SUPPLY CHAIN MANAGEMENT - APPLICATIONS AND SIMULATIONS

Edited by **Mamun Habib**

INTECHWEB.ORG

Supply Chain Management - Applications and Simulations
Edited by Mamun Habib

Published by InTech
Janeza Trdine 9, 51000 Rijeka, Croatia

Publishing Process Manager Petra Zobic
Technical Editor Teodora Smiljanic
Cover Designer Jan Hyrat
Image Copyright Kirsty Pargeter, 2010. Used under license from Shutterstock.com

First published July, 2011
Printed in Croatia

A free online edition of this book is available at www.intechopen.com
Additional hard copies can be obtained from orders@intechweb.org

Supply Chain Management - Applications and Simulations, Edited by Mamun Habib
p. cm.
ISBN 978-953-307-250-0

Contents

Preface

Supply Chain Management (SCM) has been widely researched in numerous application domains during the last decade. Despite the popularity of SCM research and applications, considerable confusion remains as to its meaning. There are several attempts made by researchers and practitioners to appropriately define SCM. Amidst fierce competition in all industries, SCM has gradually been embraced as a proven managerial approach to achieving sustainable profits and growth.

This book **"Supply Chain Management - Applications and Simulations**" is comprised of twelve chapters and has been divided into four sections, namely Supply Chain Management: Theory and Evolution, Strategic and Tactical Issues in Supply Chain Management, Project and Technology Issues in Supply Chain, and Risk Managements in Supply Chain.

Section I contains the introductory chapter that represents theory and evolution of Supply Chain Management. This chapter highlights chronological prospective of SCM in terms of time frame in different areas of manufacturing and service industries.

Section II comprised five chapters that are related to strategic and tactical issues in Supply Chain Management.

In chapter two, local consecutive Model Predictive Controllers (MPC) applied to a supply chain management system that consists of four echelons is presented. Two types of sequential decentralized MPC were used: in first method, each node completely by a decentralized model predictive controller optimized for its own policy, and in second method, decentralized model predictive controllers in each stage are updated in each time period.

A methodology is outlined in chapter 3 that utilizes electrical simulations to account for component variability and its predicted impact on yield and quality. Identified critical features in simulations from a design for reliability and manufacturability perspective are used to drive supply chain decisions to build robust designs in an efficient way.

A proposal to systematically address the problem of disruptive event management in SC is described in chapter 4. The proposal includes the definition of a SCEM (Supply

Chain Event Management) system architecture conceived to provide system support for companies willing to engage in collaboration agreements for controlling the execution of their supply processes.

Chapter 5 focuses on the integration of renewable energy, specifically the solar energy resources into conventional electric grid and deployment of smart architecture of hybrid energy system in the context of Green House Effect to Climate Change with the deployment of energy conservation efforts by Energy Service Companies (ESCOs) in Indian context for sustainable development of the rural and urban sector. This chapter illustrates the deployment of Energy Portal (EP) for Renewable Energy Resources based on Service-Oriented-Architecture (SOA) technology.

Chapter 6 reveals the relation between financing services and supply chain management, and introduces how logistics firms could add value to all parties in supply chain. This chapter sheds some light on how Supply Chain Finance (SCF) impacts agents' operational and financial decisions under the symmetric/asymmetric information and how SCF can create value for supply chain with capital constraints. In this chapter, SCF as the jointly operations/logistics and financing service, offered by a 3PL firm (Control Role), or an alliance of 3PL firm (Delegation Role) and financial institution (i.e., bank), etc. was defined.

Section III encompasses four chapters that are relevant to project and technology issues in Supply Chain.

Chapter 7 analyses main processes of the pharmaceutical supply chain and evaluates the impact of the combined use of the innovative technologies, such as RFID and EPCglobal, in some critical processes. Particular attention is focused on the wholesaler because it represents a middle point of the supply chain, very stressed in terms of constraints and products flow.

Chapter 8 presents a modeling framework for quantitative evaluation of green supply chains (GrSCs). This chapter begins presenting a literature review of the works that address the quantitative evaluation of supply chains. After presenting a brief introduction of sustainability and supply chains, it discusses some of the performance models that are often adopted when conducting a quantitative evaluation of different kinds of systems. This chapter presented a framework based on the stochastic modeling of supply chains for evaluating business and sustainability metrics.

