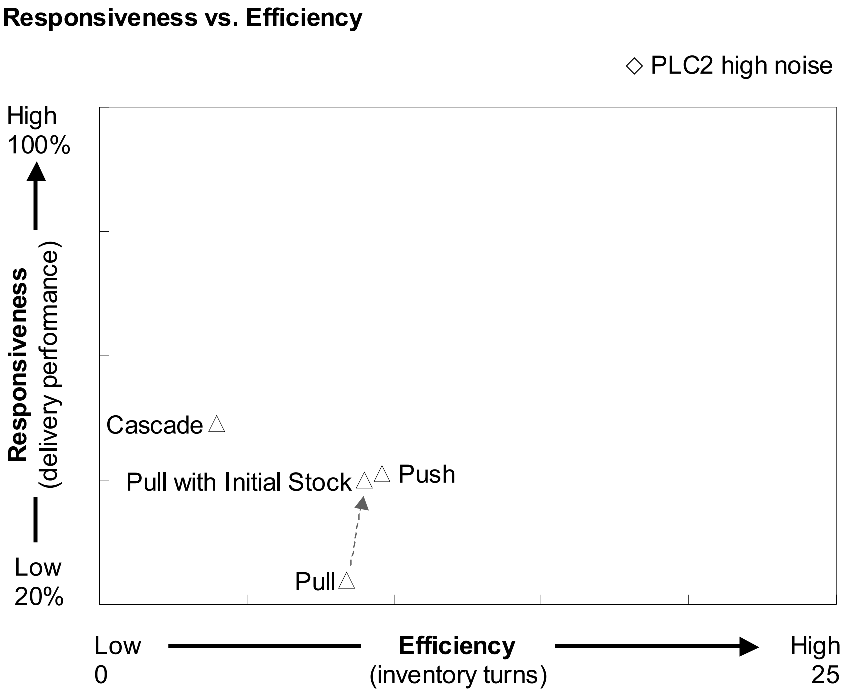

Figure D-34: PLC2: Improvements of Responsiveness and/or Efficiency through Introduction of Initial Stock in Pull Approach

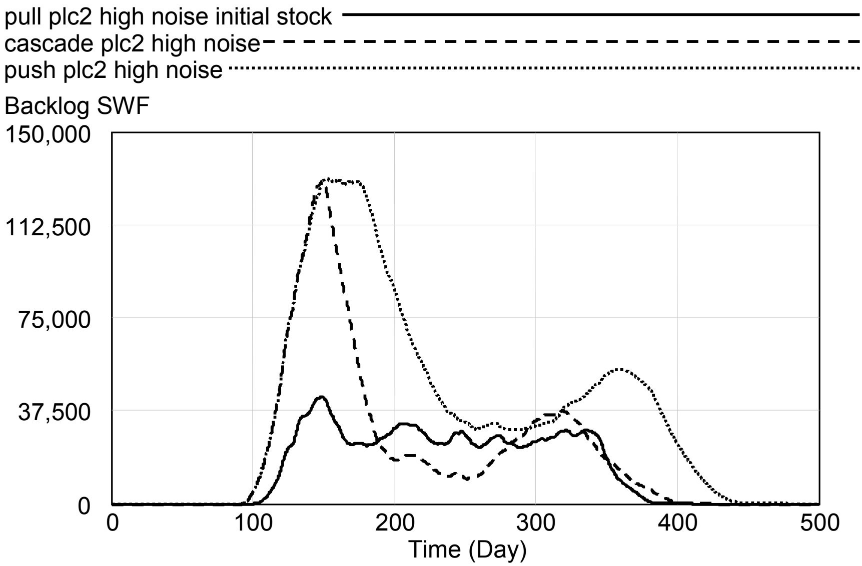

Figure D-35: PLC2: Average Backlog at Software Flashing[526]

The stability of the forecasts provided to the component suppliers in the pull approach with initial staging of the supply chain is also high, which is beneficial for the supply chain. This can be seen when comparing the forecasts sent to board printing in the pull-based and push-based planning approach in Figure D-36 to the initial forecast corresponding to the expected product life cycle.

526 The plotted values are the average values over 200 simulations with different noise seeds, i.e. the average values for 200 different demand patterns with variation in the noise that is added to the base product life cycle.

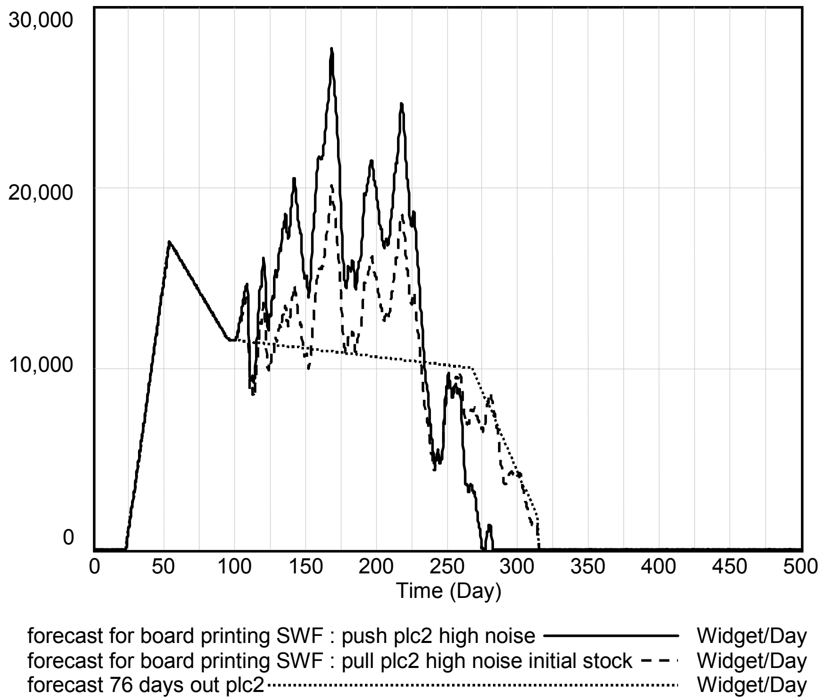

Figure D-36: PLC2: Forecast for Board Printing (example, not averaged)

A major drawback of the pull planning approach, however, is the large degree of variation in the production rate at the suppliers, which is caused by the large variability in material orders by final assembly. As can be seen in Figure D-37 for a sample simulation run, production of components in the push approach with central planning, for example, follows the actual product life cycle relatively closely, even though production may be ramped up to the full capacity at board printing. This eliminates a large degree of the variation of end customer demand, which is beneficial to the efficiency of the supply chain as high and relatively stable capacity utilization is a success factor for efficient processes at board printing. In contrast, the production rate at board printing in the pull-based planning approach experiences large fluctuations with subsequent periods of both production at the capacity limit as well as production at zero. This is caused by the direct transmission of demand data through the supply chain, where relatively large deviations in demand cause relatively large deviations in material orders, even if these are only issued in large batches. Such large variations can pose a major challenge to the production planners at the suppliers, as it may be difficult to adjust production output upwards and downwards within these relatively short time intervals. Since the equipment is costly, the companies have a strong incentive to use it for producing other products, which may require changes to the set-up of the machines. In many board printing facilities, up to 50 percent of effective capacity is not utilized because of such set-ups.[527] Such fluctuations in production volume have the potential to reduce quality and increase costs.

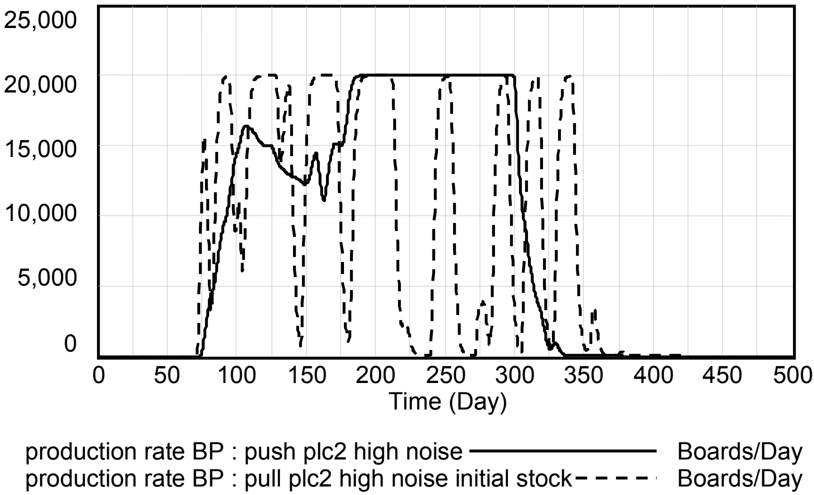

Figure D-37: PLC2: Production at Board Printing (example, not averaged)

c. Comparing the Performance of Different Forecasts

Since the initial forecasts are rarely perfect, several analyses are conducted to identify the reaction of the supply chain system to an incorrect forecast.

Product Life Cycle 1

Three different forecasts are used for the same demand pattern in order to analyse the sensitivity of the supply chain performance to incorrect forecasts. In the first analysis, demand follows the first product life cycle pattern (see Figure D-28) with no random noise added to the demand pattern. Three different initial forecasts are analysed, namely (1) a perfect forecast, forecasting demand exactly as in the first product life cycle pattern; (2) a steady forecast with 10,000 units

[527] Cf. Beckman and Sinha: Conducting Academic Research with an Industry Focus, p. 120 and Trovinger and Bohn: Setup Time Reduction for Electronics Assembly, p. 205.

per day and (3) product life cycle 2 as a forecast for product life cycle 1. The adjustments to these inaccurate forecasts are dependent on the decision-making policies in the supply chain and a major determinant of the supply chain performance.

With both the steady demand forecast and the wrong product life cycle forecast, the planning approach with cascading forecasts outperforms the other planning approaches on delivery performance and operates at the lowest level of efficiency. However, all planning approaches achieve only a very low level of delivery performance of between 12 percent and 36 percent.

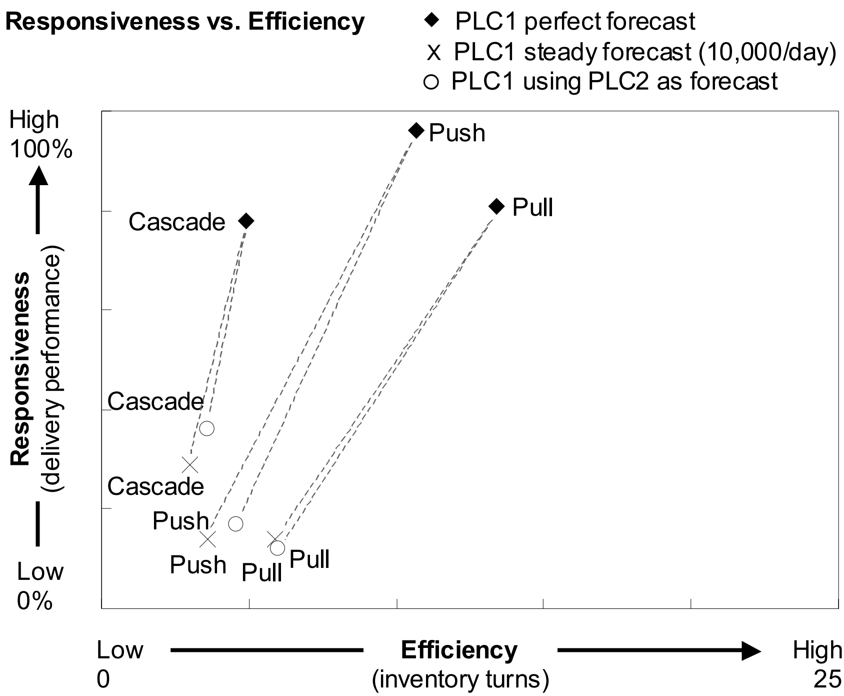

Figure D-38: Responsiveness vs. Efficiency: PLC1, Different Forecasts, No Noise[528]

[528] Note that the scale of the y-axis was adjusted compared to previous analysis, since the worst delivery performance in this analysis is below 20 percent, which was the lower limit in the other diagrams.

Product Life Cycle 2

For the second product life cycle, the forecasts used are (1) a perfect forecast, forecasting demand exactly as in the second product life cycle pattern; (2) a steady forecast with 10,000 units per day and (3) product life cycle 1 as a forecast for product life cycle 2. At first, the demand pattern follows exactly the second product life cycle pattern, while in a second analysis demand variability is added to analyse its impact.

In the no noise scenario, while the perfect forecast consistently outperforms the alternative forecasts, as expected, the performance differences are not as large as in the previous analysis of the first product life cycle. Cascade consistently outperforms the other planning approaches on delivery performance, while the pull-based planning approach is the most efficient. The push approach with central planning does not outperform the other planning approaches on both dimensions, but provides a middle ground. In this scenario, the steady forecast provides relatively good results, with the push-based planning approach with central planning deviating the most in performance from the perfect forecast scenario.

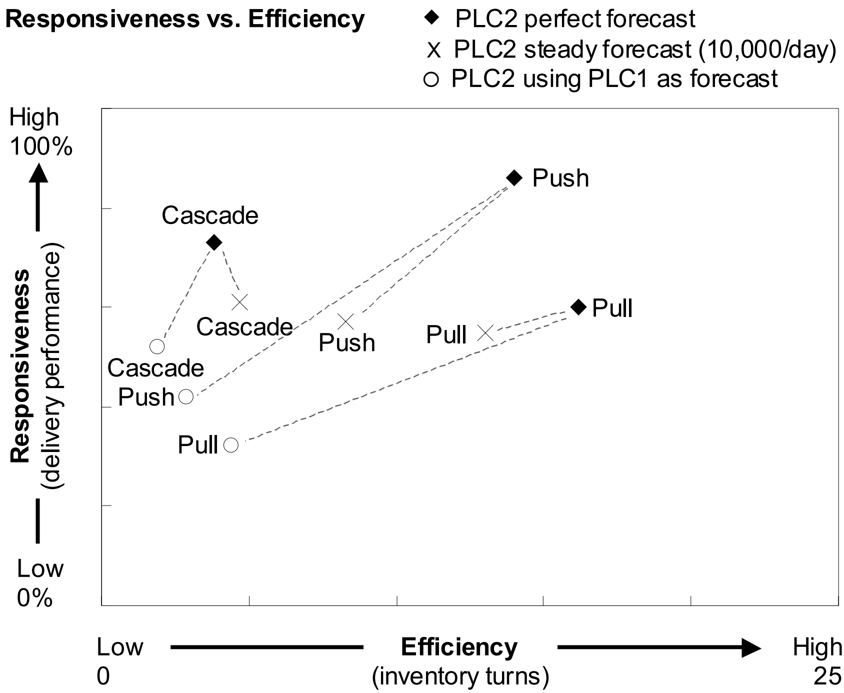

Figure D-39: Responsiveness vs. Efficiency: PLC2, Different Forecasts, No Noise

When considering high demand variability in the demand pattern, the planning approach with cascading forecasts performs almost equally on both performance measures in the steady forecast case compared to the perfect forecast. If responsiveness is the primary objective, then the planning approach with cascading forecasts achieves the highest performance using any of the three simulated forecasts.

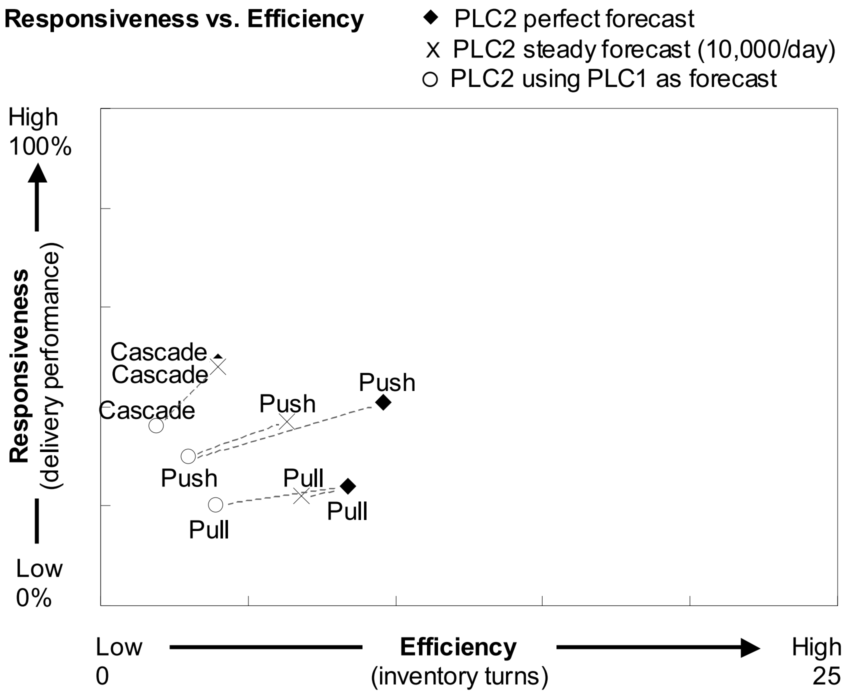

Figure D-40: Responsiveness vs. Efficiency: PLC2, Different Forecasts, High Noise

d. Overforecasting to Increase Responsiveness

In the demand scenarios where sales follow typical product life cycles, the observations about the impact of overforecasting on efficiency and responsiveness are similar to those made in the previous analysis with demand of 10,000 units per day. For example, consider an analysis of the demand scenario where sales follow the second product life cycle and demand is subject to large variations. In the planning approach with cascading forecasts, an overforecast improves delivery performance from 49 percent to 52 percent and improves inventory turns from 4.0 to 4.4. Similarly, in the push approach with central planning, overforecasting by 20 percent increases delivery performance from 41 percent to 47 percent. At the same time inventory turnover increases from 9.6 to 9.9. In the pull-based planning approach without an initial stock to plan for the product introduction, overforecasting increases delivery performance from 24 percent to 26 percent and simultaneously increases inventory turns from 8.4 to 8.9. In the pull-based planning approach with initial stock levels overforecasting has a smaller impact. While average delivery performance is increased from 40 percent to 41 percent when the forecast is inflated by 20 percent, the efficiency increases from 9.0 inventory turns to 9.1 inventory turns. Similar observations can also be made for the first product life cycle, indicating that in each of the different demand scenarios analysed overforecasting is useful, as delivery performance as well as efficiency can be improved compared to the scenarios with perfect forecasts. In all planning approaches, therefore, it is sensible to overestimate the forecast slightly, as the consequences are typically positive on both performance dimensions, responsiveness and efficiency. In contrast, an underestimation of demand would have undesirable consequences.

II. Simulating Disruptions and Response Options

In addition to volatility in demand, disturbances to supply chains can also be disruptions in upstream supply. For example, the fire that broke out in a Philips plant in Albuquerque, New Mexico, in 2000 because of lightning disrupted the supply of radio-frequency chips for months.[529] The fire lasted ten minutes and affected only a small production cell, but the consequences were more dramatic, as one of the clean rooms, an area in which very small amounts of dust can cause major damage, was affected.[530] One customer of the chips produced in this plant, Nokia, was able to switch production to other suppliers almost immediately by demanding the chips from other Philips plants, redesigning the chips so they could be produced elsewhere and convincing Japanese and U.S. suppliers to supply the chips to them. In contrast, Ericsson employed a single-sourcing policy and as a consequence faced disrupted production for months, causing lost sales of US$400 million, which finally resulted in the decision to exit handset manufacturing completely and outsource production.[531] Other examples of risk sources that can affect supply chains are natural disasters, such as hurricanes, and diseases, such as the foot-and-mouth disease which, for example, affected luxury car manufacturers due to lack of leather supply.[532]

In the following, by simulating a supply disruption at board printing during which production of boards ceases for ten days, between day 150 and 159, the capability of the three different planning approaches to react to such a disruption

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[529] Cf. Chopra and Sodhi: Managing Risk To Avoid Supply-Chain Breakdown, p. 53 and Morais: Damn the torpedoes, p. 2.

[530] Cf. Norrmann, Andreas and Uld Jansson: Ericsson's proactive supply chain risk management approach after a serious sub-supplier accident, in: International Journal of Physical Distribution & Logistics Management, Vol. 34 (2004), No. 5, p. 441.

[531] Cf. Chopra and Sodhi: Managing Risk To Avoid Supply-Chain Breakdown, p. 53; Norrmann and Jansson: Ericsson's proactive supply chain risk management approach after a serious sub-supplier accident, pp. 441–442, and Morais: Damn the torpedoes, p. 2.

[532] Cf. Norrmann and Jansson: Ericsson's proactive supply chain risk management approach after a serious sub-supplier accident, p. 435.

is analysed for the demand scenario with steady demand and for the two product life cycles. The simulated disruption is not as large as the Albuquerque incident, which makes it more appropriate for an analysis within the fixed decision rules of the supply chain simulation model. A longer supply chain disruption would most likely cause actions that overrule existing policies, such as those that are today in place at Ericsson as a reaction to the Albuquerque incident, which include a large amount of interaction and cooperation with suppliers when handling such incidents.[533]

1. Scenario 1: Steady Demand

In the case of steady demand with no noise, the planning approach with cascading forecasts achieves the same level of responsiveness and efficiency in the scenario with the supply disruption as in the scenario without such a disruption, as shown in Figure D-41. This can be explained by the high amount of inventory held throughout the supply chain that can buffer the supply disruption. The pull planning approach achieves lower efficiency and responsiveness, which is in line with expectations that a supply disruption will cause backlog situations as well as adjustments to the forecast and emergency orders that lead to higher inventory levels at the end of the life cycle. Nevertheless, the push-based planning approach with central planning achieves slightly higher responsiveness and slightly higher efficiency compared to the scenario without the supply disruptions. The explanation for this observation is that the level of raw materials inventory at software flashing is higher than the desired level when the supply disruption occurs. Therefore, a backlog situation following the disruption is avoided. At the same time, the raw materials inventory at software flashing is depleted more quickly following the supply disruption, causing an upward adjustment to the forecasts for the suppliers. This upward adjustment allows a quicker reduction of the backlog that occurs at the end of the product life cycle, allowing a slight increase in overall responsiveness (see Figure D-42, Figure D-43 and Figure D-44).

[533] Cf. Norrmann and Jansson: Ericsson's proactive supply chain risk management approach after a serious sub-supplier accident, p. 453.

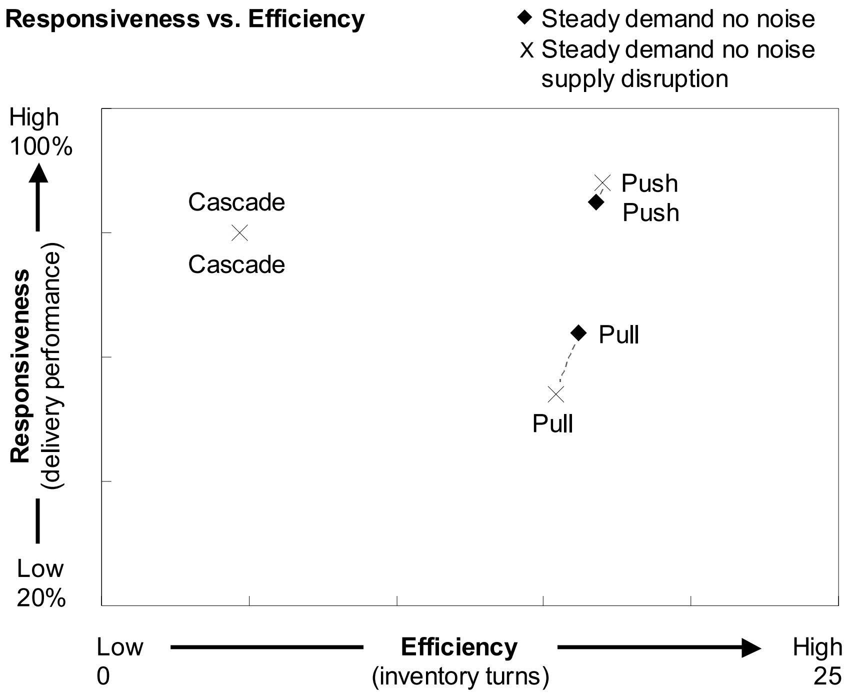
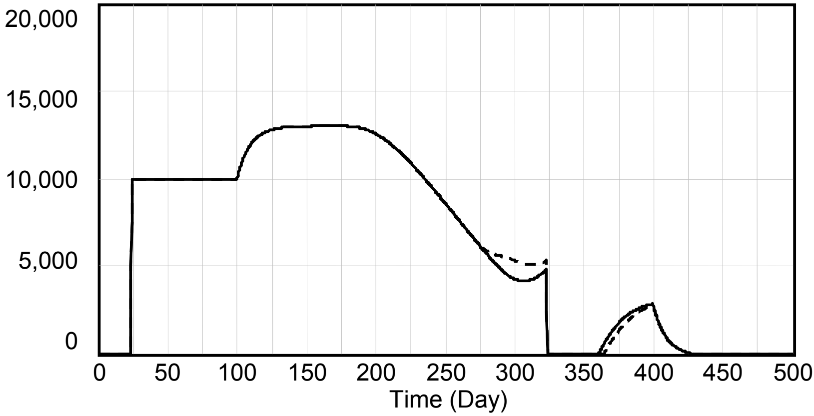
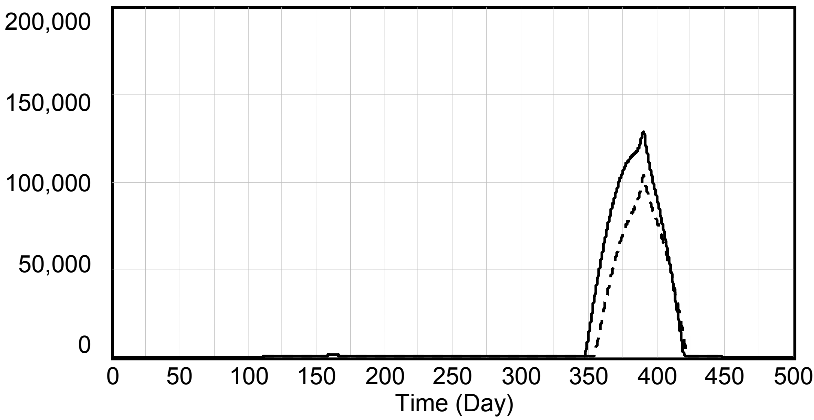


Figure D-41: Responsiveness vs. Efficiency: Supply Disruption, Steady Demand, No Noise



forecast for board printing SWF : push steady no noise Widgets/Day
forecast for board printing SWF : push steady no noisedisrupt Widgets/Day

Figure D-42: Supply Disruption: forecast for board printing SWF



Backlog SWF : push steady no noise Widgets
Backlog SWF : push steady no noise disrupt Widgets

Figure D-43: Supply Disruption: Backlog at Software Flashing

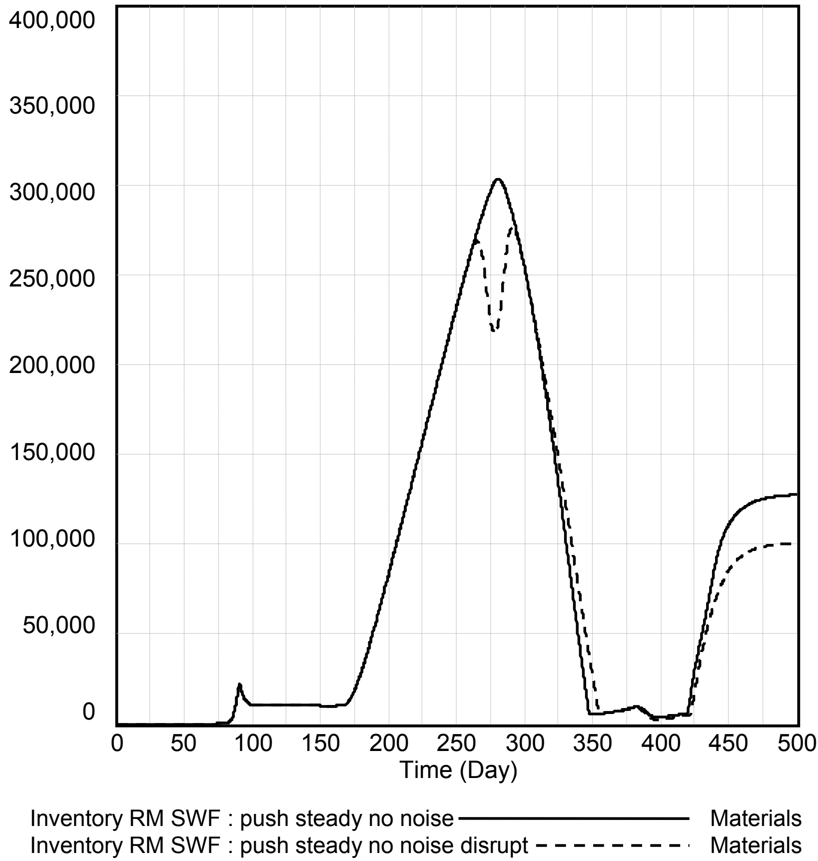


Figure D-44: Supply Disruption: Raw Materials Inventory at Software Flashing

The same behaviour can be observed in the demand scenario with low noise, as depicted in Figure D-45 below. Again, the push-based planning approach outperforms the other two planning approaches on both responsiveness and efficiency.

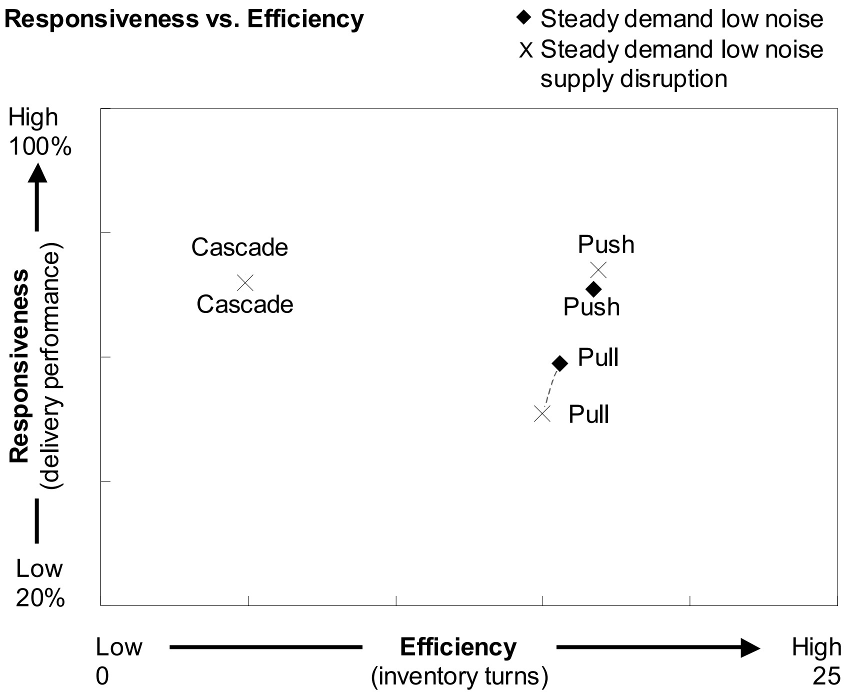


Figure D-45: Responsiveness vs. Efficiency: Supply Disruption, Steady Demand, Low Noise

In the scenario with high noise, the supply disruption has a smaller impact on the supply chain performance. This can be explained by the higher level of demand volatility and resulting adjustments, such as, for example, increased safety stocks in the pull-based planning approach. The planning approach with cascading forecasts suffers no reduction in efficiency or responsiveness, while both the push approach with central planning and the pull-based planning approach are faced with a minor reduction in delivery performance and efficiency compared to the case without the supply chain disruption.

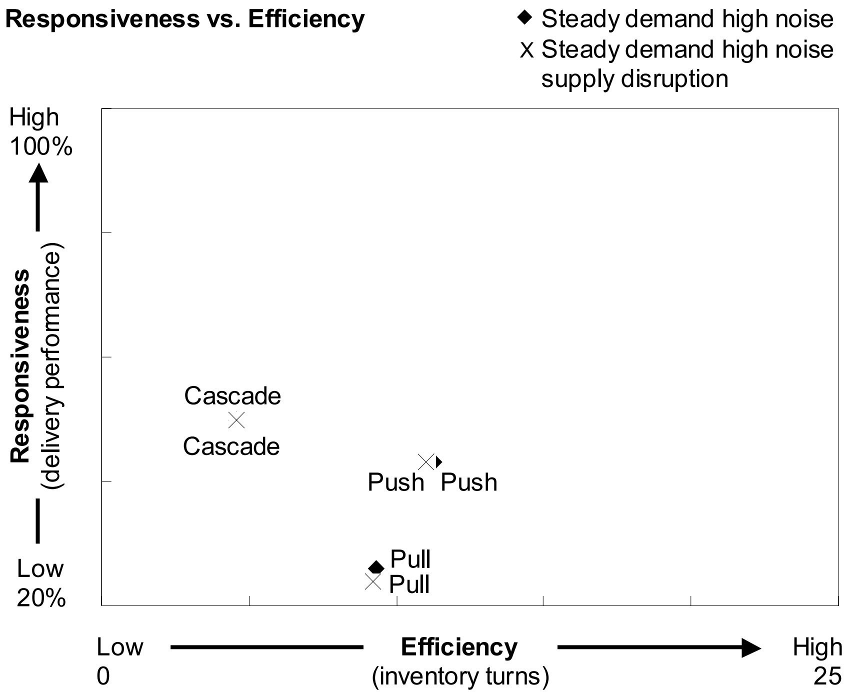


Figure D-46: Responsiveness vs. Efficiency: Supply Disruption, Steady Demand, High Noise

Table D-9: Steady Demand: Sensitivity of Responsiveness and Efficiency to Supply Disruptions

	Steady Demand with Perfect Forecasts – With Supply Disruption					
	No Noise		Low Noise[534]		High Noise[535]	
Planning Approach	Delivery Perf.	Inventory Turns	Delivery Perf.	Inventory Turns	Delivery Perf.	Inventory Turns
Cascade	80%	4.7	72%	4.9	50%	4.6
Push	88%	17.0	74%	16.9	43%	11.0
Pull	54%	15.4	51%	15.0	24%	9.2

2. *Scenario 2: Different Product Life Cycles*

For both simulated product life cycles, a disruption at board printing reduces delivery performance only in the pull-based planning approach and to a small extend in the push approach with central planning. The performance of the planning approach with cascading forecasts is not influenced by such a disruption, again due to the relatively high level of inventory throughout the supply chain. This means that in the planning approach with cascading forecasts a ten day disruption in the production of boards does not have a negative effect on the performance of the supply chain as measured by delivery performance and inventory turns. In the scenario with high demand volatility, the situation is similar. In these scenarios, however, the impact of the supply disruption on delivery performance is even smaller than in the scenarios without demand volatility, which can be explained by larger safety stock levels in the pull-based planning approach and lower initial levels of delivery performance in all planning approaches (see also Figure D-47). All simulated planning approaches are therefore capable of handling the simulated disruption to board printing without significant performance reductions.

[534] Mean values over 200 simulations with different noise seeds; standard deviation of white noise used for pink noise process is 0.1; this noise is added to the constant demand.

[535] Mean values over 200 simulations with different noise seeds; standard deviation of white noise used for pink noise process is 0.8.

Table D-10: PLC1: Sensitivity of Responsiveness and Efficiency to Supply Disruptions

Product Life Cycle 1 – With Supply Disruption						
	No Noise		Low Noise[536]		High Noise[537]	
Planning Approach	Delivery Perf.	Inventory Turns	Delivery Perf.	Inventory Turns	Delivery Perf.	Inventory Turns
Cascade	78%	4.9	67%	4.9	43%	4.6
Push	96%	10.2	78%	10.3	27%	6.9
Pull	73%	13.8	67%	13.5	17%	6.7

Table D-11: PLC2: Sensitivity of Responsiveness and Efficiency to Supply Disruptions

Product Life Cycle 2 – With Supply Disruption						
	No Noise		Low Noise[538]		High Noise[539]	
Planning Approach	Delivery Perf.	Inventory Turns	Delivery Perf.	Inventory Turns	Delivery Perf.	Inventory Turns
Cascade	73%	3.8	70%	3.9	49%	4.0
Push	88%	14.6	76%	14.8	41%	9.4
Pull	50%	14.7	47%	15.1	22%	8.1

[536] Mean values over 200 simulations with different noise seeds; standard deviation of white noise used for pink noise process is 0.1; this noise is added to the demand.

[537] Mean values over 200 simulations with different noise seeds; standard deviation of white noise used for pink noise process is 0.8.

[538] Mean values over 200 simulations with different noise seeds; standard deviation of white noise used for pink noise process is 0.1; this noise is added to the demand.

[539] Mean values over 200 simulations with different noise seeds; standard deviation of white noise used for pink noise process is 0.8.

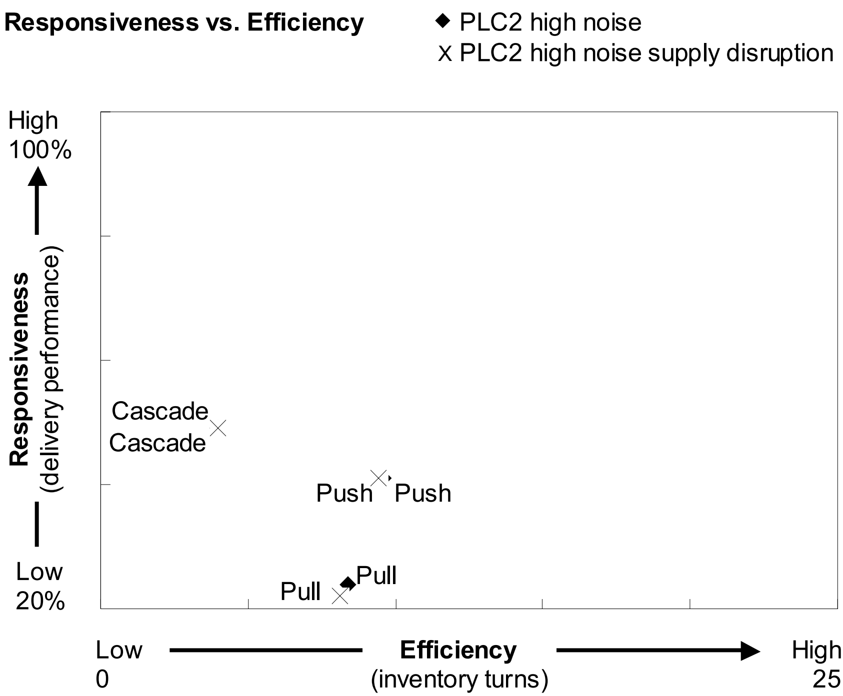


Figure D-47: Responsiveness vs. Efficiency: Supply Disruption, PLC2, High Noise

III. Achieving Responsiveness and Efficiency over the Product Life Cycle

The push-based planning approach with cascading forecasts is currently predominant in the high-tech electronics industry. The preceding analyses have shown that independent of the demand pattern the supply chain can be redesigned such that both responsiveness and efficiency are improved. When operating at the same level of efficiency, both the push approach with central planning and the pull approach enable levels of delivery performance and efficiency that are higher than in the planning approach with cascading forecasts. In addition, in the demand scenarios with high volatility planning for the product introduction in the pull approach through the initial staging of components in the supply chain increases delivery performance even further, in particular in the introduction phase of the product life cycle.

A detailed analysis of the results shows that the efficiency of the planning approach with cascading forecasts is relatively low compared to the other planning approaches. In general, both the push approach with central planning and the pull approach outperform planning with cascading forecasts regarding inventory turns. However, the responsiveness when planning with cascading forecasts is relatively higher in most scenarios, particularly if demand is subject to random noise. This is due to the buffer stocks at all nodes of the supply chain. Nevertheless, the responsiveness in this planning approach in all simulations across all demand scenarios never exceeds 90 percent.

Achieving improved responsiveness and efficiency at the same time is difficult in this approach because of uncoordinated decision making policies at the supply chain nodes and lack of transparency in the system. Overforecasting, for example, in this planning approach can improve responsiveness and efficiency in some demand scenarios. However, in other scenarios, like those without noise, overforecasting can reduce average delivery performance because of resulting adjustments by the supply chain members and consequential backlog build-ups. Such overforecasting is therefore not recommendable in such a planning system. The reason for companies to rely on a planning system with cascading forecasts is mostly that these structures are already in place and that it is difficult to improve the information flows in the supply chain system because of the high degree of fragmentation of the supply chain.

The push-based planning approach with central planning performs well on both responsiveness and efficiency. It outperforms planning with cascading forecasts on efficiency in all scenarios and on responsiveness in all *no noise*- and *low noise*-scenarios. In the *high noise*-scenarios, the push-based planning approach with central planning achieves the highest efficiency, but the planning approach with cascading forecasts achieves the highest delivery performance.

Pull-based planning in its pure form, i.e. without a plan for the product introduction phase, outperforms the push approach with central planning on efficiency in the two product life cycle scenarios (*no noise* and *low noise* only). This lower level of average inventory in the system, combined with the other characteristics of this planning approach, are responsible for the relatively low level of delivery performance achieved. In terms of delivery performance, the pull-based approach in the base case performs worst in most scenarios. This also causes the highest amount of costly emergency orders. However, when planning for the product introduction by introducing an additional initial stock during the product introduction phase, average delivery performance can be significantly improved in demand scenarios with high demand uncertainty. Furthermore, efficiency as measured by the inventory turn rate is only slightly lower than in the push approach.

The decisions taken to achieve appropriate supply chain performance on both dimensions, efficiency and responsiveness, need to take into consideration aspects related to the product life cycle. These considerations are related to the discussion of the challenges to supply chains in the high-tech industry as well as to the simulation results. In particular, sales in the initial phase of the product life cycle are important, as higher prices can be charged and product life cycles are often very short. Also, the actions of competitors are unpredictable. Therefore, high delivery performance is especially desirable during the initial phase of the product life cycle. For the typical product life cycle of a high-tech product as modelled in the simulations, the time behaviour of delivery performance over time varies significantly among the different planning approaches. As an example Figure D-48 shows delivery performance for the demand scenario of the product life cycle PLC2 with high noise. Both push-based planning approaches achieve delivery performance at the beginning of the product life cycle that ranges between 100 percent and around 50 percent. The pull-based planning approach in its pure form is unable to deliver on time from the beginning of the product life cycle – the first unit is delivered on time around day 250 – and therefore a large amount of sales are potentially lost as customers move to competitors.

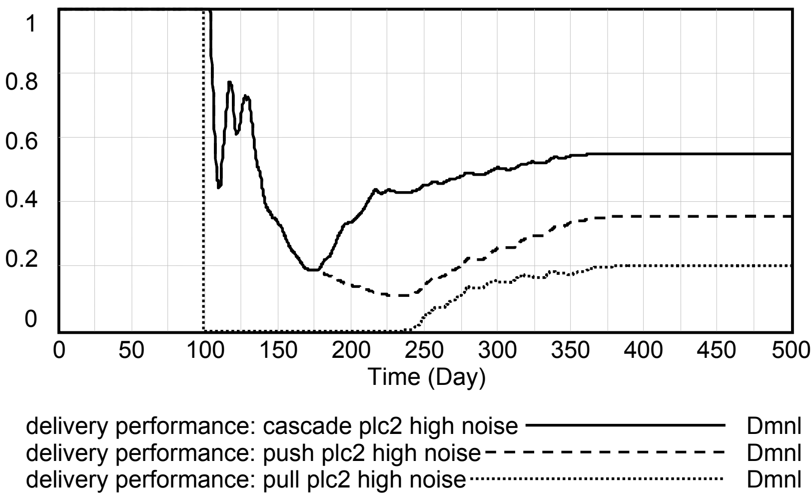


Figure D-48: Delivery Performance to Customer Request (example, not averaged)

It has been shown that in such a demand scenario planning for the product introduction by producing a certain amount of products before customer demand is first observed can increase delivery performance with only a small reduction in efficiency. As Figure D-49 illustrates for a sample simulation of the PLC2 demand scenario with high demand volatility, such an initial stock enables the achievement of an average delivery performance that is similar to that achieved when planning with cascading forecasts. However, as shown in Figure D-35, page 205, the backlog in the pull approach is on average lower than in the other two planning approaches, indicating that the delivery delays faced by the customers are also shorter in the pull approach. While the planning approach with cascading forecasts enables the highest average level of delivery performance in this demand scenario when compared to the other planning approaches, the performance of the pull approach is superior in the initial phase of the product life cycle and also achieves lower backlog accumulations. In this example with initial stock, the range of delivery performance is between 75 percent and 100 percent in the first weeks after the product introduction. At the same time a level of inventory turns is achieved on average that is better than in the planning approach with cascading forecasts.[540]

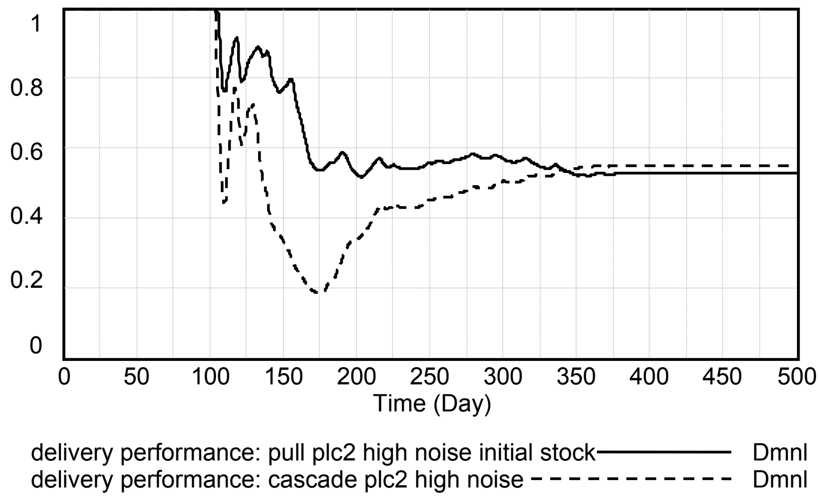


Figure D-49: Delivery Performance to Customer Request (example, not averaged)

In addition, both the push approach and the pull approach with initial staging of the supply chain are able to react to supply chain disruptions in a meaningful way, such that delivery performance only experiences a small reduction. On average, delivery performance in the different demand scenarios with low and high noise is only reduced by one or two percentage points, depending on the planning approach and the demand scenario, if production at board printing is disrupted for 10 days.

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[540] See also section D.I.2.b. As in the preceding discussion, an initial stock of 100,000 units is introduced for the raw materials inventory levels at software flashing and final assembly.

Due to the characteristics of the two push-based planning approaches, both are subject to major inventory build-ups at all stages of the supply chain both during and at the end of the product life cycle. Inventory build-ups are particularly detrimental downstream in the supply chain due to the higher value of the products as they near completion. The two push-based planning approaches produce based on forecasts and not based on actual demand. Therefore the average inventory levels downstream in the supply chain are higher in these planning approaches than in the pull-based planning approach. As Figure D-50 illustrates for the product life cycle demand pattern PLC2 with high demand variation as an example, the planning approach with cascading forecasts has the highest average inventory levels. These inventories are distributed relatively evenly among the supply chain layers in this planning approach.[541] Because of its multiple inventory locations and decentralised decision making, the planning approach with cascading forecasts has a high risk of mismanaged inventory. This problem is observable in actual high-tech electronics supply chains, such as those of Hewlett-Packard, where too much inventory was often held in supply chains with a large number of stocking locations.[542] Similarly, in the push-based planning approach there is a major stocking location downstream the supply chain at software flashing and no inventory buffers at final assembly. Here, there is also a large average inventory of semi-finished products at software flashing, corresponding to 20 days of stock on average. This is also a concern in the real world. At Hewlett-Packard, for instance, the problem of holding inventory primarily at the final stage of the supply chain is that inventory at this stage is fully differentiated and therefore most expensive.[543] The differences in the value of inventory across the supply chain nodes is represented through the inventory cost factors in the model.[544] Downstream inventory build-ups, as well as inventory build-ups at final assembly, are avoided through pull-based planning.

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[541] The inventory values in Figure D-50 are the average inventory levels over the simulation duration at each supply chain node, calculated as the average of 200 simulations with different noise seeds, i.e. 200 different demand patterns each with PLC2 as a basis and different random variation in demand. All values are rounded to full 5,000.

[542] Cf. Billington *et al.*: Accelerating the Profitability of Hewlett-Packard's Supply Chains, p. 70.

[543] Cf. Billington *et al.*: Accelerating the Profitability of Hewlett-Packard's Supply Chains, p. 70.

[544] Refer to the relative inventory cost table developed in section C.I.3.