Chapter 9 aims to provide a block analysis technique for complex electronic systems. This technique is based on the partitioning of the chain in several functional blocks and allows an identification of the block responsible for any specification violation and hence a more easy and quick solution of the problem. This chapter describes a systematic approach for the analysis of the signal integrity of a supply voltage pulse propagating from the input to the output port of a complex supply chain of devices for spatial and military applications.

Chapter 10 has launched a thorough study of the measurement and evolutionary mechanisms of supply chain flexibility, including building the dimension and measurement index system of supply chain flexibility, presenting integrated measurement method and offering the evolution framework and process, and studied on environmental uncertainty and matching models of supply chain flexibility, proposing a complete theory of supply chain flexibility evolution.

Section IV consists of two chapters which are pertinent to risk managements in supply chain.

Chapter 11 describes a control chart model for supplier risk management. In the supply chain system, prompt response of supplier to the feedback trouble from the maker is important, and has become a key point of the supplier competitive edge. To improve supplier quality, there has been an increased interest in IT (information technology) control charts which are used to monitor online production processes. For the above problem, a feedback model of control chart is developed for supplier in this chapter.

Chapter 12 illustrates a different approach in studying the changes in the supply chains due to mergers and acquisitions activities, based on constructing a set of Virtualized Supply Chains (VSCs) and applying the mergers-induced changes to these Virtualized Supply Chains. This chapter introduces the terminology of the virtual modeling of the Supply Chains: business class, business dependency, bounded and unbounded Virtualized Supply Chain, risk of a business class and global risk of the Virtualized Supply Chain Set. The objective of this chapter is to reduce the risks in the supply chain by highlighting which one of the three investigated mergers alternatives (upstream vertical merger, downstream vertical merger and conglomerate merger) is better suited for diminishing the risks in the supply chains sets.

I am honored to be editing such a valuable book, which contains contributions of a selected group of researchers presenting the best of their works. I would like to thank all the authors for their excellent contributions in the different areas of supply chain management. The editor truly hopes that this book would be fruitful for researchers, scientists, students, academicians and practitioners who are involved in supply chain management.

I would like to convey heartiest thanks to my family members, especially to my beloved parents and wife for their excellent cooperation. Finally, I express my gratitude to Almighty Allah for the successful completion of this book in the scheduled time.

Asst. Prof. Dr. Md. Mamun Habib
American International University – Bangladesh (AIUB)
Bangladesh

Part 1

Supply Chain Management: Theory and Evolution

1

Supply Chain Management (SCM): Theory and Evolution

Mamun Habib
American International University - Bangladesh (AIUB)
Bangladesh

1. Introduction

During last decade, researchers usually focused on Supply Chain Management (SCM) issues in profit organizations. Research objectives may include adding value, reducing cost, or slashing response time in various parties involved in the manufacturing supply chain. However, very few studies were attempted in non-profit organizations. An extremely scarce number of research papers focused on SCM in the academia (Habib, 2011, 2010e, 2010d, 2010f, 2010g).

Hay (1990) states that a profit organization attempts to maximize profits, whereas a non-profit organization considers monetary returns of less importance. Their major objectives may include improved literacy rate, better quality of life, equal opportunities for all genders or races, etc. The revenues gained by a non-profit organization would be used primarily to balance the expenditure of the organization. Due to conflicting objectives, managing a successful profit organization may be drastically different from a non-profit organization (Firstenberg, 1996; Drucker, 1992). Recently, an increasingly large number of research studies highlight the criticalness of SCM as a means to assuring organizational success.

SCM assists the business organization to compete in the dynamic international market. The objective of SCM is to incorporate activities across and within organizations for providing the customer value. This should also be applicable to the academia, which represents a type of non-profit organizations. The goal is to provide the society value by producing high quality graduates and research outcomes. An integrated educational supply chain involves coordination and information sharing up and down the process among all stakeholders. With technology facilitating information flow, a coordinated supply chain can be designed to meet the strategic, planning, and operating objectives of the educational institutions. It also means establishing effective and feasible relationships both inside and outside the organization (Sandelands, 1994).