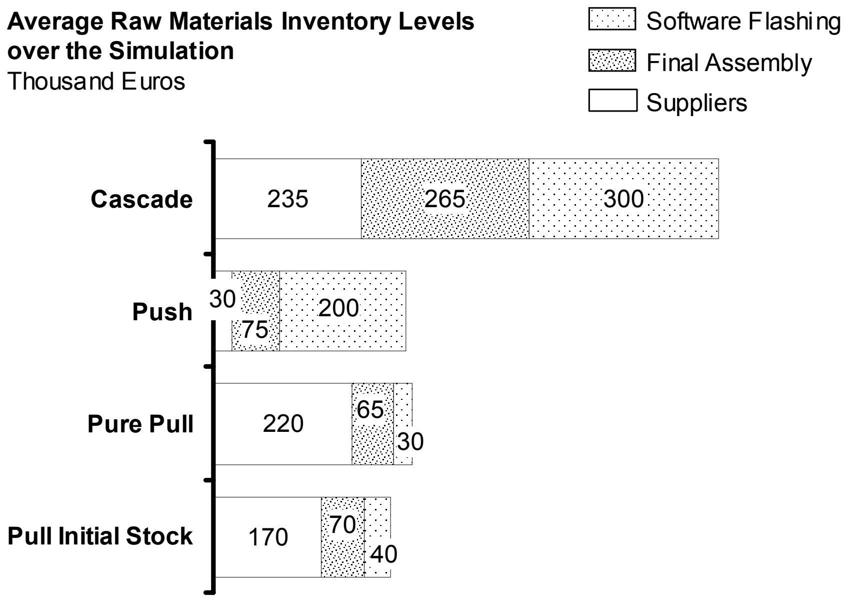

Figure D-50: Average Raw Materials Inventory Levels over the Simulation Duration (PLC2, high noise)

A major concern with regard to short product life cycles is inventory of products and components that is unsold at the end of the product life cycle. This is shown in Figure D-51 for the demand scenario with the product life cycle PLC2, perfect forecasts and high noise, as an example.[545] Due to the different decision making policies in the pull approach, with no adjustments for desired inventory levels, inventory of semi-finished products at software flashing at the end of the product life cycles is also significantly lower than in the other planning approaches, independent of the demand pattern. Nevertheless, inventory build-ups in the pull approach may still occur at the upstream suppliers, which are driven by a forecast. There, however, the cost of inventory per unit is significantly lower, which also reduces the damage if obsolete inventory needs to be discarded. In the example, the raw materials inventory levels at software flashing at the end of the simulation in the push approach with cascading forecasts correspond to 675,000 Euros and in the push approach with central planning to 420,000 Euros. In the pure pull planning approach the raw materials at software flashing at the end of the simulation are only 45,000 Euros. In the pull

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[545] The indicated values are the averages of the ending inventory levels over 200 simulations with different noise seeds.

approach with initial staging of components for the first phase of the product life cycle, the end raw materials inventory level at software flashing in this demand scenario is worth 50,000 Euros on average. To put these values into perspective, consider that total sales over the product life cycle are 3,000,000 units, with each finished goods unit valued at 1 Euro.[546] At the first tier suppliers, mean inventory levels at the end of the simulations are highest in the pull-based planning approaches, with 270,000 Euros (Pull) and 180,000 Euros (Pull with initial stock). More expensive downstream inventory is avoided to a large extent. The results in all of the other simulations with different levels of demand volatility are comparable.

Inventory levels at the end of the product life cycle can therefore, on average, reach up to almost 50 percent of total sales, as in the planning approach with cascading forecasts. Selling these products may require an additional effort towards the end of the product life cycle, for example through a promotion or price reductions. Compared to the push approach with central planning, the pull approach that plans for the product introduction therefore achieves a comparable delivery performance with lower average inventory levels in the supply chain at the end of the simulation, and higher inventory turnover over the course of the product life cycle.

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[546] The valuation at 1 Euro is related to the relative inventory cost table developed in section C.I.3. Since these are relative values, the insights are independent of the actual price of the product, which is likely to be higher than 1 Euro.

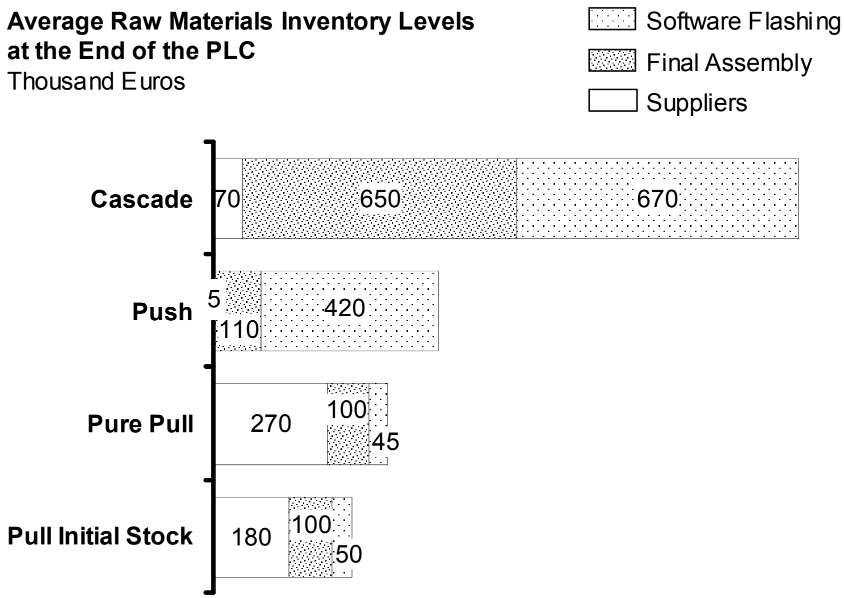

Figure D-51: Average Raw Materials Inventory Levels at the End of the Product Life Cycle (PLC2, high noise)

E. Implementing Robust Policies for an Efficient and Responsive Supply Chain Strategy

The use of a holistic System Dynamics simulation model representing decision making policies in supply chains in the high-tech electronics industry enables a variety of insights that extend previous quantitative, qualitative and empirical work. The System Dynamics model is a valuable tool for evaluating changes to the planning policies that are currently in place. It allows the systematic testing of new decision making structures in a controlled environment without requiring access to detailed empirical data. The findings based on the analyses of the various simulation runs have implications both for theory and future research as well as for the practical implementation of such planning policies in the high-tech electronics industry. Based on the literature review, expert input and analyses of the simulation model, several conclusions could be reached.

It has been shown that it is possible to design the planning policies in the high-tech electronics industry in such a way that the performance of the supply chain is improved on both dimensions, responsiveness and efficiency. Regarding the two analysed alternatives, a simple pull-based planning system that plans for the initial phase of the product introduction can perform similarly or better than a centrally planned push system on both dimensions of supply chain performance, responsiveness and efficiency. This observation is independent of the demand characteristics of the product. In particular, the pull system with an initial stock performs better on delivery performance in the first phase of the product life cycle. At the same time, such a pull-based system generates smaller accumulations of backlog at software flashing and therefore allows shorter delivery delays.

These findings have a number of implications. First, they show that both objectives, responsiveness and efficiency, can be achieved in a supply chain with one planning approach. Segmenting the product portfolio and setting up different supply chains may not be necessary. This result is valuable, as running multiple supply chain planning approaches within an organization can be challenging. A practical example is a microcomputer equipment manufacturer with a wide product range that changed the planning and production processes from batch processes scheduled with a MRP system to a simple pull-based planning system with small order quantities. As a result, the manufacturing lead-times could be reduced from 75 days to four days, increasing the responsiveness. At the same time, efficiency was improved through lower inventory levels and avoidance of obsolete stock, which previously was a major problem.[547] Such

[547] Cf. Berry and Hill: Linking Systems to Strategy, p. 10.

lower inventory levels, in particular avoiding expensive stocks of semi-finished products downstream the supply chain, are also achieved with the pull-based planning approach in the simulation model.

A second implication of the findings is related to this example. Push-based planning approaches are more difficult to implement than pull planning approaches, in particular if the supply chain crosses multiple organizational boundaries. The finding resulting from the simulations indicating that pull approaches can be used even in environments with high demand uncertainty and long component lead times is therefore valuable if one considers aspects of implementation. Planners in push planning systems depend on information about capacities, inventory levels, and generally the structure of the supply chain. For example, if information about supply chain disruptions at the supplier side is not communicated to the supply chain planners, as in this model, then their observations of such disruptions will only occur after a significant time delay.

In contrast, a pull-based system needs much less information and depends entirely on local decision rules at each supply chain echelon, which would immediately adjust to supply chain disruptions, for example, through local decision heuristics. Such a system does, however, require a certain degree of organizational discipline as overriding the decision heuristics needs to be avoided. The only act of planning that is needed is the long-term forecast that is communicated to the suppliers. As has been shown, these forecasts can be more stable in a pull-based planning system. This is advantageous for the supply chain. Moreover, inflating the initial forecasts, i.e. overforecasting demand, may improve both responsiveness and efficiency in such a pull-based planning system, while erring in the other direction and underforecasting demand has a negative effect on delivery performance. However, such overforecasting should be carried out with extreme care, as it may cause order cancellations and as a consequence severe disruptions to the planning processes in the supply chain.

However, there are also notable drawbacks to implementing the pull-based planning approach in the high-tech electronics industry. A complication when implementing pull systems in such an environment with a high potential for demand variability is that the production rate at suppliers may be subject to large fluctuations if these are integrated in the pull-based planning system. These fluctuations may require higher average inventory levels at the suppliers. If there were several product variants, however, that use some of the same base components that could be produced on the same line at board printing, then this could smooth the overall production rate. Nokia, for example, produces generic “engines” for its mobile phones in a process with very long lead times. These engines can later be transformed into unique built-to-order phones within a very short time frame.[548] The feasibility of a pull-based planning system therefore depends on the product characteristics in terms of mix variability as well as the flexibility of changing production volumes at board printing. Reductions in set-up times therefore become important, as the high equipment cost requires high levels of capacity utilization and multiple products may have to be produced on the same equipment.[549] This is particularly relevant if demand variability is high. Also, the suppliers may need to be financially compensated for larger variations in demand that cause increases and fluctuations of their raw materials inventory levels and may require increases in flexibility.

A large number of variables needed to be considered in order to provide insights into the balance between responsiveness and efficiency in the high-tech electronics industry. In any System Dynamics simulation model, a balance needs to be found between representing the structures and policy levers in the system well while capturing the feedback effects that are typically unaccounted for by the mental models of decision makers.[550] As the dynamics of the system behaviour emerge from the interactions of the different parts of the system, capturing the interlinkages and feedback effects is more important than adding a large amount of detail in representing the individual parts of the system.[551] The System Dynamics model developed in this work is consistent with a wide spectrum of available information, including past research and qualitative assessments obtained through interviews with industry experts. Nevertheless, the model necessarily relies on a number of assumptions, each of which could serve as an indicator for potential future research. One of the most important limitations of the model is that only one product is considered in each simulation run, with no consideration of different product variants. Framiñán, Reichhart and Holweg provide some initial pointers into this research area, and extending the existing model to incorporate the dynamics of changes in the product mix is a promising area for future research.[552] The model could further be extended to cover multiple product generations, which would also allow the inclusion of long-term capacity decisions into the model. Currently, these capacity decisions are excluded because due to the long delays for capacity acquisitions in this industry they have no relevance within the relatively short product life cycles

[548] Cf. Reinhardt: Nokia's Magnificent Mobile-Phone Manufacturing Machine, p. 1.

[549] Cf. Beckman and Sinha: Conducting Academic Research with an Industry Focus, p. 120.

[550] Cf. Sterman: Business Dynamics, pp. 61–62 and p. 81.

[551] Cf. Sterman: Business Dynamics, p. 81.

[552] See Framiñán, Reichhart and Holweg: Modelling Supply Chain Responsiveness.

modelled.[553] Incorporating demand as an endogenous variable also promises further insights, as, for example, shown by Gonçalves et al. for the semiconductor industry.[554] Also, stochastic throughput times at board printing are currently incorporated implicitly through the third-order exponential delays that are used for the production processes as well as through the exogenous trigger for a production disruption at board printing; a more explicit incorporation of such variations may be useful.[555] Similarly, explicitly incorporating yield variations at board printing due to learning curve effects may also add value.[556]

The results of the analyses confirm that there is no single optimal strategy of achieving an appropriate balance of responsiveness and efficiency in the high-tech electronics industry for products with different products at different phases of the product life cycle. As the previous analyses show, both push-based planning systems as well as pull-based planning systems can provide performance improvements over the planning approach that is currently common in the industry, while simultaneous improvements of responsiveness and efficiency within the planning approach with cascading forecasts are difficult. In the high-tech electronics sector, high responsiveness is an important success factor especially at the beginning of the product life cycle, which may warrant intentional reductions in the efficiency of the supply chain in order to accommodate customer demand in this critical phase. The appropriateness of different planning approaches depends to a large extent to the flexibility of component suppliers to react to changes in demand. Even if lead times for components are long, a pull-based planning approach can be appropriate, as long as the product introduction phase is planned and suppliers can accommodate variations in demand well. An interesting area of future research would be an empirical study examining to

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553 See Gonçalves: Demand Bubbles and Phantom Orders in Supply Chains, p. 74, who argues that the long delays involved in adding new capacity have the consequence that in the short run production can only be changed by changing capacity utilization. This approach of assuming a fixed capacity is also taken in this work. See also Lertpattarapong: Applying system dynamics approach to the supply chain management problem, p. 7, and Vaidyanathan, Metcalf and Martin: Using Capacity Options to Better Enable Our Factory Ramps, p. 185.

554 See Gonçalves, Hines and Sterman: The impact of endogenous demand on push-pull production systems; Gonçalves: Demand Bubbles and Phantom Orders in Supply Chains; Lertpattarapong: Applying system dynamics approach to the supply chain management problem.

555 See Kok *et al.*: Philips Electronics Synchronizes Its Supply Chain to End the Bullwhip Effect, p. 40.

556 See Kok *et al.*: Philips Electronics Synchronizes Its Supply Chain to End the Bullwhip Effect, p. 40.

what extent these conclusions drawn from the simulation model can be tested in real-world high-tech electronics supply chains.[557]

High-tech electronics companies are recognizing the importance of supply chain management as a competitive differentiator and important lever for business success. Using System Dynamics simulation models such as that developed in this work can support these organizations in transforming their supply chains into systems that are both responsive to customer demand and efficient.

[557] This need is also identified by Reichhart and Holweg: Creating the Customer-responsive Supply Chain, pp. 27–28.