SCM is needed for various reasons: improving operations, better outsourcing, increasing profits, enhancing customer satisfaction, generating quality outcomes, tackling competitive pressures, increasing globalization, increasing importance of E-commerce, and growing complexity of supply chains (Stevenson, 2002). Supply chains are relatively easy to define for manufacturing industries, where each participant in the chain receives inputs from a set of suppliers, processes those inputs, and delivers them to a different set of customers. With

educational institutions, one of the primary suppliers of process inputs is customers themselves, who provide their bodies, minds, belongings, or knowledge as inputs to the service processes (Habib and Jungthirapanich, 2009b, 2009c, 2010a, 2010c, 2010h, 2010i).
This chapter reveals the following objectives:

- Analysis the overview of SCM through different citations.
- Review extensive literature reviews regarding SCM based on secondary data.
- Define the SCM and the evolution of SCM.
- Analysis the trends of SCM and its future perspectives.

2. Literature review

The term, "supply chain management," has risen to eminence over the last ten years. About 13.55% of the concurrent session titles contained the words "supply chain" at the 1995 Annual Conference of the Council of Logistics Management. The number of sessions containing the term rose to 22.4% at the 1997 conference, just two years later. The term is commonly used to illustrate executive responsibilities in corporations (La Londe 1997). SCM has become such a "hot topic" that it is difficult to pick up a periodical on manufacturing, distribution, marketing, customer management, or transportation without seeing any article about SCM or SCM-related topics (Ross, 1998).
Some authors defined SCM in operational terms involving the flow of materials and products, some viewed it as a management philosophy, and some viewed it in terms of a management process (Tyndall et al., 1998), some viewed it as integrated system. Authors have even conceptualized SCM differently within the same article: as a management philosophy on the one hand, and as a form of integrated system between vertical integration and separate identities on the other hand (Cooper and Ellram, 1993).
According to Christopher (1994), a supply chain is "a network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customer." An example of a basic supply chain is shown in Figure 1.

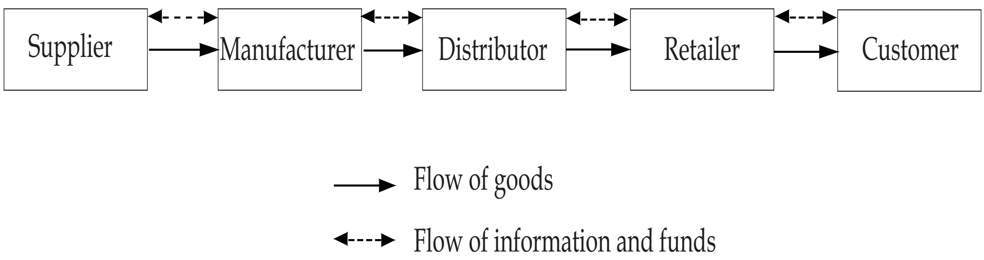


Fig. 1. The basic supply chain (Chopra and Meindl, 2001)

The supply chain includes suppliers, manufacturers, distributors, retailers, and customers. The customers are the main focus of the chain, since the primary purpose of the existence of any supply chain is to satisfy customer needs, in the process generating profit for itself (Chopra and Meindl, 2001). SCM was initially related to the inventory management within a supply chain. This concept was later broadened to include management of all functions within a supply chain. According to Chopra and Meindl (2001), “SCM engages the management of flows between and among stages in a supply chain to minimize total cost”. This definition implies that SCM involves management of flows of products, information, and finance upstream and downstream in the supply chain.

In the course of time, the most considerable benefits to businesses with advanced SCM capabilities will be radically improved customer responsiveness, developed customer service and satisfaction, increased flexibility for changing market conditions, improved customer retention and more effective marketing (Horvath, 2001).

SCM is a concept, “whose primary objective is to integrate and manage the sourcing, flow, and control of materials using a total systems perspective across multiple functions and multiple tiers of suppliers” (Monczka, Trent and Handfield, 1994). Stevens (1989) stated the objective of SCM was to synchronize the customers’ requirements with materials flow to strike a balance among conflicting goals of maximum customer service, minimum inventory management, and low unit costs.

The supply chain is viewed as a single process. Responsibility for the different divisions in the chain is not fragmented and transferred to functional areas such as manufacturing, purchasing, distribution, and sales. SCM calls for, and in the end depends on, strategic decision-making. “Supply” is a shared objective of practically every function in the chain and is of particular strategic importance because of its impact on overall costs, profits and market share. SCM calls for a different point of view on inventories that are utilized as a balancing mechanism of last, not first, resort. A latest approach to systems is required - integration rather than interfacing (Houlihan, 1988).

SCM is delivering major economic benefits to businesses as diverse as manufacturing, retail, and service organizations, etc. (Horvath, 2001). The scope of SCM was further expanded to include re-cycling (Baatz, 1995). SCM deals with the total flow of materials from suppliers through end users (Jones and Riley, 1985). It highlights “total” integration of all stakeholders within the supply chain, a realistic approach is to consider only strategic suppliers and customers since most supply chains are too complex to attain full integration of all the supply chain entities (Tan et al., 1998).

Supply chain strategy includes “two or more firms in a supply chain entering into a long-term agreement; the development of mutual trust and commitment to the relationship; the integration of logistics events involving the sharing of demand and supply data; the potential for a change in the locus of control of the logistics process” (La Londe and Masters, 1994). Manufacturers are able to develop alternative conceptual solutions, select the best components and technologies, and assist in design assessment by involving suppliers early in the design stage, (Burt and Soukup, 1985).

SCM incorporates logistics into the strategic decisions of the business (Carter and Ferrin, 1995). Eventually, the philosophy developed and combined into a common body of knowledge that encompassed all the value-adding activities of the manufacturers and logistics providers (Tan, 2001). Many SCM strategic models have been investigated to link its vital role in overall strategic corporate planning (Frohlich et al., 1997; Watts et al., 1992). Experts agree that a formal supply chain strategy will be critical to both manufacturing and service industries (Kathawala, 2003).

Such ambiguity suggests a need to examine the phenomena of SCM more closely to define clearly the term and concept, to identify those factors that contribute to effective SCM, and to suggest how the adoption of an SCM approach can affect corporate strategies, plans, operations and performance.

Proper performance measures and metrics including activity-based costing and management may be helpful in identifying non-value-adding activities across a supply chain. Total Quality Management (TQM) methods can be utilized to eradicate these inefficiencies, thereby improving the overall effectiveness of a supply chain. Customer demands and supply chain relationships are the key in selecting the most appropriate method of target costing for supply chains. Activity-based, process-based, value-based and cost management approaches may be fit for TQM in SCM (Lockamy and Smith, 2000).

2.1 Definitions of SCM

American Production and Inventory Control Society (APICS, 1990) define the supply chain as the processes from the initial raw materials to final consumption of the finished products linking across supplier-user industries. The supply chain constitutes all functions within and outside an industry, which enable the value chain to make products and provide services to customers (Inman, 1992). Some researchers suggested a clearer SCM definition by adding the information system necessary to monitor all of the activities (Lee, 2002; Morgan, 1995; Talluri, 2002).

Recently, the Council of SCM Professionals (CSCMP), which is the premier organization of supply chain practitioners, researchers, and academicians, has defined SCM as: “SCM encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all Logistics Management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third-party service providers, and customers. In essence, SCM integrates supply and demand management within and across companies” (Ballou, 2007).

Scott and Westbrook (1991) described SCM as the chain linking each element of the manufacturing and supply process from raw materials to the end user. This management philosophy focused on how firms utilized their suppliers’ processes, technology, information, and capability to enhance competitive advantage (Farley, 1997), and the coordination of the manufacturing, materials, logistics, distribution and transportation functions within an organization (Lee and Billington, 1992). SCM is an integrative philosophy to manage the total flow of a distribution channel from supplier to the ultimate user (Cooper et al., 1997).

Supply chain is defined as all the activities involved in delivering a product from raw materials to the customer including sourcing raw materials and parts, manufacturing and assembly, warehousing and inventory tracking, order entry and order management, distribution across all channels, delivery to the customer, and the information systems necessary to monitor all of these activities. SCM coordinates and integrates all of these activities into a seamless process. It links all of the stakeholders in the chain including parties within an organization and the external partners including suppliers, carriers, third party companies, and information systems providers (Lummus, 1999).

SCM is defined as the systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular organization and across businesses within the supply chain, for improving the long-term performance of the individual organization and the supply chain as a whole (Mentzer and et al., 2001).

Most of the recent SCM literature focused on the purchasing function, stating that it was a basic strategic business process, rather than a specialized supporting function (Wisner and Tan, 2000). It was a management philosophy that extended traditional internal activities by adopting an inter-enterprise scope, allowing trading partners together with the common goal of optimization and efficiency (Harwick, 1997).