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Appendices

I. Listing of Model Equations: Cascade

```
added forecast error 35=
       RANDOM NORMAL(0, 2, 1, 0 ,0 )
   Units: Dimensionless

added forecast error 75=
   RANDOM NORMAL(0, 2, 1, 0 ,0 )
Units: Dimensionless

adjusted forecast for BP by SWF=
   MAX(0,((forecast 76 days out*adjustment to demand for BP SWF)
   +adjustment to Inventory RM SWF))
Units: Widgets/Day

adjusted forecast for supplier by SWF=
   MAX(0, ((forecast 36 days out*adjustment to demand for Sup SWF)
   +adjustment to Inventory RM SWF
   ))
Units: Widgets/Day

adjustment time for emergency orders SWF=
   36
Units: Day

adjustment to demand for BP SWF=
   MIN(fractional difference demand and forecast for BP at SWF,
   1+XIDZ(averaged demand for the current day for BP FC at SWF
, forecast 76 days out, 0))
Units: Dmnl

adjustment to demand for Sup SWF=
   MIN(fractional difference demand and forecast for 36 days at
   SWF, 1+XIDZ(averaged demand for the current day for Sup FC at
   SWF
, forecast 36 days out, 0))
Units: Dimensionless

adjustment to forecast boards FAT=
   adjustment to inventory boards FAT/boards used per FG unit
Units: Widget/Day

adjustment to forecast BP=
   adjustment to Inventory RM BP/materials used per FG unit
```

```
Units: Widget/Day

adjustment to forecast RM FAT=
   adjustment to inventory RM FAT/materials used per FG unit
Units: Widget/Day

adjustment to forecast Sup=
   adjustment to Inventory RM Sup/materials used per FG unit Sup
Units: Widget/Day

adjustment to inventory boards FAT=
   ((gap desired inventory and average inventory boards FAT-
   (cumulated adjustment to inventory boards FAT
*switch to consider cum adj to inventory boards FAT))
   /inventory adjustment time boards FAT)
   *switch adjustment to Inventory boards FAT
Units: Board/Day

adjustment to Inventory RM BP=
   ((gap between desired inventory and average inventory RM BP-
   (cumulated adjustment to inventory RM BP
*switch to consider cum adj to inventory RM BP))
   /inventory adjustment time BP)
   *switch adjustment to Inventory RM BP
Units: Materials/Day

adjustment to inventory RM FAT=
   ((gap desired inventory and average inventory RM FAT-(cumulated
   adjustment to inventory RM FAT
*switch to consider cum adj to inventory RM FAT))
   /inventory adjustment time RM FAT)
   *switch adjustment to Inventory RM FAT
Units: material/Day

adjustment to Inventory RM Sup=
   ((gap between desired inventory and average inventory RM Sup-
   (cumulated adjustment to inventory RM Sup
*switch to consider cum adj to inventory RM Sup))
   /inventory adjustment time Sup)
   *switch adjustment to Inventory RM Sup
Units: material/Day

adjustment to Inventory RM SWF=
   ((gap desired inventory and average inventory RM SWF-(cumulated
   adjustment to inventory RM SWF
*switch consider cum adj to inventory RM SWF))
   /inventory adjustment time SWF)
   *switch adjustment to Inventory RM SWF
Units: Widget/Day
```

```
average backlog SWF=
   SMOOTH(Backlog SWF,averaging time backlog SWF)
Units: Widgets

average inventory boards FAT=
   smooth3(Inventory Boards FAT, inventory adjustment time boards
   FAT)
Units: Boards

average inventory RM BP=
   smooth3(Inventory RM BP,inventory adjustment time BP)
Units: Materials

average inventory RM FAT=
   smooth3(Inventory RM FAT, inventory adjustment time RM FAT)
Units: Materials

average inventory RM Sup=
   smooth3(Inventory RM Sup, inventory adjustment time Sup)
Units: Materials

average inventory RM SWF=
   smooth3(Inventory RM SWF, inventory adjustment time SWF)
Units: material

average total inventory cost over time=
   ZIDZ(cum total total inventory cost, Time)
Units: Dollars/Day

averaged demand for the current day for BP FC at SWF=
   SMOOTH(demand for the current day, avg time for difference de-
   mand and 76 day forecast SWF
)
Units: Widget/Day

averaged demand for the current day for Sup FC at SWF=
   SMOOTH(demand for the current day, averaging time adjustment for
   difference demand and 36 day forecast SWF
)
Units: Widget/Day

averaged forecast 36 days out shifted to match demand at SWF=
   SMOOTH(forecast 36 days out shifted to match demand at SWF, av-
   eraging time adjustment for difference demand and 36 day fore-
   cast SWF
)
Units: Widget/Day
```

```
averaged forecast for BP shifted to match demand SWF=
   SMOOTH(forecast 76 days out shifted to match demand at SWF, avg
   time for difference demand and 76 day forecast SWF
)
Units: Widget/Day

averaging time adjustment for difference demand and 36 day forecast
   SWF=
   10
Units: Day

averaging time backlog SWF=
   14
Units: Days

avg time for difference demand and 76 day forecast SWF=
   10
Units: Day

Backlog BP= INTEG (
   incoming order rate BP-order fulfillment rate BP,
        0)
Units: Boards

Backlog Emergency IC supplier= INTEG (
   +incoming emergency IC orders-backlog reduction emergency IC
   supplier,
        0)
Units: Materials

Backlog FAT= INTEG (
   +incoming forecast FAT-forecast fulfillment rate FAT,
        0)
Units: Widget

backlog reduction emergency IC supplier=
   emergency IC deliveries
Units: Materials/Day

Backlog Sup= INTEG (
   incoming order rate Sup-order fulfillment rate Sup,
        0)
Units: Widgets

Backlog SWF= INTEG (
   incoming production requests SWF-production starts SWF,
        0)
Units: Widgets
```

```
batch size BP=
   5000
Units: Boards/Day

boards per material=
   1
Units: Board/material

boards used per FG unit=
   1
Units: Boards/Widget

boards used per FG unit FAT=
   1
Units: Board/Widget

capacity FAT=
   50000
Units: Widget/Day

capacity limit BP=
   20000
Units: Boards/Day

capacity limit FAT=
   MIN(capacity FAT,feasible production based on inventory FAT)
Units: Widget/Day

Change in Pink Noise = (White Noise - Pink Noise)/Noise Correlation
   Time
Units: 1/Day

cum demand requested for the current week= INTEG (
   demand for the current day,
        0)
Units: Widgets

cum orders not filled on time= INTEG (
   IF THEN ELSE((customer backlog/dimensional consistency
   day+inflow customer backlog
-outflow customer backlog)>0, MIN(demand for the current day, cus-
   tomer backlog
/dimensional consistency day+inflow customer backlog-outflow cus-
   tomer backlog
), 0),
        0)
Units: Widgets

cum total total inventory cost=
```

```
   total cumulated inventory cost BP+total cumulated inventory cost
   FAT+total cumulated inventory cost Sup
+total cumulated inventory cost SWF
Units: Dollars

cumulated adjustment to inventory boards FAT= INTEG (
   adjustment to inventory boards FAT,
        0)
Units: Boards

cumulated adjustment to inventory RM BP= INTEG (
   adjustment to Inventory RM BP,
        0)
Units: Materials

cumulated adjustment to inventory RM FAT= INTEG (
   adjustment to inventory RM FAT,
        0)
Units: Materials

cumulated adjustment to inventory RM Sup= INTEG (
   adjustment to Inventory RM Sup,
        0)
Units: Materials

cumulated adjustment to inventory RM SWF= INTEG (
   adjustment to Inventory RM SWF,
        0)
Units: Widget

Cumulated emergency orders SWF= INTEG (
   Emergency orders to account for Backlog SWF,
        0)
Units: Boards

Cumulated Inventory Cost Boards FAT= INTEG (
   Inventory Cost Boards FAT,
        0)
Units: Dollars

Cumulated Inventory Cost FG BP= INTEG (
   Inventory Cost FG BP,
        0)
Units: Dollars

Cumulated Inventory Cost FG FAT= INTEG (
   Inventory Cost FG FAT,
        0)
Units: Dollars
```

```
Cumulated Inventory Cost FG Sup= INTEG (
   Inventory Cost FG Sup,
        0)
Units: Dollars

Cumulated Inventory Cost FG SWF= INTEG (
   Inventory Cost FG SWF,
        0)
Units: Dollars

Cumulated Inventory Cost RM BP= INTEG (
   Inventory Cost RM BP,
        0)
Units: Dollars

Cumulated Inventory Cost RM FAT= INTEG (
   Inventory Cost RM FAT,
        0)
Units: Dollars

Cumulated Inventory Cost RM Sup= INTEG (
   Inventory Cost RM Sup,
        0)
Units: Dollars

Cumulated Inventory Cost RM SWF= INTEG (
   Inventory Cost RM SWF,
        0)
Units: Dollars

Cumulated Inventory Cost WIP BP= INTEG (
   Inventory Cost WIP BP,
        0)
Units: Dollars

Cumulated Inventory Cost WIP FAT= INTEG (
   Inventory Cost WIP FAT,
        0)
Units: Dollars

Cumulated Inventory Cost WIP Sup= INTEG (
   Inventory Cost WIP Sup,
        0)
Units: Dollars

Cumulated Inventory Cost WIP SWF= INTEG (
   Inventory Cost WIP SWF,
        0)
```

```
Units: Dollars

customer backlog= INTEG (
   inflow customer backlog-outflow customer backlog,
        0)
Units: Widget

delivery delay SWF=
   ZIDZ(Backlog SWF, shipment rate SWF)
Units: Days

delivery performance to customer request=
   XIDZ((cum demand requested for the current week-cum orders not
   filled on time
), cum demand requested for the current week,1)
Units: Dimensionless

delivery time=
   1
Units: Days

demand adj Cust 9 days ahead=
   MIN(demand Cust 9 days ahead,Market potential/delivery time)
Units: Widgets/Day

demand Cust 9 days ahead=
   input from excel file 9 days out*Input
Units: Widgets/Day

demand for the current day= DELAY FIXED (
    demand adj Cust 9 days ahead, 9, demand adj Cust 9 days ahead)
Units: Widget/Day

desired Backlog SWF=
   0
Units: Widgets

desired days of stock SWF=
   10
Units: Days

desired Inventory boards FAT=
   STEP(inventory size boards FAT, inventory begin time boards
   FAT)-STEP(inventory size boards FAT
,inventory end time boards FAT)
Units: Board

desired Inventory RM BP=
```

```
   STEP(inventory size BP, inventory begin time BP)-STEP(inventory
   size BP,inventory end time BP
)
Units: material

desired Inventory RM FAT=
   STEP(inventory size RM FAT, inventory begin time RM FAT)-
   STEP(inventory size RM FAT
,inventory end time RM FAT)
Units: Materials

desired Inventory RM Sup=
   STEP(inventory size Sup, inventory begin time Sup)-
   STEP(inventory size Sup
,inventory end time Sup)
Units: Materials

desired inventory RM SWF=
   desired days of stock SWF*averaged demand for the current day
   for Sup FC at SWF
*materials used per FG unit SWF
Units: material

desired no of batches BP=
   INTEGER(
      ((waiting for production BP
        /minimum time to start production BP
        +inflow waiting for production BP)
       /batch size BP)
     )
Units: Dimensionless

desired orders in production SWF=
   MAX(0,Backlog SWF/minimum time to start production SWF+incoming
   production requests SWF
)
Units: Widgets/Day

desired production batched BP=
   MAX(0,
   MIN(desired no of batches BP*batch size BP, maximum possible no
   of batches BP
*batch size BP)
   *(1-probablity of problem BP)
   )
Units: Boards/Day

desired production Sup=
```

```
   MIN(waiting for production Sup/minimum time to start production
   Sup+inflow waiting for production Sup
, Inventory RM Sup/materials used per FG unit Sup/minimum time to
   start production Sup
)
Units: Widget/Day

dimensional consistency day=
   1
Units: Day

emergency IC deliveries=
   IF THEN ELSE(Emergency Inventory ICs at IC supplier/minimum time
   to start shipping from inventory emergency IC supplier
>0, MIN(Backlog Emergency IC supplier/minimum time to start ship-
   ping from inventory emergency IC supplier
, Emergency Inventory ICs at IC supplier/minimum time to start
   shipping from inventory emergency IC supplier
), Emergency Inventory ICs at IC supplier/minimum time to start
   shipping from inventory emergency IC supplier
)
Units: Materials/Day

Emergency Inventory ICs at IC supplier= INTEG (
   +receiving rate ICs IC supplier-emergency IC deliveries,
        initial level emergency inventory supplier)
Units: Materials

emergency material orders=
   emergency orders placed at BP/boards per material
Units: Materials/Day

emergency orders placed at BP=
   MAX(0,Emergency orders to account for Backlog SWF)
Units: Boards/Day

emergency orders placed at Sup=
   MAX(0,Emergency orders to account for Backlog SWF)
Units: Boards/Day

Emergency orders to account for Backlog SWF=
   switch emergency orders to account for Backlog SWF*MAX(0,
   ((((gap desired BL and average BL SWF
)-(Cumulated emergency orders SWF*switch consider emergency orders
   already placed
)))/adjustment time for emergency orders SWF))
Units: Boards/Day

expected emergency IC arrival rate BP=
```

```
   DELAY3(emergency IC deliveries, shipment delay emergency IC de-
   liveries)
Units: material/Day

expected material arrival rate BP= DELAY FIXED (
   material orders BP, expected order lead time BP, 0)
Units: Materials/Day

expected material arrival rate IC emergency supplies at IC sup-
   plier= DELAY FIXED
  (
   emergency material orders, expected order lead time emergency
   ICs, 0)
Units: Materials/Day

expected material arrival rate Sup= DELAY FIXED (
   material orders Sup, expected order lead time Sup, 0)
Units: Materials/Day

expected order lead time BP=
   46
Units: Days

expected order lead time emergency ICs=
   15
Units: Days

expected order lead time Sup=
   6
Units: Days

feasible production based on inventory FAT=
   MIN(Inventory Boards FAT/boards used per FG unit FAT, Inventory
   RM FAT/materials used per FG unit FAT
)/minimum time to start production FAT
Units: Widget/Day

feasible production SWF=
   MIN(desired orders in production SWF, Inventory RM SWF/materials
   used per FG unit SWF
/minimum time to start production SWF)
Units: Widgets/Day

final adjusted forecast used for material orders Sup=
   MAX(0,forecast for supplier FAT+adjustment to forecast
   Sup+emergency orders placed at Sup
/boards used per FG unit)
Units: Widget/Day
```

```
FINAL TIME  = 500
Units: Day

forecast 36 days out:=
   forecast 36 days out read from excel*systematic forecast error
   factor
Units: Widgets/Day

forecast 36 days out read from excel:=
   GET XLS DATA('input.xls', 'input', 'B', 'D1')
Units: Widget/Day

forecast 36 days out shifted to match demand at SWF= DELAY FIXED (
   forecast 36 days out, 36, 0)
Units: Widget/Day

forecast 76 days out:=
   forecast 76 days out read from excel*systematic forecast error
   factor
Units: Widgets/Day

forecast 76 days out read from excel:=
   GET XLS DATA('input.xls', 'input', 'B', 'E1')
Units: Widget/Day

forecast 76 days out shifted to match demand at SWF= DELAY FIXED (
   forecast 76 days out, 76, 0)
Units: Widget/Day

forecast for board printing FAT=
   MAX(0,forecast for board printing SWF+adjustment to forecast
   boards FAT)
Units: Widget/Day

forecast for board printing SWF=
   MAX( switch adjustment to forecast*adjusted forecast for BP by
   SWF, (1-switch adjustment to forecast
)*forecast 76 days out
   )
Units: Widgets/Day

forecast for material orders BP=
   MAX(0,forecast for board printing FAT+adjustment to forecast BP)
Units: Widget/Day

forecast for supplier FAT=
   MAX(0,forecast for supplier SWF+adjustment to forecast RM FAT)
Units: Widget/Day
```

```
forecast for supplier SWF=
   MAX(switch adjustment to forecast*adjusted forecast for supplier
   by SWF, (
1-switch adjustment to forecast)*forecast 36 days out)
Units: Widgets/Day

forecast fulfillment rate FAT=
   shipment rate FAT
Units: Widget/Day

forecast used for FAT=
   DELAY FIXED(forecast for supplier SWF, 16, 0)
Units: Widget/Day

fractional difference demand and forecast for 36 days at SWF=
   XIDZ(averaged demand for the current day for Sup FC at SWF, av-
   eraged forecast 36 days out shifted to match demand at SWF
, 1)
Units: Dimensionless

fractional difference demand and forecast for BP at SWF=
   XIDZ(averaged demand for the current day for BP FC at SWF, aver-
   aged forecast for BP shifted to match demand SWF
, 1)
Units: Dmnl

gap between desired inventory and average inventory RM BP=
   (desired Inventory RM BP-average inventory RM BP)
Units: Materials

gap between desired inventory and average inventory RM Sup=
   (desired Inventory RM Sup-average inventory RM Sup)
Units: Materials

gap desired BL and average BL SWF=
   (average backlog SWF-desired Backlog SWF)*boards used per FG
   unit FAT
Units: Boards

gap desired inventory and average inventory boards FAT=
   (desired Inventory boards FAT-average inventory boards FAT)
Units: Board

gap desired inventory and average inventory RM FAT=
   (desired Inventory RM FAT-average inventory RM FAT)
Units: Materials

gap desired inventory and average inventory RM SWF=
```

```
   (desired inventory RM SWF-average inventory RM SWF)/materials
   used per FG unit SWF
Units: Widgets

incoming emergency IC orders=
   emergency material orders
Units: Materials/Day

incoming forecast board orders BP=
   ((forecast for board printing FAT*boards used per FG
   unit+emergency orders placed at BP
))
Units: Boards/Day

incoming forecast FAT=
   forecast used for FAT+(Emergency orders to account for Backlog
   SWF/boards used per FG unit FAT
)
Units: Widget/Day

incoming forecast material orders SUP=
   ((forecast for supplier FAT*materials used per FG unit+emergency
   orders placed at Sup
/boards per material))
Units: material/Day

incoming order rate BP=
   incoming forecast board orders BP
Units: Boards/Day

incoming order rate Sup=
   (incoming forecast material orders SUP)*widgets per material Sup
Units: Widget/Day

incoming production requests SWF=
   demand adj Cust 9 days ahead
Units: Widget/Day

inflow customer backlog=
   demand for the current day
Units: Widget/Day

inflow waiting for production BP=
   incoming order rate BP
Units: Boards/Day

inflow waiting for production FAT=
   incoming forecast FAT
Units: Widget/Day
```

```
inflow waiting for production Sup=
   incoming order rate Sup
Units: Widget/Day

ini installed base=
   0
Units: Widgets

ini market potential=
   7e+006
Units: Widgets

ini materials on order BP=
   0
Units: Materials

ini materials on order Sup=
   0
Units: Materials

initial Inventory Boards Man=
   0
Units: Boards

initial inventory FG BP=
   0
Units: Boards

initial inventory FG Man=
   0
Units: Widgets

initial inventory FG Sup=
   0
Units: Widgets

initial inventory FG SWF=
   0
Units: Widgets

initial inventory RM BP=
   0
Units: Materials

initial inventory RM FAT=
   0
Units: Materials
```

```
initial inventory RM Sup=
   0
Units: Materials

initial inventory RM SWF=
   0
Units: material

initial level emergency inventory supplier=
   10000
Units: Materials

INITIAL TIME  = 0
Units: Day

Input=
   MAX(0,
   (
   1+STEP(Step Height,Step Time)
   +STEP(Step2 Height,Step2 Time)+
   (Pulse Quantity/TIME STEP)*PULSE(Pulse Time,TIME STEP)+
   RAMP(Ramp Slope,Ramp Start Time,Ramp End Time)+
   Sine Amplitude*SIN(2*3.14159*Time/Sine Period)+
   (Life Cycle Test Input*switch Life Cycle Test Input)+
        STEP(1,Noise Start Time)*Pink Noise
   )
    )
Units: Dimensionless

input from excel file 9 days out:=
   GET XLS DATA('input.xls', 'input', 'B', 'C1')
Units: Widget/Day

input from excel shifted to be demand requested for the current
   week:=
   TIME SHIFT(input from excel file 9 days out, -9)
Units: Widget/Day

Installed base= INTEG (
   demand adj Cust 9 days ahead,
        ini installed base)
Units: Widgets

inventory adjustment time boards FAT=
   6
Units: Day

inventory adjustment time BP=
   46
```

```
Units: Day

inventory adjustment time RM FAT=
   6
Units: Day

inventory adjustment time Sup=
   6
Units: Day

inventory adjustment time SWF=
   6
Units: Day

inventory begin time boards FAT=
   81
Units: Days

inventory begin time BP=
   71
Units: Days

inventory begin time RM FAT=
   81
Units: Days

inventory begin time Sup=
   71
Units: Days

Inventory Boards FAT= INTEG (
   +receiving rate Boards FAT-outgoing rate Boards FAT,
        initial Inventory Boards Man)
Units: Boards

Inventory Cost Boards FAT=
   inventory cost per unit Boards FAT*Inventory Boards FAT
Units: Dollars/Day

Inventory Cost FG BP=
   inventory cost per unit FG BP*Inventory FG BP
Units: Dollars/Day

Inventory Cost FG FAT=
   inventory cost per unit FG FAT*Inventory FG FAT
Units: Dollars/Day

Inventory Cost FG Sup=
   inventory cost per unit FG Sup*Inventory FG Sup
```

```
Units: Dollars/Day

Inventory Cost FG SWF=
   inventory cost per unit FG SWF*Inventory FG SWF
Units: Dollars/Day

inventory cost per unit Boards FAT=
   0.5
Units: Dollars/Board/Day

inventory cost per unit FG BP=
   0.5
Units: Dollars/Board/Day

inventory cost per unit FG FAT=
   0.9
Units: Dollars/Widget/Day

inventory cost per unit FG Sup=
   0.2
Units: Dollars/Widget/Day

inventory cost per unit FG SWF=
   1
Units: Dollars/Widget/Day

inventory cost per unit RM BP=
   0.45
Units: Dollars/Materials/Day

inventory cost per unit RM FAT=
   0.2
Units: Dollars/Materials/Day

inventory cost per unit RM Sup=
   0.1
Units: Dollars/Materials/Day

inventory cost per unit RM SWF=
   0.9
Units: Dollars/Materials/Day

inventory cost per unit WIP BP=
   0.45
Units: Dollars/Boards/Day

inventory cost per unit WIP FAT=
   0.7
Units: Dollars/Widget/Day
```

```
inventory cost per unit WIP Sup=
   0.2
Units: Dollars/Widget/Day

inventory cost per unit WIP SWF=
   0.9
Units: Dollars/Widget/Day

Inventory Cost RM BP=
   inventory cost per unit RM BP*Inventory RM BP
Units: Dollars/Day

Inventory Cost RM FAT=
   inventory cost per unit RM FAT*Inventory RM FAT
Units: Dollars/Day

Inventory Cost RM Sup=
   inventory cost per unit RM Sup*Inventory RM Sup
Units: Dollars/Day

Inventory Cost RM SWF=
   inventory cost per unit RM SWF*Inventory RM SWF
Units: Dollars/Day

Inventory Cost WIP BP=
   inventory cost per unit WIP BP*Inventory WIP BP var
Units: Dollars/Day

Inventory Cost WIP FAT=
   inventory cost per unit WIP FAT*Inventory WIP Man var
Units: Dollars/Day

Inventory Cost WIP Sup=
   inventory cost per unit WIP Sup*Inventory WIP Sup var
Units: Dollars/Day

Inventory Cost WIP SWF=
   inventory cost per unit WIP SWF*Inventory WIP SWF var
Units: Dollars/Day

inventory end time boards FAT=
   400
Units: Days

inventory end time BP=
   400
Units: Days
```

```
inventory end time RM FAT=
   400
Units: Days

inventory end time Sup=
   400
Units: Days

Inventory FG BP= INTEG (
   +production rate BP-shipment rate BP,
        initial inventory FG BP)
Units: Boards

Inventory FG FAT= INTEG (
   product completions FAT-shipment rate FAT,
        initial inventory FG Man)
Units: Widgets

Inventory FG Sup= INTEG (
   product completions FG Sup-shipment rate Sup,
        initial inventory FG Sup)
Units: Widget

Inventory FG SWF= INTEG (
   product completions SWF-shipment rate SWF,
        initial inventory FG SWF)
Units: Widgets

Inventory RM BP= INTEG (
   +receiving rate RM BP-(desired production batched BP/boards per
   material),
        initial inventory RM BP)
Units: Materials

Inventory RM FAT= INTEG (
   +receiving rate RM FAT-outgoing rate RM FAT,
        initial inventory RM FAT)
Units: Materials

Inventory RM Sup= INTEG (
   +receiving rate RM Sup-outgoing rate RM Sup,
        initial inventory RM Sup)
Units: Materials

Inventory RM SWF= INTEG (
   -outgoing rate RM SWF+receiving rate RM SWF,
        initial inventory RM SWF)
Units: Materials
```

```
inventory size boards FAT=
   100000
Units: Board

inventory size BP=
   100000
Units: Materials

inventory size RM FAT=
   100000
Units: Materials

inventory size Sup=
   100000
Units: Materials

inventory turns=
   ZIDZ(cum demand requested for the current week,average total
   inventory cost over time
)
Units: Day*Widget/Dollars

Inventory WIP BP  =

   #LV3<DELAYP(desiredproductionbatchedBP,productiontimeBP:Inventor
   yWIPBP)#

            +
   #LV2<DELAYP(desiredproductionbatchedBP,productiontimeBP:Inventor
   yWIPBP)#

            +
   #LV1<DELAYP(desiredproductionbatchedBP,productiontimeBP:Inventor
   yWIPBP)#

   Units: Days*Boards/Day

Inventory WIP BP var=
   Inventory WIP BP
Units: Boards

Inventory WIP Man  =

   #LV3<DELAYP(productionstartsFAT,productiontimeFAT:InventoryWIPMa
   n)#

            +
   #LV2<DELAYP(productionstartsFAT,productiontimeFAT:InventoryWIPMa
   n)#
```

```
          +
   #LV1<DELAYP(productionstartsFAT,productiontimeFAT:InventoryWIPMa
   n)#

   Units: Days*Widget/Day

Inventory WIP Man var=
   Inventory WIP Man
Units: Widget

Inventory WIP Sup  =

   #LV3<DELAYP(outgoingrateRMSup/materialsusedperFGunitSup,producti
   ontimeSup:InventoryWIPSup)#

          +
   #LV2<DELAYP(outgoingrateRMSup/materialsusedperFGunitSup,producti
   ontimeSup:InventoryWIPSup)#

          +
   #LV1<DELAYP(outgoingrateRMSup/materialsusedperFGunitSup,producti
   ontimeSup:InventoryWIPSup)#

   Units: Days*Widget/Day

Inventory WIP Sup var=
   Inventory WIP Sup
Units: Widgets

Inventory WIP SWF  =

   #LV3<DELAYP(feasibleproductionSWF,productiontimeSWF:InventoryWIP
   SWF)#

          +
   #LV2<DELAYP(feasibleproductionSWF,productiontimeSWF:InventoryWIP
   SWF)#

          +
   #LV1<DELAYP(feasibleproductionSWF,productiontimeSWF:InventoryWIP
   SWF)#

   Units: Days*Widgets/Day

Inventory WIP SWF var=
   Inventory WIP SWF
Units: Widget
```

```
largest possible RM outflow BP=
   MIN(capacity limit BP, Inventory RM BP/materials used per FG
   unit BP/minimum time to start production BP
)
Units: Boards/Day

Life Cycle Test Input=
   lkup Life Cycle Test Input and forecast for demand nine days
   ahead(Time/FINAL TIME
)-1
Units: Dimensionless

lkup Life Cycle Test Input and forecast for demand nine days ahead(
   [(0,0)-
   (1,2)],(0,0),(0.18,0),(0.256881,0.298246),(0.30581,0.684211),(0.
   324159
,0.95614),(0.376147,1.38596),(0.434251,1.62281),(0.498471,1.7077),(
   0.547401
,1.67544),(0.587156,1.57018),(0.623853,1.34211),(0.703364,0.54386),
   (0.730887
,0.280702),(0.782,0),(1,0),(1,0))
Units: Dimensionless

lkup Life Cycle Test Input PLC standard(
   [(0,0)-
   (1,2)],(0,0),(0.185,0),(0.259939,1.21053),(0.293578,1.7193),(0.3
   21101
,1.87719),(0.357798,1.95614),(0.415902,2),(0.440367,1.95614),(0.477
   064,1.85965
),(0.508235,1.62989),(0.569412,1.21708),(0.651765,0.733096),(0.7364
   71,0.362989
),(0.835294,0.0711744),(0.938824,0),(1,0))
Units: Dimensionless

lkup Life Cycle Test Input SCENARIO 1(
   [(0,0)-
   (1,2)],(0,0),(0.185,0),(0.259939,1.21053),(0.293578,1.7193),(0.3
   21101
,1.87719),(0.357798,1.95614),(0.415902,2),(0.461774,1.95614),(0.516
   82,1.81579
),(0.571865,1.5614),(0.626911,1.19298),(0.66055,0.929825),(0.697248
   ,0.578947
),(0.752294,0.27193),(0.834862,0.114035),(0.938824,0),(1,0))
Units: Dimensionless

lkup Life Cycle Test Input simple v01(
   [(0,0)-
   (1,2)],(0,0),(0.185,0),(0.185,2),(0.504587,2),(0.504587,0),(0.93
   8824
```

```
,0),(1,0))
Units: Dimensionless

lkup Life Cycle Test Input simple v02(
   [(0,0)-
   (1,2)],(0,0),(0.185,0),(0.185,0.5),(0.287462,0.5),(0.504587,2),(
   0.504587
,0),(0.938824,0),(1,0))
Units: Dimensionless

lkup Life Cycle Test Input simple v03(
   [(0,0)-
   (1,2)],(0,0),(0.185,0),(0.185,0.5),(0.287462,0.5),(0.504587,2),(
   0.9388
,2),(0.938824,0),(1,0))
Units: Dimensionless

lkup probability of problem BP(
   [(0,0)-
   (1,2)],(0,0),(0.185,0),(0.259939,0),(0.499,0),(0.5,1),(0.519,1),
   (0.52
,0),(1,0))
Units: Dimensionless

lkup probability of problem Sup(
   [(0,0)-
   (1,2)],(0,0),(0.185,0),(0.259939,0),(0.3,0),(0.301,1),(0.302,0),
   (1,
0))
Units: Dimensionless

Market potential= INTEG (
   -demand adj Cust 9 days ahead,
        ini market potential)
Units: Widgets

material arrival rate BP=
   receiving rate RM BP
Units: Materials/Day

material arrival rate Sup=
   receiving rate RM Sup
Units: Materials/Day

material order rate BP=
   emergency material orders+material orders BP
Units: Materials/Day

material order rate Sup=
```

```
   material orders Sup
Units: Materials/Day

material orders BP=
   MAX(0,  forecast for material orders BP*materials used per FG
   unit)
Units: Materials/Day

material orders Sup=
   MAX(0,final adjusted forecast used for material orders
   Sup)/widgets per material Sup
Units: Materials/Day

materials from Sup needed for a RM FAT=
   1
Units: material/Widget

Materials on order BP= INTEG (
   +material order rate BP-material arrival rate BP,
        ini materials on order BP)
Units: Materials

Materials on order Sup= INTEG (
   +material order rate Sup-material arrival rate Sup,
        ini materials on order Sup)
Units: Materials

materials used per FG unit=
   1
Units: material/Widget

materials used per FG unit BP=
   1
Units: Materials/Board

materials used per FG unit FAT=
   1
Units: Materials/Widget

materials used per FG unit Sup=
   1
Units: Materials/Widget

materials used per FG unit SWF=
   1
Units: material/Widget

maximum possible no of batches BP=
   INTEGER((largest possible RM outflow BP/batch size BP))
```

```
Units: Dimensionless

mean of input data from excel 9 days out=
   GET DATA MEAN(input from excel file 9 days out, 91, 413)
Units: Widget/Day

minimum time to start production BP=
   1
Units: Day

minimum time to start production FAT=
   1
Units: Day

minimum time to start production Sup=
   1
Units: Days

minimum time to start production SWF=
   1
Units: Day

minimum time to start shipping FAT=
   1
Units: Day

minimum time to start shipping from inventory emergency IC sup-
   plier=
   1
Units: Days

minimum time to start shipping SWF=
   1
Units: Day

Noise Correlation Time = 4
Units: Day

NOISE SEED=
   1
Units: Dimensionless

Noise Standard Deviation=
   0.8
Units: Dimensionless

Noise Start Time=
   92
Units: Day
```

```
order fulfillment rate BP=
   shipment rate BP
Units: Boards/Day

order fulfillment rate Sup=
   shipment rate Sup
Units: Widgets/Day

outflow customer backlog=
   receiving rate Cust
Units: Widgets/Day

outgoing rate Boards FAT=
   MAX(0,production starts FAT*boards used per FG unit FAT)
Units: Boards/Day

outgoing rate RM FAT=
   MAX(0,production starts FAT*materials used per FG unit FAT)
Units: Materials/Day

outgoing rate RM Sup=
   MAX(0,IF THEN ELSE(desired production Sup*materials used per FG
   unit Sup>Inventory RM Sup
/minimum time to start production Sup
   , Inventory RM Sup/minimum time to start production Sup, desired
   production Sup
*materials used per FG unit Sup))
Units: Materials/Day

outgoing rate RM SWF=
   MAX(0,feasible production SWF*materials used per FG unit SWF)
Units: Materials/Day

Pink Noise = INTEG(Change in Pink Noise,0)
Units: Dimensionless

probablity of problem BP=
   lkup probability of problem BP(Time/FINAL TIME)*switch probabil-
   ity of problem BP
Units: Dimensionless

probablity of problem Sup=
   lkup probability of problem Sup(Time/FINAL TIME)*switch prob-
   ability of problem Sup
Units: Dimensionless

product completions FAT=
```

```
   MAX(0,DELAYP(production starts FAT, production time FAT : Inven-
   tory WIP Man
 ))
Units: Widget/Day

product completions FG Sup=
   DELAYP(outgoing rate RM Sup/materials used per FG unit Sup, pro-
   duction time Sup
 : Inventory WIP Sup )
Units: Widget/Day

product completions SWF=
   DELAYP(feasible production SWF, production time SWF : Inventory
   WIP SWF)
Units: Widgets/Day

production rate BP=
   DELAYP(desired production batched BP, production time BP : In-
   ventory WIP BP
 )
Units: Boards/Day

production starts FAT=
   MAX(0,
   MIN(waiting for production FAT/minimum time to start production
   FAT+inflow waiting for production FAT
, capacity limit FAT)
   )
Units: Widget/Day

production starts SWF=
   feasible production SWF
Units: Widgets/Day

production time BP=
   4
Units: Days

production time FAT=
   4
Units: Days

production time Sup=
   4
Units: Days

production time SWF=
   4
Units: Days
```

```
Pulse Quantity=
   0
Units: Dimensionless*Day

Pulse Time=
   50
Units: Day

pulse train duration=
   1
Units: Day

pulse train end=
   500
Units: Day

Pulse Train Input=
   PULSE TRAIN(pulse train start, pulse train duration , pulse
   train repeattime
 , pulse train end )
Units: Dimensionless

pulse train repeattime=
   5
Units: Days

pulse train start=
   0
Units: Day

Ramp End Time=
   150
Units: Day

Ramp Slope=
   0
Units: 1/Day

Ramp Start Time=
   92
Units: Day

receiving rate Boards FAT=
   DELAY3(shipment rate BP,shipment delay BP)
Units: Boards/Day

receiving rate Cust=
   DELAY3(shipment rate SWF,shipment delay SWF)
```

```
Units: Widget/Day

receiving rate ICs IC supplier=
   expected material arrival rate IC emergency supplies at IC sup-
   plier
Units: material/Day

receiving rate RM BP=
   expected material arrival rate BP+expected emergency IC arrival
   rate BP
Units: Materials/Day

receiving rate RM FAT=
   DELAY3(shipment rate Sup,shipment delay Sup)*materials from Sup
   needed for a RM FAT
Units: Materials/Day

receiving rate RM Sup=
   expected material arrival rate Sup
Units: Materials/Day

receiving rate RM SWF=
   DELAY3(shipment rate FAT*materials used per FG unit SWF,shipment
   delay FAT
)
Units: Materials/Day

SAVEPER  =
        TIME STEP
Units: Day

shipment delay BP=
   4
Units: Days

shipment delay emergency IC deliveries=
   4
Units: Days

shipment delay FAT=
   4
Units: Days

shipment delay Sup=
   4
Units: Days

shipment delay SWF=
   4
```

```
Units: Days

shipment rate BP=
   Inventory FG BP/dimensional consistency day
Units: Boards/Day

shipment rate FAT=
   Inventory FG FAT/minimum time to start shipping FAT
Units: Widgets/Day

shipment rate Sup=
   Inventory FG Sup/dimensional consistency day
Units: Widget/Day

shipment rate SWF=
   Inventory FG SWF/minimum time to start shipping SWF
Units: Widgets/Day

Sine Amplitude=
   0
Units: Dimensionless

Sine Period=50
Units: Days

stddev of input data from excel 9 days out=
   GET DATA STDV( input from excel file 9 days out, 91, 413)
Units: Widget/Day

Step Height=
   0
Units: Dimensionless

Step Time=
   0
Units: Day

Step2 Height=
   0
Units: Dimensionless

Step2 Time=
   91
Units: Days

switch adjustment to forecast=
   1
Units: Dimensionless
```

```
switch adjustment to Inventory boards FAT=
   1
Units: Dimensionless

switch adjustment to Inventory RM BP=
   1
Units: Dimensionless

switch adjustment to Inventory RM FAT=
   1
Units: Dimensionless

switch adjustment to Inventory RM Sup=
   1
Units: Dimensionless

switch adjustment to Inventory RM SWF=
   1
Units: Dimensionless

switch consider cum adj to inventory RM SWF=
   0
Units: Dmnl

switch consider emergency orders already placed=
   0
Units: Dimensionless

switch emergency orders to account for Backlog BP setup D=
   1
Units: Dimensionless

switch emergency orders to account for Backlog SWF=
   1
Units: Dimensionless

switch Life Cycle Test Input=
   0
Units: Dimensionless

switch probability of problem BP=
   0
Units: Dimensionless

switch probability of problem Sup=
   0
Units: Dimensionless

switch to consider cum adj to inventory boards FAT=
```

```
   0
Units: Dmnl

switch to consider cum adj to inventory RM BP=
   0
Units: Dmnl

switch to consider cum adj to inventory RM FAT=
   0
Units: Dmnl

switch to consider cum adj to inventory RM Sup=
   0
Units: Dmnl

systematic forecast error factor=
   1
Units: Dimensionless

time base week=
   TIME BASE(0, 0.2 )
Units: Dimensionless

TIME STEP  = 0.25
Units: Day

total cumulated inventory cost BP=
   Cumulated Inventory Cost FG BP+Cumulated Inventory Cost RM
   BP+Cumulated Inventory Cost WIP BP
Units: Dollars

total cumulated inventory cost FAT=
   Cumulated Inventory Cost FG FAT+Cumulated Inventory Cost Boards
   FAT+Cumulated Inventory Cost WIP FAT
+Cumulated Inventory Cost RM FAT
Units: Dollars

total cumulated inventory cost Sup=
   Cumulated Inventory Cost FG Sup+Cumulated Inventory Cost RM
   Sup+Cumulated Inventory Cost WIP Sup
Units: Dollars

total cumulated inventory cost SWF=
   Cumulated Inventory Cost FG SWF+Cumulated Inventory Cost RM
   SWF+Cumulated Inventory Cost WIP SWF
Units: Dollars

total inventory cost BP=
   Inventory Cost FG BP+Inventory Cost RM BP+Inventory Cost WIP BP
```

```
Units: Dollars/Day

total inventory cost FAT=
   Inventory Cost FG FAT+Inventory Cost Boards FAT+Inventory Cost
   WIP FAT+Inventory Cost RM FAT
Units: Dollars/Day

total inventory cost Sup=
   Inventory Cost FG Sup+Inventory Cost RM Sup+Inventory Cost WIP
   Sup
Units: Dollars/Day

total inventory cost SWF=
   Inventory Cost FG SWF+Inventory Cost RM SWF+Inventory Cost WIP
   SWF
Units: Dollars/Day

Total products shipped to Cust= INTEG (
   receiving rate Cust,
        0)
Units: Widgets

waiting for production BP= INTEG (
   +inflow waiting for production BP-desired production batched BP,
        0)
Units: Boards

waiting for production FAT= INTEG (
   +inflow waiting for production FAT-production starts FAT,
        0)
Units: Widgets

waiting for production Sup= INTEG (
   +inflow waiting for production Sup-desired production Sup,
        0)
Units: Widget

White Noise=
   Noise Standard Deviation*((24*Noise Correlation Time/TIME
   STEP)^0.5*(RANDOM UNIFORM
(0, 1, NOISE SEED) - 0.5
   ))
Units: Dimensionless

widgets per material Sup=
   1
Units: Widget/material
```

II. Listing of Model Equations: Push

```
added forecast error 35=
       RANDOM NORMAL(0, 2, 1, 0 ,0 )
   Units: Dimensionless

added forecast error 75=
   RANDOM NORMAL(0, 2, 1, 0 ,0 )
Units: Dimensionless

adjusted forecast for BP by SWF=
   MAX(0,((forecast 76 days out*adjustment to demand for BP SWF)
   +adjustment to Inventory RM SWF))
Units: Widgets/Day

adjusted forecast for supplier by SWF=
   MAX(0, ((forecast 36 days out*adjustment to demand for Sup SWF)
   +adjustment to Inventory RM SWF
   ))
Units: Widgets/Day

adjustment time for emergency orders SWF=
   36
Units: Day

adjustment to demand for BP SWF=
   MIN(fractional difference demand and forecast for 76 days at
   SWF, 1+XIDZ(averaged demand requested for the current week 76
   day FC at SWF
, forecast 76 days out, 0))
Units: Dimensionless

adjustment to demand for Sup SWF=
   MIN(fractional difference demand and forecast for 36 days at
   SWF, 1+XIDZ(averaged demand requested for the current week 36
   day FC at SWF
, forecast 36 days out, 0))
Units: Dimensionless

adjustment to Inventory RM SWF=
   ((gap between desired inventory and average inventory RM SFW-
   (cumulated adjustment to inventory RM SWF
*switch to consider cum adj to inventory RM SWF))
   /inventory adjustment time SWF)
   *switch adjustment to Inventory RM SWF
Units: Widget/Day

average Backlog SWF=
   SMOOTH(Backlog SWF,averaging time backlog SWF)
```

```
Units: Widgets

average cum positive customer backlog=
   ZIDZ(cum positive customer backlog, Time-150)
Units: Widget/Day

average demand requested for the current day=
   ZIDZ(cum demand requested for the current day, Time-150)
Units: Widget/Day

average inventory RM SWF=
   smooth3(Inventory RM SWF, inventory adjustment time SWF)
Units: material

average total inventory cost over time=
   ZIDZ(cum total total inventory cost, Time)
Units: Dollars/Day

averaged demand requested for the current week 36 day FC at SWF=
   SMOOTH(demand requested for the current day, averaging time ad-
   justment for difference demand and 36 day forecast SWF
)
Units: Widget/Day

averaged demand requested for the current week 76 day FC at SWF=
   SMOOTH(demand requested for the current day, averaging time ad-
   justment for difference demand and 76 day forecast SWF
)
Units: Widget/Day

averaged forecast 36 days out shifted to match demand at SWF=
   SMOOTH(forecast 36 days out shifted to match demand at SWF, av-
   eraging time adjustment for difference demand and 36 day fore-
   cast SWF
)
Units: Widget/Day

averaged forecast 76 days out shifted to match demand at SWF=
   SMOOTH(forecast 76 days out shifted to match demand at SWF, av-
   eraging time adjustment for difference demand and 76 day fore-
   cast SWF
)
Units: Widget/Day

averaging time adjustment for difference demand and 36 day forecast
   SWF=
   10
Units: Day
```

```
averaging time adjustment for difference demand and 76 day forecast
   SWF=
   10
Units: Day

averaging time backlog SWF=
   14
Units: Days

Backlog BP= INTEG (
   incoming order rate BP-order fulfillment rate BP,
        0)
Units: Boards

Backlog Emergency IC supplier= INTEG (
   +incoming emergency IC orders-backlog reduction emergency IC
   supplier,
        0)
Units: Materials

backlog reduction emergency IC supplier=
   emergency IC deliveries
Units: Materials/Day

Backlog Sup= INTEG (
   incoming order rate Sup-order fulfillment rate Sup,
        0)
Units: Widgets

Backlog SWF= INTEG (
   incoming production requests SWF-production starts SWF,
        0)
Units: Widgets

batch size BP=
   5000
Units: Boards/Day

boards per material=
   1
Units: Board/material

boards used per FG unit=
   1
Units: Boards/Widget

boards used per FG unit FAT=
   1
Units: Board/Widget
```

```
capacity FAT=
   50000
Units: Widget/Day

capacity limit BP=
   20000
Units: Boards/Day

capacity limit FAT=
   MIN(capacity FAT,feasible production based on inventory FAT)
Units: Widget/Day

Change in Pink Noise = (White Noise - Pink Noise)/Noise Correlation
   Time
Units: 1/Day

cum demand requested for the current day= INTEG (
   demand requested for the current day,
        0)
Units: Widgets

cum orders not filled on time= INTEG (
   IF THEN ELSE((customer backlog/dimensional consistency
   day+inflow customer backlog
-outflow customer backlog)>0, MIN(demand requested for the current
   day, customer backlog
/dimensional consistency day+inflow customer backlog-outflow cus-
   tomer backlog
), 0),
        0)
Units: Widgets

cum positive customer backlog= INTEG (
   positive customer backlog,
        0)
Units: Widget

cum total total inventory cost=
   total cumulated inventory cost BP+total cumulated inventory cost
   FAT+total cumulated inventory cost Sup
+total cumulated inventory cost SWF
Units: Dollars

cumulated adjustment to inventory RM SWF= INTEG (
   adjustment to Inventory RM SWF,
        0)
Units: Widget
```

```
Cumulated emergency orders to account for Backlog SWF= INTEG (
   Emergency orders to account for Backlog SWF,
        0)
Units: Boards

Cumulated Inventory Cost Boards FAT= INTEG (
   Inventory Cost Boards FAT,
        0)
Units: Dollars

Cumulated Inventory Cost FG BP= INTEG (
   Inventory Cost FG BP,
        0)
Units: Dollars

Cumulated Inventory Cost FG FAT= INTEG (
   Inventory Cost FG FAT,
        0)
Units: Dollars

Cumulated Inventory Cost FG Sup= INTEG (
   Inventory Cost FG Sup,
        0)
Units: Dollars

Cumulated Inventory Cost FG SWF= INTEG (
   Inventory Cost FG SWF,
        0)
Units: Dollars

Cumulated Inventory Cost RM BP= INTEG (
   Inventory Cost RM BP,
        0)
Units: Dollars

Cumulated Inventory Cost RM FAT= INTEG (
   Inventory Cost RM FAT,
        0)
Units: Dollars

Cumulated Inventory Cost RM Sup= INTEG (
   Inventory Cost RM Sup,
        0)
Units: Dollars

Cumulated Inventory Cost RM SWF= INTEG (
   Inventory Cost RM SWF,
        0)
Units: Dollars
```

```
Cumulated Inventory Cost WIP BP= INTEG (
   Inventory Cost WIP BP,
        0)
Units: Dollars

Cumulated Inventory Cost WIP FAT= INTEG (
   Inventory Cost WIP FAT,
        0)
Units: Dollars

Cumulated Inventory Cost WIP Sup= INTEG (
   Inventory Cost WIP Sup,
        0)
Units: Dollars

Cumulated Inventory Cost WIP SWF= INTEG (
   Inventory Cost WIP SWF,
        0)
Units: Dollars

customer backlog= INTEG (
   inflow customer backlog-outflow customer backlog,
        0)
Units: Widget

delivery delay SWF=
   ZIDZ(Backlog SWF, shipment rate SWF)
Units: Days

delivery performance to customer request=
   XIDZ((cum demand requested for the current day-cum orders not
   filled on time
), cum demand requested for the current day,1)
Units: Dimensionless

delivery time=
   1
Units: Days

demand adj Cust 4 days ahead= DELAY FIXED (
   demand adj Cust 9 days ahead,5,demand adj Cust 9 days ahead)
Units: Widget/Day

demand adj Cust 9 days ahead=
   MIN(demand Cust 9 days ahead,Market potential/delivery time)
Units: Widgets/Day

demand Cust 9 days ahead=
```

```
   input from excel file 9 days out*Input
Units: Widgets/Day

demand requested for the current day= DELAY FIXED (
    demand adj Cust 9 days ahead, 9, demand adj Cust 9 days ahead)
Units: Widget/Day

desired Backlog SWF=
   0
Units: Widgets

desired days of stock SWF=
   10
Units: Days

desired inventory RM SWF=
   desired days of stock SWF*averaged demand requested for the cur-
   rent week 36 day FC at SWF
*materials used per FG unit SWF
Units: material

desired orders in production SWF=
   MAX(0,Backlog SWF/minimum time to start production SWF+incoming
   production requests SWF
)
Units: Widgets/Day

desired production batched BP=
   MAX(0,
   IF THEN ELSE(
        (INTEGER(((waiting for production BP/minimum time to start
   production BP
+inflow waiting for production BP)/batch size BP))*batch size
   BP<largest possible RM outflow BP
),
        (INTEGER(((waiting for production BP/minimum time to start
   production BP
+inflow waiting for production BP)/batch size BP))*batch size BP),
        (INTEGER((largest possible RM outflow BP/batch size
   BP))*batch size BP
)
   )*(1-probablity of problem BP)
     )
Units: Boards/Day

desired production Sup=
   MIN(waiting for production Sup/dimensional consistency
   day+inflow waiting for production Sup
```

```
, Inventory RM Sup/materials used per FG unit Sup/dimensional con-
   sistency day
)
Units: Widget/Day

dimensional consistency day=
   1
Units: Day

emergency IC deliveries=
   IF THEN ELSE(Emergency Inventory ICs at IC supplier/minimum
   shipment time from inventory emergency IC supplier
>0, MIN(Backlog Emergency IC supplier/minimum shipment time from
   inventory emergency IC supplier
, Emergency Inventory ICs at IC supplier/minimum shipment time from
   inventory emergency IC supplier
), Emergency Inventory ICs at IC supplier/minimum shipment time
   from inventory emergency IC supplier
)
Units: Materials/Day

Emergency Inventory ICs at IC supplier= INTEG (
   +receiving rate ICs IC supplier-emergency IC deliveries,
        initial level emergency inventory supplier)
Units: Materials

emergency material orders=
   emergency orders placed at BP/boards per material
Units: Materials/Day

emergency orders placed at BP=
   MAX(0,Emergency orders to account for Backlog SWF)
Units: Boards/Day

emergency orders placed at Sup=
   MAX(0,Emergency orders to account for Backlog SWF)
Units: Boards/Day

Emergency orders to account for Backlog SWF=
   switch emergency orders to account for Backlog SWF*MAX(0, ((gap
   desired BL and average BL SWF
-(Cumulated emergency orders to account for Backlog SWF*switch con-
   sider emergency orders already placed
))/adjustment time for emergency orders SWF))
Units: Boards/Day

expected emergency IC arrival rate BP=
   DELAY3(emergency IC deliveries, shipment delay emergency IC de-
   liveries)
```

```
Units: material/Day

expected material arrival rate BP= DELAY FIXED (
   material orders BP, expected order lead time BP, 0)
Units: Materials/Day

expected material arrival rate IC emergency supplies at IC supplier
   FG inventory
= DELAY FIXED (
   emergency material orders, expected order lead time emergency
   ICs, 0)
Units: Materials/Day

expected material arrival rate Sup= DELAY FIXED (
   material orders Sup, expected order lead time Sup, 0)
Units: Materials/Day

expected order lead time BP=
   46
Units: Days

expected order lead time emergency ICs=
   15
Units: Days

expected order lead time Sup=
   6
Units: Days

Feasible FG production SWF=
   MIN(desired orders in production SWF, Inventory RM SWF/materials
   used per FG unit SWF
/minimum time to start production SWF)
Units: Widgets/Day

feasible production based on inventory FAT=
   MIN(Inventory Boards FAT/boards used per FG unit FAT, Inventory
   RM FAT/materials used per FG unit FAT
)/minimum time to start production FAT
Units: Widget/Day

FINAL TIME  = 500
   Units: Day

forecast 36 days out:=
   forecast 36 days out read from excel*systematic forecast error
   factor
Units: Widgets/Day
```

```
forecast 36 days out read from excel:=
   GET XLS DATA('input.xls', 'input', 'B', 'D1')
Units: Widget/Day

forecast 36 days out shifted to match demand at SWF= DELAY FIXED (
   forecast 36 days out, 36, 0)
Units: Widget/Day

forecast 76 days out:=
   forecast 76 days out read from excel*systematic forecast error
   factor
Units: Widgets/Day

forecast 76 days out read from excel:=
   GET XLS DATA('input.xls', 'input', 'B', 'E1')
Units: Widget/Day

forecast 76 days out shifted to match demand at SWF= DELAY FIXED (
   forecast 76 days out, 76, 0)
Units: Widget/Day

forecast for board printing SWF=
   MAX( switch adjustment to forecast*adjusted forecast for BP by
   SWF, (1-switch adjustment to forecast
)*forecast 76 days out
   )
Units: Widgets/Day

forecast for supplier SWF=
   MAX(switch adjustment to forecast*adjusted forecast for supplier
   by SWF, (
1-switch adjustment to forecast)*forecast 36 days out)
Units: Widgets/Day

fractional difference demand and forecast for 36 days at SWF=
   XIDZ(averaged demand requested for the current week 36 day FC at
   SWF, averaged forecast 36 days out shifted to match demand at
   SWF
, 1)
Units: Dimensionless

fractional difference demand and forecast for 76 days at SWF=
   XIDZ(averaged demand requested for the current week 76 day FC at
   SWF, averaged forecast 76 days out shifted to match demand at
   SWF
, 1)
Units: Dimensionless

gap between desired inventory and average inventory RM SFW=
```

```
   (desired inventory RM SWF-average inventory RM SWF)/materials
   used per FG unit SWF
Units: Widgets

gap desired BL and average BL SWF=
   (average Backlog SWF-desired Backlog SWF)*boards used per FG
   unit FAT
Units: Boards

incoming emergency IC orders=
   emergency material orders
Units: Materials/Day

incoming forecast board orders BP=
   ((forecast for board printing SWF*boards used per FG
   unit+emergency orders placed at BP
))
Units: Boards/Day

incoming order rate BP=
   incoming forecast board orders BP
Units: Boards/Day

incoming order rate Sup=
   (incoming orders Sup)/materials used per FG unit Sup
Units: Widget/Day

incoming orders Sup=
   ((forecast for supplier SWF*materials per FG unit+emergency or-
   ders placed at Sup
/boards per material))
Units: material/Day

incoming production requests SWF=
   demand adj Cust 9 days ahead
Units: Widget/Day

inflow customer backlog=
   demand requested for the current day
Units: Widget/Day

inflow waiting for production BP=
   incoming order rate BP
Units: Boards/Day

inflow waiting for production FAT=
   feasible production based on inventory FAT
Units: Widget/Day
```

```
inflow waiting for production Sup=
   incoming order rate Sup
Units: Widget/Day

ini installed base=
   0
Units: Widgets

ini market potential=
   7e+006
Units: Widgets

ini materials on order BP=
   0
Units: Materials

ini materials on order Sup=
   0
Units: Materials

initial Inventory Boards Man=
   0
Units: Boards

initial inventory FG BP=
   0
Units: Boards

initial inventory FG Man=
   0
Units: Widgets

initial inventory FG Sup=
   0
Units: Widgets

initial inventory FG SWF=
   0
Units: Widgets

initial inventory RM BP=
   0
Units: Materials

initial inventory RM FAT=
   0
Units: Materials

initial inventory RM Sup=
```

```
   0
Units: Materials

initial inventory RM SWF=
   0
Units: material

initial level emergency inventory supplier=
   10000
Units: Materials

INITIAL TIME  = 0
   Units: Day

Input=
   MAX(0,
   (
   1+STEP(Step Height,Step Time)
   +STEP(Step2 Height,Step2 Time)+
   (Pulse Quantity/TIME STEP)*PULSE(Pulse Time,TIME STEP)+
   RAMP(Ramp Slope,Ramp Start Time,Ramp End Time)+
   Sine Amplitude*SIN(2*3.14159*Time/Sine Period)+
   (Life Cycle Test Input*switch Life Cycle Test Input)+
        STEP(1,Noise Start Time)*Pink Noise
   )
    )
Units: Dimensionless

input from excel file 9 days out:=
   GET XLS DATA('input.xls', 'input', 'B', 'C1')
Units: Widget/Day

input from excel shifted to be demand requested for the current
   week:=
   TIME SHIFT(input from excel file 9 days out, -9)
Units: Widget/Day

Installed base= INTEG (
   demand adj Cust 9 days ahead,
        ini installed base)
Units: Widgets

inventory adjustment time SWF=
   30
Units: Day

Inventory Boards FAT= INTEG (
   +receiving rate Boards FAT-outgoing rate Boards FAT,
        initial Inventory Boards Man)
```

```
Units: Boards

Inventory Cost Boards FAT=
   inventory cost per unit Boards FAT*Inventory Boards FAT
Units: Dollars/Day

Inventory Cost FG BP=
   inventory cost per unit FG BP*Inventory FG BP
Units: Dollars/Day

Inventory Cost FG FAT=
   inventory cost per unit FG FAT*Inventory FG FAT
Units: Dollars/Day

Inventory Cost FG Sup=
   inventory cost per unit FG Sup*Inventory FG Sup
Units: Dollars/Day

Inventory Cost FG SWF=
   inventory cost per unit FG SWF*Inventory FG SWF
Units: Dollars/Day

inventory cost per unit Boards FAT=
   0.5
Units: Dollars/Board/Day

inventory cost per unit FG BP=
   0.5
Units: Dollars/Board/Day

inventory cost per unit FG FAT=
   0.9
Units: Dollars/Widget/Day

inventory cost per unit FG Sup=
   0.2
Units: Dollars/Widget/Day

inventory cost per unit FG SWF=
   1
Units: Dollars/Widget/Day

inventory cost per unit RM BP=
   0.45
Units: Dollars/Materials/Day

inventory cost per unit RM FAT=
   0.2
Units: Dollars/Materials/Day
```

```
inventory cost per unit RM Sup=
   0.1
Units: Dollars/Materials/Day

inventory cost per unit RM SWF=
   0.9
Units: Dollars/Materials/Day

inventory cost per unit WIP BP=
   0.45
Units: Dollars/Boards/Day

inventory cost per unit WIP FAT=
   0.7
Units: Dollars/Widget/Day

inventory cost per unit WIP Sup=
   0.2
Units: Dollars/Widget/Day

inventory cost per unit WIP SWF=
   0.9
Units: Dollars/Widget/Day

Inventory Cost RM BP=
   inventory cost per unit RM BP*Inventory RM BP
Units: Dollars/Day

Inventory Cost RM FAT=
   inventory cost per unit RM FAT*Inventory RM FAT
Units: Dollars/Day

Inventory Cost RM Sup=
   inventory cost per unit RM Sup*Inventory RM Sup
Units: Dollars/Day

Inventory Cost RM SWF=
   inventory cost per unit RM SWF*Inventory RM SWF
Units: Dollars/Day

Inventory Cost WIP BP=
   inventory cost per unit WIP BP*Inventory WIP BP var
Units: Dollars/Day

Inventory Cost WIP FAT=
   inventory cost per unit WIP FAT*Inventory WIP Man var
Units: Dollars/Day
```

```
Inventory Cost WIP Sup=
   inventory cost per unit WIP Sup*Inventory WIP Sup var
Units: Dollars/Day

Inventory Cost WIP SWF=
   inventory cost per unit WIP SWF*Inventory WIP SWF var
Units: Dollars/Day

Inventory FG BP= INTEG (
   +production rate BP-shipment rate BP,
        initial inventory FG BP)
Units: Boards

Inventory FG FAT= INTEG (
   product completions FAT-shipment rate FAT,
        initial inventory FG Man)
Units: Widgets

Inventory FG Sup= INTEG (
   product completions FG Sup-shipment rate Sup,
        initial inventory FG Sup)
Units: Widget

Inventory FG SWF= INTEG (
   product completions SWF-shipment rate SWF,
        initial inventory FG SWF)
Units: Widgets

Inventory RM BP= INTEG (
   +receiving rate RM BP-(desired production batched BP/boards per
   material),
        initial inventory RM BP)
Units: Materials

Inventory RM FAT= INTEG (
   +receiving rate RM FAT-outgoing rate RM FAT,
        initial inventory RM FAT)
Units: Materials

Inventory RM Sup= INTEG (
   +receiving rate RM Sup-outgoing rate RM Sup,
        initial inventory RM Sup)
Units: Materials

Inventory RM SWF= INTEG (
   -outgoing rate RM SWF+receiving rate RM SWF,
        initial inventory RM SWF)
Units: Materials
```

```
inventory turns=
   ZIDZ(cum demand requested for the current day,average total in-
   ventory cost over time
)
Units: Day*Widget/Dollars

Inventory WIP BP  =

   #LV3<DELAYP(desiredproductionbatchedBP,productiontimeBP:Inventor
   yWIPBP)#

             +
   #LV2<DELAYP(desiredproductionbatchedBP,productiontimeBP:Inventor
   yWIPBP)#

             +
   #LV1<DELAYP(desiredproductionbatchedBP,productiontimeBP:Inventor
   yWIPBP)#

   Units: Board

Inventory WIP BP var=
   Inventory WIP BP
Units: Boards

Inventory WIP Man  =

   #LV3<DELAYP(productionstartsFAT,productiontimeFAT:InventoryWIPMa
   n)#

             +
   #LV2<DELAYP(productionstartsFAT,productiontimeFAT:InventoryWIPMa
   n)#

             +
   #LV1<DELAYP(productionstartsFAT,productiontimeFAT:InventoryWIPMa
   n)#

   Units: Widget

Inventory WIP Man var=
   Inventory WIP Man
Units: Widget

Inventory WIP Sup  =

   #LV3<DELAYP(outgoingrateRMSup/materialsusedperFGunitSup,producti
   ontimeSup:InventoryWIPSup)#
```

```
          +
 #LV2<DELAYP(outgoingrateRMSup/materialsusedperFGunitSup,producti
 ontimeSup:InventoryWIPSup)#

          +
 #LV1<DELAYP(outgoingrateRMSup/materialsusedperFGunitSup,producti
 ontimeSup:InventoryWIPSup)#

 Units: Widget

Inventory WIP Sup var=
 Inventory WIP Sup
Units: Widgets

Inventory WIP SWF  =

 #LV3<DELAYP(FeasibleFGproductionSWF,productiontimeSWF:InventoryW
 IPSWF)#

          +
 #LV2<DELAYP(FeasibleFGproductionSWF,productiontimeSWF:InventoryW
 IPSWF)#

          +
 #LV1<DELAYP(FeasibleFGproductionSWF,productiontimeSWF:InventoryW
 IPSWF)#

 Units: Widget

Inventory WIP SWF var=
 Inventory WIP SWF
Units: Widget

largest possible RM outflow BP=
 MIN(capacity limit BP, Inventory RM BP/materials used per FG
 unit BP/minimum time to start production BP
)
Units: Boards/Day

Life Cycle Test Input=
 lkup Life Cycle Test Input and forecast for demand nine days
 ahead(Time/FINAL TIME
)-1
Units: Dimensionless

lkup Life Cycle Test Input and forecast for demand nine days ahead(
 [(0,0)-
 (1,2)],(0,0),(0.18,0),(0.256881,0.298246),(0.30581,0.684211),(0.
 324159
```

```
,0.95614),(0.376147,1.38596),(0.434251,1.62281),(0.498471,1.7077),(
   0.547401
,1.67544),(0.587156,1.57018),(0.623853,1.34211),(0.703364,0.54386),
   (0.730887
,0.280702),(0.782,0),(1,0),(1,0))
Units: Dimensionless

lkup Life Cycle Test Input PLC standard(
   [(0,0)-
   (1,2)],(0,0),(0.185,0),(0.259939,1.21053),(0.293578,1.7193),(0.3
   21101
,1.87719),(0.357798,1.95614),(0.415902,2),(0.440367,1.95614),(0.477
   064,1.85965
),(0.508235,1.62989),(0.569412,1.21708),(0.651765,0.733096),(0.7364
   71,0.362989
),(0.835294,0.0711744),(0.938824,0),(1,0))
Units: Dimensionless

lkup Life Cycle Test Input SCENARIO 1(
   [(0,0)-
   (1,2)],(0,0),(0.185,0),(0.259939,1.21053),(0.293578,1.7193),(0.3
   21101
,1.87719),(0.357798,1.95614),(0.415902,2),(0.461774,1.95614),(0.516
   82,1.81579
),(0.571865,1.5614),(0.626911,1.19298),(0.66055,0.929825),(0.697248
   ,0.578947
),(0.752294,0.27193),(0.834862,0.114035),(0.938824,0),(1,0))
Units: Dimensionless

lkup Life Cycle Test Input simple v01(
   [(0,0)-
   (1,2)],(0,0),(0.185,0),(0.185,2),(0.504587,2),(0.504587,0),(0.93
   8824
,0),(1,0))
Units: Dimensionless

lkup Life Cycle Test Input simple v02(
   [(0,0)-
   (1,2)],(0,0),(0.185,0),(0.185,0.5),(0.287462,0.5),(0.504587,2),(
   0.504587
,0),(0.938824,0),(1,0))
Units: Dimensionless

lkup Life Cycle Test Input simple v03(
   [(0,0)-
   (1,2)],(0,0),(0.185,0),(0.185,0.5),(0.287462,0.5),(0.504587,2),(
   0.9388
,2),(0.938824,0),(1,0))
Units: Dimensionless
```

```
lkup probability of problem BP(
   [(0,0)-
   (1,2)],(0,0),(0.185,0),(0.259939,0),(0.499,0),(0.5,1),(0.519,1),
   (0.52
,0),(1,0))
Units: Dimensionless

lkup probability of problem Sup(
   [(0,0)-
   (1,2)],(0,0),(0.185,0),(0.259939,0),(0.3,0),(0.301,1),(0.302,0),
   (1,
0))
Units: Dimensionless

Market potential= INTEG (
   -demand adj Cust 9 days ahead,
        ini market potential)
Units: Widgets

material arrival rate BP=
   receiving rate RM BP
Units: Materials/Day

material arrival rate Sup=
   receiving rate RM Sup
Units: Materials/Day

material order rate BP=
   emergency material orders+material orders BP
Units: Materials/Day

material order rate Sup=
   material orders Sup
Units: Materials/Day

material orders BP=
   MAX(0,  forecast for board printing SWF*materials per FG unit)
Units: Materials/Day

material orders Sup=
   MAX(0,incoming orders Sup)
Units: Materials/Day

materials from Sup needed for a RM FAT=
   1
Units: material/Widget

Materials on order BP= INTEG (
```

```
   +material order rate BP-material arrival rate BP,
        ini materials on order BP)
Units: Materials

Materials on order Sup= INTEG (
   +material order rate Sup-material arrival rate Sup,
        ini materials on order Sup)
Units: Materials

materials per FG unit=
   1
Units: material/Widget

materials used per FG unit BP=
   1
Units: Materials/Board

materials used per FG unit FAT=
   1
Units: Materials/Widget

materials used per FG unit Sup=
   1
Units: Materials/Widget

materials used per FG unit SWF=
   1
Units: material/Widget

mean of input data from excel 9 days out=
   GET DATA MEAN(input from excel file 9 days out, 91, 413)
Units: Widget/Day

minimum shipment time from inventory emergency IC supplier=
   1
Units: Days

minimum time to start production BP=
   1
Units: Day

minimum time to start production FAT=
   1
Units: Day

minimum time to start production SWF=
   1
Units: Day
```

```
Noise Correlation Time = 4
Units: Day

NOISE SEED=
   1
Units: Dimensionless

Noise Standard Deviation=
   0.8
Units: Dimensionless

Noise Start Time=
   92
Units: Day

order fulfillment rate BP=
   shipment rate BP
Units: Boards/Day

order fulfillment rate Sup=
   shipment rate Sup
Units: Widgets/Day

outflow customer backlog=
   receiving rate Cust
Units: Widgets/Day

outgoing rate Boards FAT=
   MAX(0,production starts FAT*boards used per FG unit FAT)
Units: Boards/Day

outgoing rate RM FAT=
   MAX(0,production starts FAT*materials used per FG unit FAT)
Units: Materials/Day

outgoing rate RM Sup=
   MAX(0,IF THEN ELSE(desired production Sup*materials used per FG
   unit Sup>Inventory RM Sup
/dimensional consistency day
   , Inventory RM Sup/dimensional consistency day, desired produc-
   tion Sup*materials used per FG unit Sup
))
Units: Materials/Day

outgoing rate RM SWF=
   MAX(0,Feasible FG production SWF*materials used per FG unit SWF)
Units: Materials/Day

Pink Noise = INTEG(Change in Pink Noise,0)
```

```
Units: Dimensionless

positive customer backlog=
   MAX(0,customer backlog/dimensional consistency day)
Units: Widget/Day

probablity of problem BP=
   lkup probability of problem BP(Time/FINAL TIME)*switch probabil-
   ity of problem BP
Units: Dimensionless

probablity of problem Sup=
   lkup probability of problem Sup(Time/FINAL TIME)*switch prob-
   ability of problem Sup
Units: Dimensionless

product completions FAT=
   MAX(0,DELAYP(production starts FAT, production time FAT : Inven-
   tory WIP Man
 ))
Units: Widget/Day

product completions FG Sup=
   DELAYP(outgoing rate RM Sup/materials used per FG unit Sup, pro-
   duction time Sup
 : Inventory WIP Sup )
Units: Widget/Day

product completions SWF=
   DELAYP(Feasible FG production SWF, production time SWF : Inven-
   tory WIP SWF
)
Units: Widgets/Day

production rate BP=
   DELAYP(desired production batched BP, production time BP : In-
   ventory WIP BP
 )
Units: Boards/Day

production starts FAT=
   MAX(0,
   MIN(waiting for production FAT/minimum time to start production
   FAT+inflow waiting for production FAT
, capacity limit FAT)
   )
Units: Widget/Day

production starts SWF=
```

```
   Feasible FG production SWF
Units: Widgets/Day

production time BP=
   4
Units: Days

production time FAT=
   4
Units: Days

production time Sup=
   4
Units: Days

production time SWF=
   4
Units: Days

Pulse Quantity=
   0
Units: Dimensionless*Day

Pulse Time=
   50
Units: Day

pulse train duration=
   1
Units: Day

pulse train end=
   500
Units: Day

Pulse Train Input=
   PULSE TRAIN(pulse train start, pulse train duration , pulse
   train repeattime
 , pulse train end )
Units: Dimensionless

pulse train repeattime=
   5
Units: Days

pulse train start=
   0
Units: Day
```

```
Ramp End Time=
   150
Units: Day

Ramp Slope=
   0
Units: 1/Day

Ramp Start Time=
   92
Units: Day

receiving rate Boards FAT=
   DELAY3(shipment rate BP,shipment delay BP)
Units: Boards/Day

receiving rate Cust=
   DELAY3(shipment rate SWF,shipment delay SWF)
Units: Widget/Day

receiving rate ICs IC supplier=
   expected material arrival rate IC emergency supplies at IC sup-
   plier FG inventory
Units: material/Day

receiving rate RM BP=
   expected material arrival rate BP+expected emergency IC arrival
   rate BP
Units: Materials/Day

receiving rate RM FAT=
   DELAY3(shipment rate Sup,shipment delay Sup)*materials from Sup
   needed for a RM FAT
Units: Materials/Day

receiving rate RM Sup=
   expected material arrival rate Sup
Units: Materials/Day

receiving rate RM SWF=
   DELAY3(shipment rate FAT*materials used per FG unit SWF,shipment
   delay FAT
)
Units: Materials/Day

SAVEPER  =
        TIME STEP
   Units: Day
```

```
shipment delay BP=
   4
Units: Days

shipment delay emergency IC deliveries=
   4
Units: Days

shipment delay FAT=
   4
Units: Days

shipment delay Sup=
   4
Units: Days

shipment delay SWF=
   4
Units: Days

shipment rate BP=
   Inventory FG BP/dimensional consistency day
Units: Boards/Day

shipment rate FAT=
   Inventory FG FAT/dimensional consistency day
Units: Widgets/Day

shipment rate Sup=
   Inventory FG Sup/dimensional consistency day
Units: Widget/Day

shipment rate SWF=
   Inventory FG SWF/dimensional consistency day
Units: Widgets/Day

Sine Amplitude=
   0
Units: Dimensionless

Sine Period=50
Units: Days

stddev of input data from excel 9 days out=
   GET DATA STDV( input from excel file 9 days out, 91, 413)
Units: Widget/Day

Step Height=
   0
```

```
Units: Dimensionless

Step Time=
   0
Units: Day

Step2 Height=
   0
Units: Dimensionless

Step2 Time=
   91
Units: Days

switch adjustment to forecast=
   1
Units: Dimensionless

switch adjustment to Inventory RM SWF=
   1
Units: Dimensionless

switch consider emergency orders already placed=
   0
Units: Dimensionless

switch emergency orders to account for Backlog BP setup D=
   1
Units: Dimensionless

switch emergency orders to account for Backlog SWF=
   1
Units: Dimensionless

switch Life Cycle Test Input=
   0
Units: Dimensionless

switch probability of problem BP=
   0
Units: Dimensionless

switch probability of problem Sup=
   0
Units: Dimensionless

switch to consider cum adj to inventory RM SWF=
   0
Units: Dimensionless
```

```
systematic forecast error factor=
   1
Units: Dimensionless

time base week=
   TIME BASE(0, 0.2 )
Units: Dimensionless

TIME STEP  = 0.25
   Units: Day

total cumulated inventory cost BP=
   Cumulated Inventory Cost FG BP+Cumulated Inventory Cost RM
   BP+Cumulated Inventory Cost WIP BP
Units: Dollars

total cumulated inventory cost FAT=
   Cumulated Inventory Cost FG FAT+Cumulated Inventory Cost Boards
   FAT+Cumulated Inventory Cost WIP FAT
+Cumulated Inventory Cost RM FAT
Units: Dollars

total cumulated inventory cost Sup=
   Cumulated Inventory Cost FG Sup+Cumulated Inventory Cost RM
   Sup+Cumulated Inventory Cost WIP Sup
Units: Dollars

total cumulated inventory cost SWF=
   Cumulated Inventory Cost FG SWF+Cumulated Inventory Cost RM
   SWF+Cumulated Inventory Cost WIP SWF
Units: Dollars

total inventory cost BP=
   Inventory Cost FG BP+Inventory Cost RM BP+Inventory Cost WIP BP
Units: Dollars/Day

total inventory cost FAT=
   Inventory Cost FG FAT+Inventory Cost Boards FAT+Inventory Cost
   WIP FAT+Inventory Cost RM FAT
Units: Dollars/Day

total inventory cost Sup=
   Inventory Cost FG Sup+Inventory Cost RM Sup+Inventory Cost WIP
   Sup
Units: Dollars/Day

total inventory cost SWF=
```

```
   Inventory Cost FG SWF+Inventory Cost RM SWF+Inventory Cost WIP
   SWF
Units: Dollars/Day

Total products shipped to Cust= INTEG (
   receiving rate Cust,
        0)
Units: Widgets

waiting for production BP= INTEG (
   +inflow waiting for production BP-desired production batched BP,
        0)
Units: Boards

waiting for production FAT= INTEG (
   +inflow waiting for production FAT-production starts FAT,
        0)
Units: Widgets

waiting for production Sup= INTEG (
   +inflow waiting for production Sup-desired production Sup,
        0)
Units: Widget

White Noise=
   Noise Standard Deviation*((24*Noise Correlation Time/TIME
   STEP)^0.5*(RANDOM UNIFORM
(0, 1, NOISE SEED) - 0.5
   ))
Units: Dimensionless
```