The customized definition for the service industry is as follows: The SCM for the service industry is the ability of the company/firm to get closer to the customer by improving its supply chain channels. The services supply chain will include responsiveness, effectiveness, efficiency, and controlling (Kathawala, 2003). One of the primary suppliers of process inputs is customers themselves in service organizations. This concept of customers being suppliers is recognized as 'customer-supplier duality.' The duality implies that service supply chains are bi-directional (Sampson, 2000). The concept may be applicable to the academia as well. (Habib, 2010e, 2010g).

Integrated SCM is about going from the external customer and then managing all the processes that are needed to provide the customer with value in a horizontal way (Monczka and Morgan, 1997). Generally, SCM comprises integrated functions from raw materials to final products. It also covers integrated management of every organization throughout the whole chain (Horvath, 2001; Talluri, 2002). An analysis of SCM for manufacturing illustrates the integrated processes required for managing goods from the initial source of supply to point of consumption. It also includes a wide range of activities that material and service suppliers, manufacturers, wholesalers, and retailers have performed for years. Each supply chain participants manage to enhance performance of their own enterprises. Very little concentration is given to the benefits of managing the total supply chain process on an integrated basis (Closs, 1995).

SCM, as applied to manufacturing, has been defined differently. These varieties of definitions often carry through to the extent that the key people in the same organization are not speaking about the same things, when they discuss the concept of SCM (Monczka and Morgan, 1997).

First, there are definitions characterized by the simplest concepts of SCM, one is "the ability to get closer to the customer" (Weil, 1998). Another is that the supply chain is the flow of information and material from suppliers to customers (Crom, 1996). A company's supply chain, either internal or external, is a resource to be exploited for better market position and enhanced competitive advantage. Strategic use of this resource requires that companies do the following (Monczka and Morgan, 1997):

1. Gain a closer understanding of their customer' and future customers' needs, both nationally and internationally;
2. Understand their suppliers' core competencies in meeting customer needs;
3. Determine where redundancies and inefficiencies lie within the supply chain in relation to current and future competitive needs;
4. Develop relationships and alliances with suppliers who have key competencies that strengthen, supplement, and enhance internal core competencies nationally and internationally.

SCM, from the viewpoint of a manufacturing sector, may be defined as "taking control of all goods within the supply chain, all materials, no matter how to handle or manage (Sandelands, 1994)." In particular, SCM is the process of effectively managing the flow of materials and finished goods from retailers to customers using the manufacturing facilities and warehouses as potential intermediate steps (Sengupta and Turnbull, 1996).

2.2 Evolution of SCM

The supply chain literature review was conducted to study the past researches. Before the 1950s, logistics was thought of in military terms (Ballou, 1978). It had to do with procurement, maintenance, and transportation of military facilities, materials, and personnel. The study and practice of physical distribution and logistics emerged in the 1960s and 1970s (Heskett et al., 1973).

The logistics era prior to 1950 has been characterized as the “dormant years,” when logistics was not considered a strategic function (Ballou, 1978). Around 1950s changes occurred that could be classified as a first “Transformation.” The importance of logistics increased considerably, when physical distribution management in manufacturing firms was recognized as a separate organizational function (Heskett et al., 1964). The SCM concept was coined in the early 1980s by consultants in logistics (Oliver and Webber, 1992). The authors emphasized that the supply chain must have been viewed as a single entity and that strategic decision-making at the top level was needed to manage the chain in their original formulation. This perspective is shared with logisticians as well as channel theorists in marketing (Gripsrud, 2006).

SCM has become one of the most popular concepts within management in general (La Londe, 1997) since its introduction in the early 1980s (Oliver and Webber, 1992). A number of journals in manufacturing, distribution, marketing, customer management, transportation, integration, etc. published articles on SCM or SCM-related topics. The evolution of SCM continued into the 1990s due to the intense global competition (Handfield, 1998). Berry (1994) defined SCM in the electronics industry.

Drucker (1998) went as far as claiming there was a paradigm shift within the management literature: “One of the most significant changes in paradigm of modern business management is that individual businesses no longer compete as solely autonomous entities, but rather as supply chains. Business management has entered the era of inter-network competition and the ultimate success of a single business will depend on management’s ability to integrate the company’s intricate network of business relationships.”