III. Listing of Model Equations: Pull

```
acclength FAT=
        10
   Units: Days

acclength SWF=
   10
Units: Days

adjusted forecast sent to BP by SWF=
   MAX(0,((forecast 76 days out*adjustment to demand for BP SWF)))
Units: Widget/Day

adjusted forecast sent to supplier by SWF=
   MAX(0, ((forecast 36 days out*adjustment to demand for Sup
   SWF)))
```

```
Units: Widget/Day

adjustment for difference demand and forecast BP=
   (((difference demand and forecast for 75 days BP*materials used
   per FG unit Sup
*dimensional consistency day
   ))/dimensional consistency day)*switch adjustmentfor difference
   demand and forecast BP
Units: material/Day

adjustment for difference demand and forecast Sup=
   (((difference demand and forecast for 35 days Sup*materials used
   per FG unit Sup
)))        *switch adjustmentfor difference demand and forecast Sup
Units: material/Day

adjustment time for emergency orders SWF=
   36
Units: Day

adjustment to demand for BP SWF=
   MIN(fractional difference demand and forecast for 76 days at
   SWF, 1+XIDZ(averaged demand requested for the current week 76
   day FC at SWF
, forecast 76 days out, 0))
Units: Dimensionless

adjustment to demand for Sup SWF=
   MIN(fractional difference demand and forecast for 36 days at
   SWF, 1+XIDZ(averaged demand requested for the current week 36
   day FC at SWF
, forecast 36 days out, 0))
Units: Dimensionless

adjustment to desired material order rate BP=
   0+STEP( adjustment for difference demand and forecast
   BP+adjustment to Inventory RM BP
, starting time for forecast adjustments BP)
Units: Materials/Day

adjustment to desired material order rate Sup=
   0+STEP(adjustment for difference demand and forecast
   Sup+adjustment to Inventory RM Sup
, starting time for forecast adjustments Sup)
Units: material/Day

adjustment to Inventory RM BP=
   ((gap between desired inventory and average inventory RM BP-
   (cumulated adjustment to inventory RM BP
```

```
*switch to consider cum adj to inventory RM BP))
   /inventory adjustment time BP)
   *switch adjustment to Inventory RM BP
Units: Materials/Day

adjustment to Inventory RM Sup=
   ((gap between desired inventory and average inventory RM Sup-
   (cumulated adjustment to inventory RM Sup
*switch to consider cum adj to inventory RM Sup))
   /inventory adjustment time Sup)
   *switch adjustment to Inventory RM Sup
Units: material/Day

average Backlog SWF=
   SMOOTH(Backlog SWF,averaging time backlog SWF)
Units: Widgets

average cum positive customer backlog=
   ZIDZ(cum positive customer backlog, Time-150)
Units: Widget/Day

average inventory RM BP=
   smooth3(Inventory RM BP,inventory adjustment time BP)
Units: Materials

average inventory RM Sup=
   smooth3(Inventory RM Sup, inventory adjustment time Sup)
Units: Materials

average total inventory cost over time=
   ZIDZ(cum total total inventory cost, Time)
Units: Dollars/Day

averaged demand requested for the current week 36 day FC at SWF=
   SMOOTH(demand requested for the current day, averaging time ad-
   justment for difference demand and 36 day forecast SWF
)
Units: Widget/Day

averaged demand requested for the current week 76 day FC at SWF=
   SMOOTH(demand requested for the current day, averaging time ad-
   justment for difference demand and 76 day forecast SWF
)
Units: Widget/Day

averaged demand requested for the current week BP=
   SMOOTH(incoming order rate BP/boards used per FG unit FAT, aver-
   aging time adjustment for difference demand and forecast BP
)
```

```
Units: Widget/Day

averaged demand requested for the current week Sup=
   SMOOTH(incoming order rate Sup, averaging time adjustment for
   difference demand and forecast Sup
)
Units: Widget/Day

averaged forecast 35 days out delayed to match demand=
   SMOOTH(forecast 35 days out shifted to match demand, averaging
   time adjustment for difference demand and forecast Sup
)
Units: Widget/Day

averaged forecast 36 days out shifted to match demand at SWF=
   SMOOTH(forecast 36 days out shifted to match demand at SWF, av-
   eraging time adjustment for difference demand and 36 day fore-
   cast SWF
)
Units: Widget/Day

averaged forecast 75 days out delayed to match demand=
   SMOOTH(forecast 75 days out shifted to match demand, averaging
   time adjustment for difference demand and forecast BP
)
Units: Widget/Day

averaged forecast 76 days out shifted to match demand at SWF=
   SMOOTH(forecast 76 days out shifted to match demand at SWF, av-
   eraging time adjustment for difference demand and 76 day fore-
   cast SWF
)
Units: Widget/Day

averaging time adjustment for difference demand and 36 day forecast
   SWF=
   10
Units: Day

averaging time adjustment for difference demand and 76 day forecast
   SWF=
   10
Units: Day

averaging time adjustment for difference demand and forecast BP=
   5
Units: Day

averaging time adjustment for difference demand and forecast Sup=
```

```
   5
Units: Day

averaging time backlog SWF=
   14
Units: Days

averaging time FAT=
   5
Units: Days

avg cum sq diff demand and FC for 35 days setup A=
   ZIDZ(cumulated sq diff demand and FC for 35 days setup A, Time)
Units: Dimensionless

avg cum sq diff demand and FC for 75 days setup A 0=
   ZIDZ(cumulated sq diff demand and FC for 75 days setup A 0,
   Time)
Units: Dimensionless

avg forecast demand during LT materials SWF=
   forecast demand in materials LT SWF/lead time materials SWF
Units: material/Day

Backlog BP= INTEG (
   incoming order rate BP-order fulfillment rate BP,
        0)
Units: Boards

Backlog Emergency IC supplier= INTEG (
   +incoming emergency IC orders-backlog reduction emergency IC
   supplier,
        0)
Units: Materials

Backlog FAT= INTEG (
   incoming order rate FAT-order fulfillment rate FAT,
        0)
Units: Widgets

backlog reduction emergency IC supplier=
   emergency IC deliveries
Units: Materials/Day

Backlog Sup= INTEG (
   incoming order rate Sup-order fulfillment rate Sup,
        0)
Units: Widgets
```

```
Backlog SWF= INTEG (
   incoming production requests SWF-production starts SWF,
        0)
Units: Widgets

batch size BP=
   5000
Units: Boards/Day

board arrival rate FAT=
   receiving rate Boards FAT
Units: Boards/Day

board orders FAT=
   MAX(0,orders boards FAT)
Units: Boards/Day

Boards on order FAT= INTEG (
   +board orders FAT-board arrival rate FAT+Emergency orders to
   account for Backlog SWF
,
        ini boards on order FAT)
Units: Boards

boards per material=
   1
Units: Boards/Materials

boards used per FG unit FAT=
   1
Units: Board/Widget

capacity FAT=
   50000
Units: Widget/Day

capacity limit BP=
   20000
Units: Boards/Day

capacity limit FAT=
   MIN(capacity FAT,feasible FG production based on inventory FAT)
Units: Widget/Day

Change in Pink Noise = (White Noise - Pink Noise)/Noise Correlation
   Time
Units: 1/Day

counter annual acc FAT=
```

```
   AnnualAccumulation(pick FAT,acclength FAT,Time,TIME STEP)
Units: Dmnl

counter annual acc SWF=
   AnnualAccumulation(pick SWF,acclength SWF,Time,TIME STEP)
Units: Dmnl

cum demand requested for the current day= INTEG (
   demand requested for the current day,
        0)
Units: Widget

cum orders not filled on time= INTEG (
   IF THEN ELSE((customer backlog/dimensional consistency
   day+inflow customer backlog
-outflow customer backlog)>0, MIN(demand requested for the current
   day, customer backlog
/dimensional consistency day+inflow customer backlog-outflow cus-
   tomer backlog
), 0),
        0)
Units: Widgets

cum positive customer backlog= INTEG (
   positive customer backlog,
        0)
Units: Widget

cum positive customer backlog for optimization=
   IF THEN ELSE(Time > FINAL TIME-TIME STEP/2, cum positive cus-
   tomer backlog,
 0)
Units: Widgets

cum total total inventory cost=
   total cumulated inventory cost BP+total cumulated inventory cost
   FAT+total cumulated inventory cost Sup
+total cumulated inventory cost SWF
Units: Dollars

cum total total inventory cost for optimization=
   IF THEN ELSE(Time > FINAL TIME-TIME STEP/2, cum total total in-
   ventory cost
, 0)
Units: Dollars

cumulated adjustment for difference demand and forecast BP= INTEG (
   adjustment for difference demand and forecast BP,
        0)
```

```
Units: Materials

cumulated adjustment for difference demand and forecast Sup= INTEG
   (
   adjustment for difference demand and forecast Sup,
        0)
Units: material

cumulated adjustment to inventory RM BP= INTEG (
   adjustment to Inventory RM BP,
        0)
Units: Materials

cumulated adjustment to inventory RM Sup= INTEG (
   adjustment to Inventory RM Sup,
        0)
Units: Materials

Cumulated emergency orders to account for Backlog SWF= INTEG (
   Emergency orders to account for Backlog SWF,
        0)
Units: Boards

Cumulated Inventory Cost Boards FAT= INTEG (
   Inventory Cost Boards FAT,
        0)
Units: Dollars

Cumulated Inventory Cost FG BP= INTEG (
   Inventory Cost FG BP,
        0)
Units: Dollars

Cumulated Inventory Cost FG FAT= INTEG (
   Inventory Cost FG FAT,
        0)
Units: Dollars

Cumulated Inventory Cost FG Sup= INTEG (
   Inventory Cost FG Sup,
        0)
Units: Dollars

Cumulated Inventory Cost FG SWF= INTEG (
   Inventory Cost FG SWF,
        0)
Units: Dollars

Cumulated Inventory Cost RM BP= INTEG (
```

```
   Inventory Cost RM BP,
        0)
Units: Dollars

Cumulated Inventory Cost RM FAT= INTEG (
   Inventory Cost RM FAT,
        0)
Units: Dollars

Cumulated Inventory Cost RM Sup= INTEG (
   Inventory Cost RM Sup,
        0)
Units: Dollars

Cumulated Inventory Cost RM SWF= INTEG (
   Inventory Cost RM SWF,
        0)
Units: Dollars

Cumulated Inventory Cost WIP BP= INTEG (
   Inventory Cost WIP BP,
        0)
Units: Dollars

Cumulated Inventory Cost WIP FAT= INTEG (
   Inventory Cost WIP FAT,
        0)
Units: Dollars

Cumulated Inventory Cost WIP Sup= INTEG (
   Inventory Cost WIP Sup,
        0)
Units: Dollars

Cumulated Inventory Cost WIP SWF= INTEG (
   Inventory Cost WIP SWF,
        0)
Units: Dollars

cumulated sq diff demand and FC for 35 days setup A= INTEG (
   squared diff demand and FC for 35 days setup A 0 0,
        0)
Units: Day

cumulated sq diff demand and FC for 75 days setup A 0= INTEG (
   squared diff demand and FC for 75 days setup A 0,
        0)
Units: Day
```

```
customer backlog= INTEG (
   inflow customer backlog-outflow customer backlog,
        0)
Units: Widget

delay fixed 10 cum sq diff demand and FC for 35 days setup=
   DELAY FIXED(cumulated sq diff demand and FC for 35 days setup A,
   10, 0)
Units: Day

delivery delay SWF=
   ZIDZ(Backlog SWF, shipment rate SWF)
Units: Days

delivery performance to customer request=
   XIDZ((cum demand requested for the current day-cum orders not
   filled on time
), cum demand requested for the current day,1)
Units: Dimensionless

delivery time=
   1
Units: Days

demand adj Cust 4 days ahead= DELAY FIXED (
   demand adj Cust 9 days ahead,5,demand adj Cust 9 days ahead)
Units: Widget/Day

demand adj Cust 9 days ahead=
   MIN(demand Cust 9 days ahead,Market potential/delivery time)
Units: Widgets/Day

demand Cust 9 days ahead=
   input from excel file 9 days out*Input
Units: Widgets/Day

demand requested for the current day= DELAY FIXED (
    demand adj Cust 9 days ahead, 9, demand adj Cust 9 days ahead)
Units: Widget/Day

desired Backlog SWF=
   0
Units: Widgets

desired days of stock BP=
   10
Units: Days

desired days of stock Sup=
```

```
   10
Units: Days

desired Inventory RM BP=
   desired days of stock BP*averaged demand requested for the cur-
   rent week BP
*materials used per FG unit SWF
Units: material

desired Inventory RM Sup=
   desired days of stock Sup*averaged demand requested for the cur-
   rent week Sup
*materials used per FG unit Sup
Units: Materials

desired orders in production SWF=
   MAX(0,Backlog SWF/minimum time to start production SWF+incoming
   production requests SWF
)
Units: Widgets/Day

desired production batched BP=
   MAX(0,
   IF THEN ELSE(
        (INTEGER(((waiting for production BP/minimum time to start
   production BP
+inflow waiting for production BP)/batch size BP))*batch size
   BP<largest possible RM outflow BP
),
        (INTEGER(((waiting for production BP/minimum time to start
   production BP
+inflow waiting for production BP)/batch size BP))*batch size BP),
        (INTEGER((largest possible RM outflow BP/batch size
   BP))*batch size BP
)
   )*(1-probablity of problem BP)
     )
Units: Boards/Day

desired production FAT=
   MAX(0,
   MIN(waiting for production FAT/minimum time to start production
   FAT+inflow waiting for production FAT
, capacity limit FAT)
   )
Units: Widget/Day

desired production Sup=
```

```
   MIN(waiting for production Sup/dimensional consistency
   day+inflow waiting for production Sup
, Inventory RM Sup/materials used per FG unit Sup/dimensional con-
   sistency day
)
Units: Widget/Day

diff=
   (cumulated sq diff demand and FC for 35 days setup A-delay fixed
   10 cum sq diff demand and FC for 35 days setup
)/10
Units: Day

difference demand and forecast for 35 days Sup=
   averaged demand requested for the current week Sup-averaged
   forecast 35 days out delayed to match demand
Units: Widget/Day

difference demand and forecast for 36 days SWF=
   averaged demand requested for the current week 36 day FC at SWF-
   averaged forecast 36 days out shifted to match demand at SWF
Units: Widget/Day

difference demand and forecast for 75 days BP=
   averaged demand requested for the current week BP-averaged fore-
   cast 75 days out delayed to match demand
Units: Widget/Day

difference demand and forecast for 76 days SWF=
   averaged demand requested for the current week 76 day FC at SWF-
   averaged forecast 76 days out shifted to match demand at SWF
Units: Widget/Day

dimensional consistency day=
   1
Units: Day

dimensional consistency days per widget=
   1
Units: Days/Widget

dimensional difference demand and forecast for 35 days Sup=
   difference demand and forecast for 35 days Sup*dimensional con-
   sistency days per widget
Units: Dimensionless

dimensionless difference demand and forecast for 75 days BP=
   difference demand and forecast for 75 days BP*dimensional con-
   sistency days per widget
```

```
Units: Dimensionless

emergency IC deliveries=
   IF THEN ELSE(Emergency Inventory ICs at IC supplier/minimum
   shipment time from inventory emergency IC supplier
>0, MIN(Backlog Emergency IC supplier/minimum shipment time from
   inventory emergency IC supplier
, Emergency Inventory ICs at IC supplier/minimum shipment time from
   inventory emergency IC supplier
), Emergency Inventory ICs at IC supplier/minimum shipment time
   from inventory emergency IC supplier
)
Units: Materials/Day

Emergency Inventory ICs at IC supplier= INTEG (
   +receiving rate ICs IC supplier-emergency IC deliveries,
        initial level emergency inventory supplier)
Units: Materials

emergency material orders=
   MAX(0,Emergency orders to account for Backlog SWF/boards per
   material)
Units: Materials/Day

emergency orders placed at Sup=
   MAX(0,Emergency orders to account for Backlog SWF)
Units: Boards/Day

Emergency orders to account for Backlog SWF=
   switch emergency orders to account for Backlog SWF*MAX(0, (((gap
   desired BL and average BL SWF
-(Cumulated emergency orders to account for Backlog SWF*switch con-
   sider emergency orders already placed
)))/adjustment time for emergency orders SWF))
Units: Boards/Day

End Time FAT=
   FINAL TIME
Units: Days

End Time SWF=
   FINAL TIME
Units: Days

expected demand in LT boards FAT=
   five day average of FG orders FAT*boards used per FG unit
   FAT*lead time boards FAT
Units: Boards
```

```
expected demand in LT materials FAT=
   five day average of FG orders FAT*materials used per FG unit
   FAT*lead time materials FAT
Units: Materials

expected emergency IC arrival rate BP=
   DELAY3(emergency IC deliveries, shipment delay emergency IC de-
   liveries)
Units: Materials/Day

expected material arrival rate BP= DELAY FIXED (
   material orders BP, expected order lead time BP, 0)
Units: Materials/Day

expected material arrival rate IC emergency supplies at IC supplier
   FG inventory
= DELAY FIXED (
   emergency material orders, expected order lead time emergency
   ICs, 0)
Units: Materials/Day

expected material arrival rate Sup= DELAY FIXED (
   material orders Sup, expected order lead time Sup, 0)
Units: Materials/Day

expected order lead time BP=
   46
Units: Days

expected order lead time emergency ICs=
   15
Units: Days

expected order lead time Sup=
   6
Units: Days

feasible FG production based on inventory FAT=
   MIN(Inventory Boards FAT/boards used per FG unit FAT, Inventory
   RM FAT/materials used per FG unit FAT
)/minimum time to start production FAT
Units: Widget/Day

Feasible FG production SWF=
   MIN(desired orders in production SWF, Inventory RM SWF/materials
   used per FG unit SWF
/minimum time to start production SWF)
Units: Widgets/Day
```

```
FINAL TIME  = 500
Units: Day

five day average of FG orders FAT=
   SMOOTH(incoming order rate FAT, averaging time FAT )
Units: Widget/Day

forecast 35 days out shifted to match demand= DELAY FIXED (
   forecast for supplier SWF, 6, 0)
Units: Widget/Day

forecast 36 days out:=
   forecast 36 days out read from excel*systematic forecast error
   factor
Units: Widgets/Day

forecast 36 days out read from excel:=
   GET XLS DATA('input.xls', 'input', 'B', 'D1')
Units: Widget/Day

forecast 36 days out shifted to match demand at SWF= DELAY FIXED (
   forecast 36 days out, 36, 0)
Units: Widget/Day

forecast 75 days out shifted to match demand= DELAY FIXED (
   forecast for board printing SWF, 46, 0)
Units: Widget/Day

forecast 76 days out:=
   forecast 76 days out read from excel*systematic forecast error
   factor
Units: Widgets/Day

forecast 76 days out read from excel:=
   GET XLS DATA('input.xls', 'input', 'B', 'E1')
Units: Widget/Day

forecast 76 days out shifted to match demand at SWF= DELAY FIXED (
   forecast 76 days out, 76, 0)
Units: Widget/Day

forecast demand in materials LT SWF=
   (forecast Sup shifted to 0 days ahead+forecast Sup shifted to 1
   day ahead+
forecast Sup shifted to 2 days ahead+forecast Sup shifted to 3 days
   ahead+forecast Sup shifted to 4 days ahead
+forecast Sup shifted to 5 days ahead+forecast Sup shifted to 6
   days ahead+
```

```
forecast Sup shifted to 7 days ahead+forecast Sup shifted to 8 days
   ahead+forecast Sup shifted to 9 days ahead
+forecast Sup shifted to 1 day behind)*materials used per FG unit
   SWF*dimensional consistency day
Units: material

forecast error BP=
   SQRT(avg cum sq diff demand and FC for 75 days setup A 0)
Units: Dimensionless

forecast error Sup=
   SQRT(avg cum sq diff demand and FC for 35 days setup A)
Units: Dimensionless

forecast for board printing SWF=
   MAX( switch adjustment to forecast*adjusted forecast sent to BP
   by SWF, (1
-switch adjustment to forecast)*forecast 76 days out)
Units: Widget/Day

forecast for supplier SWF=
   MAX( switch adjustment to forecast*adjusted forecast sent to
   supplier by SWF
, (1-switch adjustment to forecast)*forecast 36 days out)
Units: Widget/Day

forecast Sup shifted to 0 days ahead= DELAY FIXED (
   forecast for supplier SWF, 36, 0)
Units: Widget/Day

forecast Sup shifted to 1 day ahead= DELAY FIXED (
   forecast for supplier SWF, 35, 0)
Units: Widget/Day

forecast Sup shifted to 1 day behind= DELAY FIXED (
   forecast for supplier SWF, 37, 0)
Units: Widget/Day

forecast Sup shifted to 2 days ahead= DELAY FIXED (
   forecast for supplier SWF, 34, 0)
Units: Widget/Day

forecast Sup shifted to 3 days ahead= DELAY FIXED (
   forecast for supplier SWF, 33, 0)
Units: Widget/Day

forecast Sup shifted to 4 days ahead= DELAY FIXED (
   forecast for supplier SWF, 32, 0)
Units: Widget/Day
```

```
forecast Sup shifted to 5 days ahead= DELAY FIXED (
   forecast for supplier SWF, 31, 0)
Units: Widget/Day

forecast Sup shifted to 6 days ahead= DELAY FIXED (
   forecast for supplier SWF, 30, 0)
Units: Widget/Day

forecast Sup shifted to 7 days ahead= DELAY FIXED (
   forecast for supplier SWF, 29, 0)
Units: Widget/Day

forecast Sup shifted to 8 days ahead= DELAY FIXED (
   forecast for supplier SWF, 28, 0)
Units: Widget/Day

forecast Sup shifted to 9 days ahead= DELAY FIXED (
   forecast for supplier SWF, 27, 0)
Units: Widget/Day

fractional difference demand and forecast for 36 days at SWF=
   XIDZ(averaged demand requested for the current week 36 day FC at
   SWF, averaged forecast 36 days out shifted to match demand at
   SWF
, 1)
Units: Dimensionless

fractional difference demand and forecast for 76 days at SWF=
   XIDZ(averaged demand requested for the current week 76 day FC at
   SWF, averaged forecast 76 days out shifted to match demand at
   SWF
, 1)
Units: Dimensionless

gap between desired inventory and average inventory RM BP=
   (desired Inventory RM BP-average inventory RM BP)
Units: Materials

gap between desired inventory and average inventory RM Sup=
   (desired Inventory RM Sup-average inventory RM Sup)
Units: Materials

gap desired BL and average BL SWF=
   (average Backlog SWF-desired Backlog SWF)*boards used per FG
   unit FAT
Units: Boards

incoming board orders BP=
```

```
   board orders FAT
Units: Boards/Day

incoming emergency IC orders=
   emergency material orders
Units: Materials/Day

incoming material orders SUP=
   material orders FAT+(Emergency orders to account for Backlog
   SWF/boards per material
)
Units: material/Day

incoming order rate BP=
   incoming board orders BP+Emergency orders to account for Backlog
   SWF
Units: Boards/Day

incoming order rate FAT=
   material orders from FAT SWF/materials used per FG unit
   FAT+(Emergency orders to account for Backlog SWF
/boards used per FG unit FAT
   )
Units: Widgets/Day

incoming order rate Sup=
   (incoming material orders SUP)/materials used per FG unit Sup
Units: Widget/Day

incoming production requests SWF=
   demand adj Cust 9 days ahead
Units: Widget/Day

incorporate initial stock into forecast boards=
   ((STEP( initial inventory size RM SWF/materials used per FG unit
   Sup+initial inventory size boards FAT
/boards used per FG unit FAT
   , 24)/dimensional consistency day)-(STEP( initial inventory size
   RM SWF/materials used per FG unit Sup
+
   initial inventory size boards FAT
   /boards used per FG unit FAT, 25)/dimensional consistency
   day))*switch incorporate base safety stock into forecasts
Units: Widgets/Day

incorporate initial stock into forecast materials=
   ((STEP( initial inventory size RM SWF/materials used per FG unit
   Sup+initial inventory size RM FAT
/materials used per FG unit Sup
```

```
   , 64)/dimensional consistency day)-(STEP( initial inventory size
   RM SWF/materials used per FG unit Sup
+
   initial inventory size boards FAT
   /boards used per FG unit FAT, 65)/dimensional consistency
   day))*switch incorporate base safety stock into forecasts
Units: Widgets/Day

inflow customer backlog=
   demand requested for the current day
Units: Widget/Day

inflow waiting for production BP=
   incoming order rate BP
Units: Boards/Day

inflow waiting for production FAT=
   incoming order rate FAT
Units: Widget/Day

inflow waiting for production Sup=
   incoming order rate Sup
Units: Widget/Day

ini boards on order FAT=
   0
Units: Boards

ini installed base=
   0
Units: Widgets

ini market potential=
   7e+006
Units: Widgets

ini materials on order BP=
   0
Units: Materials

ini materials on order FAT=
   0
Units: Materials

ini materials on order Sup=
   0
Units: Materials

ini materials on order SWF=
```

```
   0
Units: Materials

initial Inventory Boards Man=
   0
Units: Boards

initial inventory FG BP=
   0
Units: Boards

initial inventory FG Man=
   0
Units: Widgets

initial inventory FG Sup=
   0
Units: Widgets

initial inventory FG SWF=
   0
Units: Widgets

initial inventory RM BP=
   0
Units: Materials

initial inventory RM FAT=
   0
Units: Materials

initial inventory RM Sup=
   0
Units: Materials

initial inventory RM SWF=
   0
Units: material

initial inventory size boards FAT=
   100000
Units: Boards

initial inventory size RM FAT=
   100000
Units: Materials

initial inventory size RM SWF=
   100000
```

```
Units: Materials

initial level emergency inventory supplier=
   10000
Units: Materials

initial stock boards FAT=
   STEP(initial inventory size boards FAT, inventory begin time
   boards FAT)-STEP
(initial inventory size boards FAT,inventory end time boards FAT)
Units: Boards

initial stock RM FAT=
   STEP(initial inventory size RM FAT, inventory begin time RM
   FAT)-STEP(initial inventory size RM FAT
,inventory end time RM FAT)
Units: Materials

initial stock SWF=
   STEP(initial inventory size RM SWF, inventory begin time RM
   SWF)-STEP(initial inventory size RM SWF
,inventory end time RM SWF)
Units: Materials

INITIAL TIME  = 0
Units: Day

Input=
   MAX(0,
   (
   1+STEP(Step Height,Step Time)
   +STEP(Step2 Height,Step2 Time)+
   (Pulse Quantity/TIME STEP)*PULSE(Pulse Time,TIME STEP)+
   RAMP(Ramp Slope,Ramp Start Time,Ramp End Time)+
   Sine Amplitude*SIN(2*3.14159*Time/Sine Period)+
   (Life Cycle Test Input*switch Life Cycle Test Input)+
        STEP(1,Noise Start Time)*Pink Noise
   )
    )
Units: Dimensionless

input from excel file 9 days out:=
   GET XLS DATA('input.xls', 'input', 'B', 'C1')
Units: Widget/Day

input from excel shifted to be demand requested for the current
   week:=
   TIME SHIFT(input from excel file 9 days out, -9)
Units: Widget/Day
```

```
Installed base= INTEG (
   demand adj Cust 9 days ahead,
        ini installed base)
Units: Widgets

Interval FAT=
   1
Units: Days

Interval SWF=
   1
Units: Days

inventory adjustment time BP=
   46
Units: Day

inventory adjustment time Sup=
   6
Units: Day

inventory begin time boards FAT=
   71
Units: Days

inventory begin time RM FAT=
   71
Units: Days

inventory begin time RM SWF=
   81
Units: Days

Inventory Boards FAT= INTEG (
   +receiving rate Boards FAT-outgoing rate Boards FAT,
        initial Inventory Boards Man)
Units: Boards

Inventory Cost Boards FAT=
   inventory cost per unit Boards FAT*Inventory Boards FAT
Units: Dollars/Day

Inventory Cost FG BP=
   inventory cost per unit FG BP*Inventory FG BP
Units: Dollars/Day

Inventory Cost FG FAT=
   inventory cost per unit FG FAT*Inventory FG FAT
```

```
Units: Dollars/Day

Inventory Cost FG Sup=
   inventory cost per unit FG Sup*Inventory FG Sup
Units: Dollars/Day

Inventory Cost FG SWF=
   inventory cost per unit FG SWF*Inventory FG SWF
Units: Dollars/Day

inventory cost per unit Boards FAT=
   0.5
Units: Dollars/Board/Day

inventory cost per unit FG BP=
   0.5
Units: Dollars/Board/Day

inventory cost per unit FG FAT=
   0.9
Units: Dollars/Widget/Day

inventory cost per unit FG Sup=
   0.2
Units: Dollars/Widget/Day

inventory cost per unit FG SWF=
   1
Units: Dollars/Widget/Day

inventory cost per unit RM BP=
   0.45
Units: Dollars/Materials/Day

inventory cost per unit RM FAT=
   0.2
Units: Dollars/Materials/Day

inventory cost per unit RM Sup=
   0.1
Units: Dollars/Materials/Day

inventory cost per unit RM SWF=
   0.9
Units: Dollars/Materials/Day

inventory cost per unit WIP BP=
   0.45
Units: Dollars/Boards/Day
```

```
inventory cost per unit WIP FAT=
   0.7
Units: Dollars/Widget/Day

inventory cost per unit WIP Sup=
   0.2
Units: Dollars/Widget/Day

inventory cost per unit WIP SWF=
   0.9
Units: Dollars/Widget/Day

Inventory Cost RM BP=
   inventory cost per unit RM BP*Inventory RM BP
Units: Dollars/Day

Inventory Cost RM FAT=
   inventory cost per unit RM FAT*Inventory RM FAT
Units: Dollars/Day

Inventory Cost RM Sup=
   inventory cost per unit RM Sup*Inventory RM Sup
Units: Dollars/Day

Inventory Cost RM SWF=
   inventory cost per unit RM SWF*Inventory RM SWF
Units: Dollars/Day

Inventory Cost WIP BP=
   inventory cost per unit WIP BP*Inventory WIP BP var
Units: Dollars/Day

Inventory Cost WIP FAT=
   inventory cost per unit WIP FAT*Inventory WIP Man var
Units: Dollars/Day

Inventory Cost WIP Sup=
   inventory cost per unit WIP Sup*Inventory WIP Sup var
Units: Dollars/Day

Inventory Cost WIP SWF=
   inventory cost per unit WIP SWF*Inventory WIP SWF var
Units: Dollars/Day

inventory end time boards FAT=
   120
Units: Days
```

```
inventory end time RM FAT=
   120
Units: Days

inventory end time RM SWF=
   120
Units: Days

Inventory FG BP= INTEG (
   +production rate BP-shipment rate BP,
        initial inventory FG BP)
Units: Boards

Inventory FG FAT= INTEG (
   product completions FG FAT-shipment rate FAT,
        initial inventory FG Man)
Units: Widgets

Inventory FG Sup= INTEG (
   product completions FG Sup-shipment rate Sup,
        initial inventory FG Sup)
Units: Widget

Inventory FG SWF= INTEG (
   product completions SWF-shipment rate SWF,
        initial inventory FG SWF)
Units: Widgets

Inventory RM BP= INTEG (
   +receiving rate RM BP-(desired production batched BP/boards per
   material),
        initial inventory RM BP)
Units: Materials

Inventory RM FAT= INTEG (
   +receiving rate RM FAT-outgoing rate RM FAT,
        initial inventory RM FAT)
Units: Materials

Inventory RM Sup= INTEG (
   +receiving rate RM Sup-outgoing rate RM Sup,
        initial inventory RM Sup)
Units: Materials

Inventory RM SWF= INTEG (
   -outgoing rate RM SWF+receiving rate RM SWF,
        initial inventory RM SWF)
Units: material
```

```
inventory turns=
   ZIDZ(cum demand requested for the current day,average total in-
   ventory cost over time
)
Units: Day*Widget/Dollars

Inventory WIP BP  =

   #LV3<DELAYP(desiredproductionbatchedBP,productiontimeBP:Inventor
   yWIPBP)#

             +
   #LV2<DELAYP(desiredproductionbatchedBP,productiontimeBP:Inventor
   yWIPBP)#

             +
   #LV1<DELAYP(desiredproductionbatchedBP,productiontimeBP:Inventor
   yWIPBP)#

   Units: Boards*Days/Day

Inventory WIP BP var=
   Inventory WIP BP
Units: Boards

Inventory WIP Man  =

   #LV3<DELAYP(desiredproductionFAT,productiontimeFAT:InventoryWIPM
   an)#

             +
   #LV2<DELAYP(desiredproductionFAT,productiontimeFAT:InventoryWIPM
   an)#

             +
   #LV1<DELAYP(desiredproductionFAT,productiontimeFAT:InventoryWIPM
   an)#

   Units: Widget*Days/Day

Inventory WIP Man var=
   Inventory WIP Man
Units: Widget

Inventory WIP Sup  =

   #LV3<DELAYP(desiredproductionSup,productiontimeSup:InventoryWIPS
   up)#
```

```
             +
   #LV2<DELAYP(desiredproductionSup,productiontimeSup:InventoryWIPS
   up)#

             +
   #LV1<DELAYP(desiredproductionSup,productiontimeSup:InventoryWIPS
   up)#

   Units: Widget*Days/Day

Inventory WIP Sup var=
   Inventory WIP Sup
Units: Widgets

Inventory WIP SWF  =

   #LV3<DELAYP(FeasibleFGproductionSWF,productiontimeSWF:InventoryW
   IPSWF)#

             +
   #LV2<DELAYP(FeasibleFGproductionSWF,productiontimeSWF:InventoryW
   IPSWF)#

             +
   #LV1<DELAYP(FeasibleFGproductionSWF,productiontimeSWF:InventoryW
   IPSWF)#

   Units: Widgets*Days/Day

Inventory WIP SWF var=
   Inventory WIP SWF
Units: Widget

largest possible RM outflow BP=
   MIN(capacity limit BP, Inventory RM BP/materials used per FG
   unit BP/minimum time to start production BP
)
Units: Boards/Day

lead time boards FAT=
   10
Units: Day

lead time materials FAT=
   10
Units: Days

lead time materials SWF=
   10
```

```
Units: Days

Life Cycle Test Input=
   lkup Life Cycle Test Input and forecast for demand nine days
   ahead(Time/FINAL TIME
)-1
Units: Dimensionless

lkup Life Cycle Test Input and forecast for demand nine days ahead(
   [(0,0)-
   (1,2)],(0,0),(0.18,0),(0.24159,1.7),(0.324159,1.16),(0.67014,1),
   (0.782
,0),(1,0),(1,0))
Units: Dimensionless

lkup Life Cycle Test Input PLC standard(
   [(0,0)-
   (1,2)],(0,0),(0.185,0),(0.259939,1.21053),(0.293578,1.7193),(0.3
   21101
,1.87719),(0.357798,1.95614),(0.415902,2),(0.440367,1.95614),(0.477
   064,1.85965
),(0.508235,1.62989),(0.569412,1.21708),(0.651765,0.733096),(0.7364
   71,0.362989
),(0.835294,0.0711744),(0.938824,0),(1,0))
Units: Dimensionless

lkup Life Cycle Test Input simple v01(
   [(0,0)-
   (1,2)],(0,0),(0.185,0),(0.185,2),(0.504587,2),(0.504587,0),(0.93
   8824
,0),(1,0))
Units: Dimensionless

lkup Life Cycle Test Input simple v02(
   [(0,0)-
   (1,2)],(0,0),(0.185,0),(0.185,0.5),(0.287462,0.5),(0.504587,2),(
   0.504587
,0),(0.938824,0),(1,0))
Units: Dimensionless

lkup Life Cycle Test Input simple v03(
   [(0,0)-
   (1,2)],(0,0),(0.185,0),(0.185,0.5),(0.287462,0.5),(0.504587,2),(
   0.9388
,2),(0.938824,0),(1,0))
Units: Dimensionless

lkup PLC1(
```

```
   [(0,0)-
   (1,2)],(0,0),(0.18,0),(0.256881,0.298246),(0.30581,0.684211),(0.
   324159
,0.95614),(0.376147,1.38596),(0.434251,1.62281),(0.498471,1.7077),(
   0.547401
,1.67544),(0.587156,1.57018),(0.623853,1.34211),(0.703364,0.54386),
   (0.730887
,0.280702),(0.782,0),(1,0),(1,0))
Units: Dimensionless

lkup probability of problem BP(
   [(0,0)-
   (1,2)],(0,0),(0.185,0),(0.259939,0),(0.299,0),(0.3,1),(0.319,1),
   (0.32
,0),(1,0))
Units: Dimensionless

lkup probability of problem Sup(
   [(0,0)-
   (1,2)],(0,0),(0.185,0),(0.259939,0),(0.3,0),(0.301,1),(0.302,0),
   (1,
0))
Units: Dimensionless

Market potential= INTEG (
   -demand adj Cust 9 days ahead,
        ini market potential)
Units: Widgets

material arrival rate BP=
   receiving rate RM BP
Units: Materials/Day

material arrival rate Sup=
   receiving rate RM Sup
Units: Materials/Day

material arrival rate SWF=
   receiving rate RM SWF
Units: Materials/Day

material order rate BP=
   emergency material orders+material orders BP
Units: Materials/Day

material order rate Sup=
   material orders Sup
Units: Materials/Day
```

```
material orders BP=
   MAX(0,     (((forecast for board printing SWF*materials used per
   FG unit SWF
)+adjustment to desired material order rate BP+(incorporate initial
   stock into forecast boards
*materials used per FG unit SWF)
   )))
Units: Materials/Day

material orders FAT=
   MAX(0,orders RM FAT)
Units: Materials/Day

material orders from FAT SWF=
   MAX(0,orders SWF)
Units: Materials/Day

material orders Sup=
   MAX(0,   ((forecast for supplier SWF*materials used per FG unit
   Sup)+adjustment to desired material order rate Sup
+(Emergency orders to account for Backlog SWF/boards per mate-
   rial)+(incorporate initial stock into forecast materials
*materials used per FG unit Sup))    )
Units: Materials/Day

materials arrival rate FAT=
   receiving rate RM FAT
Units: Materials/Day

materials from Sup needed for a RM FAT=
   1
Units: material/Widget

Materials on order BP= INTEG (
   +material order rate BP-material arrival rate BP,
        ini materials on order BP)
Units: Materials

Materials on order FAT= INTEG (
   +material orders FAT-materials arrival rate FAT+(Emergency or-
   ders to account for Backlog SWF
/boards per material),
        ini materials on order FAT)
Units: Materials

Materials on order Sup= INTEG (
   +material order rate Sup-material arrival rate Sup,
        ini materials on order Sup)
Units: Materials
```

```
Materials on order SWF= INTEG (
   +material orders from FAT SWF-material arrival rate
   SWF+(Emergency orders to account for Backlog SWF
/boards per material),
        ini materials on order SWF)
Units: Materials

materials used per FG unit BP=
   1
Units: Materials/Board

materials used per FG unit FAT=
   1
Units: Materials/Widget

materials used per FG unit Sup=
   1
Units: Materials/Widget

materials used per FG unit SWF=
   1
Units: Materials/Widget

max order size boards FAT=
   1e+011
Units: Boards/Day

max order size materials FAT=
   1e+014
Units: material/Day

max order size SWF=
   1e+017
Units: material/Day

mean of input data from excel 9 days out=
   GET DATA MEAN(input from excel file 9 days out, 91, 413)
Units: Widget/Day

mean of var 2 FAT=
   ZIDZ(sum of var2 annual acc FAT,counter annual acc FAT)
Units: Widgets*Widgets/Dmnl

mean of var 2 SWF=
   ZIDZ(sum of var2 annual acc SWF,counter annual acc SWF)
Units: Widgets*Widgets/Dmnl

mean of var FAT=
```

```
   ZIDZ(sum of sampled var annual acc FAT,counter annual acc FAT)
Units: Widgets/Dmnl

mean of var SWF=
   ZIDZ(sum of sampled var annual acc SWF,counter annual acc SWF)
Units: Widgets/Dmnl

minimum shipment time for inventory BP=
   1
Units: Day

minimum shipment time from inventory emergency IC supplier=
   1
Units: Day

minimum shipment time from inventory FAT=
   1
Units: Day

minimum shipment time from inventory Sup=
   1
Units: Days

minimum shipment time from inventory SWF=
   1
Units: Days

minimum time to start production BP=
   1
Units: Day

minimum time to start production FAT=
   1
Units: Day

minimum time to start production SWF=
   1
Units: Day

no of orders boards FAT=
   (INTEGER(((incoming order rate FAT*boards used per FG unit
   FAT*dimensional consistency day
)+expected demand in LT boards FAT
   +safety stock size boards FAT+initial stock boards FAT+(Backlog
   FAT*boards used per FG unit FAT
)-Boards on order FAT-Inventory Boards FAT
   )/order size boards FAT))/dimensional consistency day
Units: Dimensionless
```

```
no of orders materials FAT=
   (INTEGER((((incoming order rate FAT*materials used per FG unit
   FAT*dimensional consistency day
)+expected demand in LT materials FAT
   +safety stock size materials FAT)+initial stock RM FAT+(Backlog
   FAT*materials used per FG unit FAT
)-Materials on order FAT-Inventory RM FAT
   )/order size materials FAT))/dimensional consistency day
Units: Materials/Materials

no of orders SWF=
   INTEGER
   (((incoming production requests SWF*materials used per FG unit
   SWF*time to place an order SWF
)
   + forecast demand in materials LT SWF
   + safety stock size SWF
   + initial stock SWF
   + (Backlog SWF*materials used per FG unit SWF)
   - Materials on order SWF
   - Inventory RM SWF
   )
   /order size SWF)
   /time to place an order SWF
Units: material/material

Noise Correlation Time = 4
Units: Day

NOISE SEED=
   1
Units: Dimensionless

Noise Standard Deviation=
   0.1
Units: Dimensionless

Noise Start Time=
   92
Units: Day

order fulfillment rate BP=
   shipment rate BP
Units: Boards/Day

order fulfillment rate FAT=
   shipment rate FAT
Units: Widgets/Day
```

```
order fulfillment rate Sup=
   shipment rate Sup
Units: Widgets/Day

order size boards FAT=
   1000
Units: Boards/Day

order size materials FAT=
   1000
Units: material/Day

order size SWF=
   1000
Units: Materials/Day

orders boards FAT=
   MIN(no of orders boards FAT*order size boards FAT, max order
   size boards FAT
)
Units: Boards/Day

orders RM FAT=
   MIN(no of orders materials FAT*order size materials FAT, max
   order size materials FAT
)
Units: material/Day

orders SWF=
   MIN(no of orders SWF*order size SWF, max order size SWF)
Units: material/Day

outflow customer backlog=
   receiving rate Cust
Units: Widget/Day

outgoing rate Boards FAT=
   MAX(0,desired production FAT*boards used per FG unit FAT)
Units: Boards/Day

outgoing rate RM FAT=
   MAX(0,desired production FAT*materials used per FG unit FAT)
Units: Materials/Day

outgoing rate RM Sup=
   MAX(0,IF THEN ELSE(desired production Sup*materials used per FG
   unit Sup>Inventory RM Sup
/dimensional consistency day
```

```
   , Inventory RM Sup/dimensional consistency day, desired produc-
   tion Sup*materials used per FG unit Sup
))
Units: Materials/Day

outgoing rate RM SWF=
   MAX(0,Feasible FG production SWF*materials used per FG unit SWF)
Units: Materials/Day

pick FAT=
   STEP(1,Start Time FAT)*(1-STEP(1,End Time FAT + TIME STEP/2))*IF
   THEN ELSE
(Time/Interval FAT = INTEGER(Time/Interval FAT),1 , 0 )
Units: Dmnl

pick SWF=
   STEP(1,Start Time SWF)*(1-STEP(1,End Time SWF + TIME STEP/2))*IF
   THEN ELSE
(Time/Interval SWF = INTEGER(Time/Interval SWF),1 , 0 )
Units: Dmnl

Pink Noise = INTEG(Change in Pink Noise,0)
Units: Dimensionless

positive customer backlog=
   MAX(0,customer backlog/dimensional consistency day)
Units: Widget/Day

power two=
   2
Units: Dimensionless

probablity of problem BP=
   lkup probability of problem BP(Time/FINAL TIME)*switch probabil-
   ity of problem BP
Units: Dimensionless

probablity of problem Sup=
   lkup probability of problem Sup(Time/FINAL TIME)*switch prob-
   ability of problem Sup
Units: Dimensionless

product completions FG FAT=
   MAX(0,DELAYP(desired production FAT, production time FAT : In-
   ventory WIP Man
 ))
Units: Widget/Day

product completions FG Sup=
```

```
   DELAYP(desired production Sup, production time Sup : Inventory
   WIP Sup )
Units: Widget/Day

product completions SWF=
   DELAYP(Feasible FG production SWF, production time SWF : Inven-
   tory WIP SWF
)
Units: Widgets/Day

production rate BP=
   DELAYP(desired production batched BP, production time BP : In-
   ventory WIP BP
 )
Units: Boards/Day

production starts SWF=
   Feasible FG production SWF
Units: Widgets/Day

production time BP=
   4
Units: Days

production time FAT=
   4
Units: Days

production time Sup=
   4
Units: Days

production time SWF=
   4
Units: Days

Pulse Quantity=
   0
Units: Dimensionless*Day

Pulse Time=
   50
Units: Day

pulse train duration=
   1
Units: Day

pulse train end=
```

```
   500
Units: Day

Pulse Train Input=
   PULSE TRAIN(pulse train start, pulse train duration , pulse
   train repeattime
 , pulse train end )
Units: Dimensionless

pulse train repeattime=
   5
Units: Days

pulse train start=
   0
Units: Day

Ramp End Time=
   150
Units: Day

Ramp Slope=0
Units: 1/Day

Ramp Start Time=
   92
Units: Day

receiving rate Boards FAT=
   DELAY3(shipment rate BP,shipment delay BP)
Units: Boards/Day

receiving rate Cust=
   DELAY3(shipment rate SWF,shipment delay SWF)
Units: Widget/Day

receiving rate ICs IC supplier=
   expected material arrival rate IC emergency supplies at IC sup-
   plier FG inventory
Units: Materials/Day

receiving rate RM BP=
   expected material arrival rate BP+expected emergency IC arrival
   rate BP
Units: Materials/Day

receiving rate RM FAT=
   DELAY3(shipment rate Sup,shipment delay Sup)*materials from Sup
   needed for a RM FAT
```

```
Units: Materials/Day

receiving rate RM Sup=
   expected material arrival rate Sup
Units: Materials/Day

receiving rate RM SWF=
   DELAY3(shipment rate FAT*materials used per FG unit SWF,shipment
   delay FAT
)
Units: material/Day

safety factor z boards FAT=
   1.65
Units: Dmnl

safety factor z materials FAT=
   1.65
Units: Dmnl

safety factor z SWF=
   1.65
Units: Dmnl

safety stock size boards FAT=
   safety factor z boards FAT*standard deviation of last 10 days
   FAT*boards used per FG unit FAT
Units: Board

safety stock size materials FAT=
   safety factor z materials FAT*standard deviation of last 10 days
   FAT*materials used per FG unit FAT
Units: Materials

safety stock size SWF=
   safety factor z SWF*standard deviation of last 10 days
   SWF*materials used per FG unit SWF
Units: material

sampled var FAT=
   pick FAT*var FAT
Units: Widget/Day

sampled var SWF=
   pick SWF*var SWF
Units: Widget/Day

SAVEPER  =
        TIME STEP
```

```
Units: Day

shipment delay BP=
   4
Units: Days

shipment delay emergency IC deliveries=
   4
Units: Days

shipment delay FAT=
   4
Units: Days

shipment delay Sup=
   4
Units: Days

shipment delay SWF=
   4
Units: Days

shipment rate BP=
   Inventory FG BP/minimum shipment time for inventory BP
Units: Boards/Day

shipment rate FAT=
   Inventory FG FAT/minimum shipment time from inventory FAT
Units: Widgets/Day

shipment rate Sup=
   IF THEN ELSE(Backlog Sup>0, Inventory FG Sup/minimum shipment
   time from inventory Sup
, 0)
Units: Widget/Day

shipment rate SWF=
   Inventory FG SWF/minimum shipment time from inventory SWF
Units: Widgets/Day

Sine Amplitude=0
Units: Dimensionless

Sine Period=50
Units: Days

squared diff demand and FC for 35 days setup A 0 0=
   POWER(dimensional difference demand and forecast for 35 days
   Sup, power two
```

```
)
Units: Dmnl

squared diff demand and FC for 75 days setup A 0=
   POWER(dimensionless difference demand and forecast for 75 days
   BP, power two
)
Units: Dmnl

standard deviation of last 10 days FAT=
   AnnualAccumulation(standard deviation of var after 10 days
   FAT,acclength FAT
,Time,TIME STEP)
Units: Widgets

standard deviation of last 10 days SWF=
   AnnualAccumulation(standard deviation of var after 10 days
   SWF,acclength SWF
,Time,TIME STEP)
Units: Widgets

standard deviation of var after 10 days FAT=
   IF THEN ELSE(
               MODULO(Time,acclength FAT)=0
               ,standard deviation of var FAT,0)
Units: Widgets

standard deviation of var after 10 days SWF=
   IF THEN ELSE(
               MODULO(Time,acclength SWF)=0
               ,standard deviation of var SWF,0)
Units: Widgets

standard deviation of var FAT=
   IF THEN ELSE( mean of var 2 FAT-(mean of var FAT*mean of var
   FAT)>0, SQRT(
mean of var 2 FAT-(mean of var FAT*mean of var FAT)), 0)
Units: Widgets

standard deviation of var SWF=
   IF THEN ELSE( mean of var 2 SWF-(mean of var SWF*mean of var
   SWF)>0, SQRT(
mean of var 2 SWF-(mean of var SWF*mean of var SWF)), 0)
Units: Widgets

Start Time FAT=
   0
Units: Days
```

```
Start Time SWF=
   0
Units: Days

starting time for forecast adjustments BP=
   0
Units: Days

starting time for forecast adjustments Sup=
   0
Units: Days

stddev of input data from excel 9 days out=
   GET DATA STDV( input from excel file 9 days out, 91, 413)
Units: Widget/Day

Step Height=
   0
Units: Dimensionless

Step Time=
   200
Units: Day

Step2 Height=
   0
Units: Dimensionless

Step2 Time=
   200
Units: Days

sum of sampled var annual acc FAT=
   AnnualAccumulation(sampled var FAT,acclength FAT,Time,TIME
   STEP)*dimensional consistency day
Units: Widgets

sum of sampled var annual acc SWF=
   AnnualAccumulation(sampled var SWF,acclength SWF,Time,TIME
   STEP)*dimensional consistency day
Units: Widgets

sum of var2 annual acc FAT=
   AnnualAccumulation(((sampled var FAT*dimensional consistency
   day)*(sampled var FAT
*dimensional consistency day)),acclength FAT,Time,TIME STEP)
Units: Widgets*Widgets

sum of var2 annual acc SWF=
```

```
   AnnualAccumulation(((sampled var SWF*dimensional consistency
   day)*(sampled var SWF
*dimensional consistency day)),acclength SWF,Time,TIME STEP)
Units: Widgets*Widgets

switch adjustment to forecast=
   1
Units: Dmnl

switch adjustment to Inventory RM BP=
   1
Units: Dimensionless

switch adjustment to Inventory RM Sup=
   1
Units: Dimensionless

switch adjustmentfor difference demand and forecast BP=
   1
Units: Dimensionless

switch adjustmentfor difference demand and forecast Sup=
   1
Units: Dimensionless

switch consider emergency orders already placed=
   0
Units: Dimensionless

switch emergency orders to account for Backlog SWF=
   1
Units: Dimensionless

switch incorporate base safety stock into forecasts=
   1
Units: Dmnl

switch Life Cycle Test Input=
   0
Units: Dimensionless

switch probability of problem BP=
   0
Units: Dimensionless

switch probability of problem Sup=
   0
Units: Dimensionless
```

```
switch to consider cum adj to inventory RM BP=
   0
Units: Dmnl

switch to consider cum adj to inventory RM Sup=
   0
Units: Dmnl

systematic forecast error factor=
   1
Units: Dmnl

time base week=
   TIME BASE(0, 0.2 )
Units: Dimensionless

TIME STEP  = 0.25
Units: Day

time to place an order SWF=
   1
Units: Day

total cumulated inventory cost BP=
   Cumulated Inventory Cost FG BP+Cumulated Inventory Cost RM
   BP+Cumulated Inventory Cost WIP BP
Units: Dollars

total cumulated inventory cost FAT=
   Cumulated Inventory Cost FG FAT+Cumulated Inventory Cost Boards
   FAT+Cumulated Inventory Cost WIP FAT
+Cumulated Inventory Cost RM FAT
Units: Dollars

total cumulated inventory cost Sup=
   Cumulated Inventory Cost FG Sup+Cumulated Inventory Cost RM
   Sup+Cumulated Inventory Cost WIP Sup
Units: Dollars

total cumulated inventory cost SWF=
   Cumulated Inventory Cost FG SWF+Cumulated Inventory Cost RM
   SWF+Cumulated Inventory Cost WIP SWF
Units: Dollars

total inventory cost BP=
   Inventory Cost FG BP+Inventory Cost RM BP+Inventory Cost WIP BP
Units: Dollars/Day

total inventory cost FAT=
```

```
   Inventory Cost FG FAT+Inventory Cost Boards FAT+Inventory Cost
   WIP FAT+Inventory Cost RM FAT
Units: Dollars/Day

total inventory cost Sup=
   Inventory Cost FG Sup+Inventory Cost RM Sup+Inventory Cost WIP
   Sup
Units: Dollars/Day

total inventory cost SWF=
   Inventory Cost FG SWF+Inventory Cost RM SWF+Inventory Cost WIP
   SWF
Units: Dollars/Day

Total products shipped to Cust= INTEG (
   receiving rate Cust,
        0)
Units: Widgets

var FAT=
   incoming order rate FAT
Units: Widget/Day

var SWF=
   demand Cust 9 days ahead
Units: Widget/Day

waiting for production BP= INTEG (
   +inflow waiting for production BP-desired production batched BP,
        0)
Units: Boards

waiting for production FAT= INTEG (
   +inflow waiting for production FAT-desired production FAT,
        0)
Units: Widget

waiting for production Sup= INTEG (
   +inflow waiting for production Sup-desired production Sup,
        0)
Units: Widget

White Noise=
   Noise Standard Deviation*((24*Noise Correlation Time/TIME
   STEP)^0.5*(RANDOM UNIFORM
(0, 1, NOISE SEED) - 0.5
   ))
Units: Dimensionless
```