Fernie (1995) adopted SCM in the National Health Service. In fact, it was the first paper of SCM in the service industry. Sampson (2000) explored the customer supplier duality in the service organizations as it pertained to SCM in the service industry. Kathawala and Abdou (2003) explored supply chain application to the service industry. O’Brien and Kenneth (1996) proposed an educational supply chain as a tool for strategic planning in tertiary education. The study was based on a survey among employers and students. Survey findings revealed that integration and coordination among students and employers should have been promoted. Cigolini et al. (2004) explored a framework for SCM based on several service industries including automobile, grocery, computers, book publishing etc. According to the case study conducted at the City University of Hong Kong, Lau (2007) defined educational supply chain as the ‘Student’ and the ‘Research’ supply chain.

Habib (2009a) represents the first large scale empirical study that systematically investigate input of the university, output of the university through educational SCM. This exploratory research addresses the education supply chain, the research supply chain, and educational

management as major constituents in an Integrated Tertiary Educational Supply Chain Management (ITESCM) model (Habib and Jungthirapanich, 2010a, 2010c, 2010h). Its applicability was successfully verified and validated through survey data from leading tertiary educational institutions around the world (Habib, 2010b, 2010d, 2010e, 2010f).
The emergence and evolution of SCM may be depicted as a timeline shown in Figure 2.

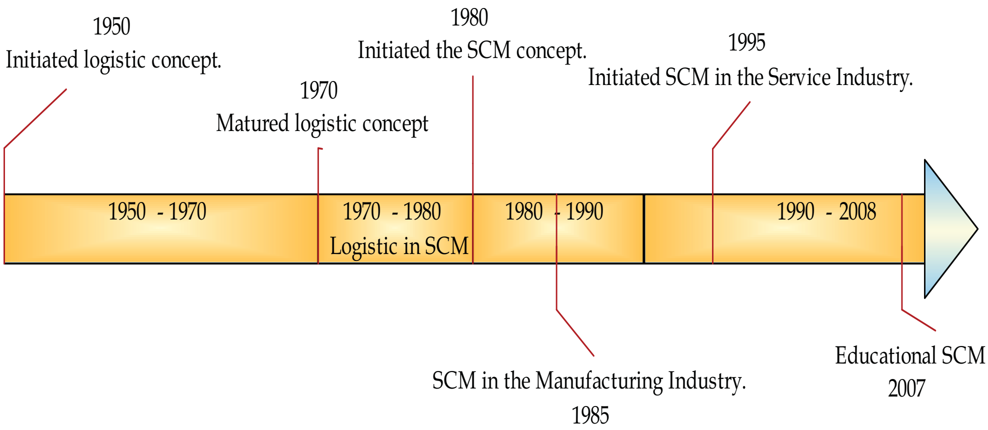


Fig. 2. Evolutionary timeline of SCM (Habib and Jungthirapanich, 2008)

3. Research methodology

The analysis of this research is based on secondary data, including online databases, digital libraries, books, journals, conference papers, etc. Extensive SCM research papers of academicians and practitioners are evolved from renowned international journals, namely PROQUEST, EMERALD, EBSCO, IEEE, ACM, JSTOR, Science Direct, etc. Evolutionary timeline and future trends were developed based on the analysis of literature. The author classifies SCM in different areas of Manufacturing and Service industries.

4. Discussion

It is quite clear that, few and very few researchers conducted SCM in the service industries and education respectively. Most of them conducted SCM in the manufacturing industries. It seems to be that SCM in the educational institutions needs more to be explored in the future (Habib, 2010e, 2011).
It is a surprising fact that researchers develop supply chain models mostly for improving business operations. Few, particularly academic researchers, do not realize that the research on academic SCM may also be conducted for their own educational institutions. The performance of the SCM depends on the seamless coordination of all supply chain stakeholders to ensure attainment of desirable outcomes. This chapter is based on only secondary data, though it is the limitation of this paper, however, this study would unlock frontiers for substantial researchers in order to further development in respect of supply chain management arena.