Short Curriculum Vitae Dennis Minnich

University Education

09/2000 – 09/2003	Undergraduate studies in business administration at the International University in Germany, Bruchsal. Degree: *Bachelor of Business Administration*
09/2003 – 09/2004	Graduate studies in business administration at the London School of Economics and Political Science. Degree: *Master of Science in Management*
05/2005 – 06/2007	Postgraduate studies at the University of Mannheim, Department of Operations Management Prof. Dr. Milling. Degree: *Dr. rer. pol.*

Professional Assignments

02/2003 – 04/2003	Allianz Australia Ltd., Sydney. Intern.
10/2004 – 01/2005	McKinsey & Company, Inc., Düsseldorf. *Associate Intern.*
03/2005 – 04/2007	International University in Germany, Bruchsal, Department of Operations Management Prof. Dr. Maier. *Research and Teaching Associate.*
Since 06/2007	McKinsey & Company, Inc., Düsseldorf. *Associate.*

Organizations can design planning systems for supply chain management in different ways in order to achieve the multiple objectives of supply chain management. In this book, a System Dynamics simulation model is used to assess the performance of planning approaches for supply chains in the high-tech electronics industry on the dimensions of responsiveness and efficiency. Supply chains in this industry are subject to a number of challenges that complicate the achievement of these two objectives, including short product life cycles and long component lead times. In recent years, companies experienced both decreasing delivery performance and increasing cost. The simulation results show that while the current planning approach in typical supply chains in this industry is not capable of supporting high responsiveness at the same time as high efficiency, it is possible to modify the planning system to achieve simultaneous improvements on both of these dimensions. Building on this simulation model, the book provides practical guidelines on how organizations can align the supply chain planning approach with different product characteristics and transform their supply chains into systems that are both responsive to customer demand and efficient.

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