5. Conclusion

Supply chain management (SCM) has been widely researched in numerous application domains during the last decade. Despite the popularity of SCM research and applications, there remains considerable confusion as to its meaning. There are several attempts made by researchers and practitioners to appropriately define SCM. Amidst fierce competition in all industries, SCM has gradually been embraced as a proven managerial approach to achieving sustainable profits and growth. This is accomplished primarily by focusing on the whole SCM process to deliver the right products or services, in the right quantity, to the right place, at the right time and with the maximum benefits.
The researcher utilized secondary data, including digital libraries, online databases, journals, conference papers, etc. to review SCM research papers in different aspects. This exploratory study reveals the evolution of SCM in various industries, including manufacturing and service industries, and its future trends. This chapter highlights chronological prospective of SCM in terms of time frame in different areas of manufacturing and service industries.

6. Acknowledgements

I would like to express heartiest gratitude to my GURU and beloved Ph.D. advisor, Dr. Chamnong Jungthirapanich, for his tireless efforts towards research works on Supply Chain Management.

7. References

Baatz, E.B. (1995). *"CIO100-best practices: the chain gang"*, CIO, Vol.8 No.19, pp.46-52

Ballou, Ronald H. (2007). *"The evaluation and future of logistics and supply chain management"*, European Business Review, Vol.19 No.4, pp. 332-348

Ballou, R. (1978). *Basic Business Logistics,* Prentice-Hall, Englewood Cliffs, NJ, 1978

Berry, D.R. Towill and N. Wadsley. (1994). *"Supply Chain Management the Electronics Products Industry"*, International Journal of Physical Distribution & Logistics Management, Vol. 24 No. 10, pp. 20-32

Burt, D.N. and Soukup, W.R. (1985). *"Purchasing's role in new product development'*, Harvard Business Review, Vol. 64 No.5, pp. 90-7

Carter, J.R. and Ferrin, B.G.(1995). *"The impact of transportation costs on supply chain management"*, Journal of Business Logistics, Vol.16 No.1, pp. 189-212

Cigolini, R., M. Cozzi and M. Perona. (2004). *"A new framework for supply chain management"*, International Journal of Operations & Production Management, Vol. 24, No. 1, pp. 7-41

Closs, D. J. (1995). *"Enhance supply chain effectiveness"*, Transportation & Distribution, Vol. 36 No.4, pp.82

Crom, S. (1996). *"De –fuse multi-cultural clashes"*, Transportation & Distribution, July, Vol. 37 No.7, pp.84

Cooper, Martha, Lisa M. Ellram, John T. Gardner, and Albert M. Hanks. (1993). *"Meshing Multiple Alliances,"* Journal of Business Logistics, Vol. 18, No. 1, pp. 67-89

Cooper, Martha C., Douglas M. Lambert, and Janus D. Pagh. *(1997). "Supply Chain Management: More Than a New Name for Logistics,"* The International Journal of Logistics Management, Vol. 8 No. 1, pp. 1-14

Christopher, M.(1994). *Logistics and Supply Chain Management*, Pitman Publishing, New York, NY

Chopra, S. and Meindl, P. (2001). *Supply Chain Management*, Prentice Hall, NJ

Drucker, P.F. (1998). Practice of Management, Butterworth Heinemann, Oxford

Farley, G.A. (1997). *"Discovering supply chain management: a roundtable discussion"*, APICS - The Performance Advantage, Vol.7 No.1, pp. 38-9

Fernie, John and Clive Rees. (1995). "*Supply chain management in the national health service*", The International Journal of Logistics Management, Vol. 6 No. 2, pp. 83-92

Firstenberg, P.B. (1996). *The 21st Century Nonprofit: Remarking the Organization in the Post-Government Era*, The Foundation Center, New York, NY

Frohlich, M., Dixon, J.R. and Arnold, P. *(1997)."A taxonomy of supply chain strategies'*, Proceedings of the 28th Annual Meeting of the Decision Sciences Institute, San Diego, CA

Gripsrud, Geir, (2006). *"Suuply chain management-back to the future?"* International Journal of Physical Distribution & Logistics Management, Vol. 36 No. 8, pp.643-659

Habib, M. and C. Jungthirapanich, (2008) *"An integrated framework for research and education supply chain for the universities"*, Proceedings of the 4th IEEE International Conference on Management of Innovation and Technology, IEEE Computer Society, Piscataway, USA, ISBN: 978-1-4244-2329-3, pp. 1027-1032

Habib, Mamun. (2009a). *"An Integrated Educational Supply Chain Management (ITESCM)"*, Ph.D. Dissertation, Graduate School of Information Technology, Assumption University of Thailand

Habib, Mamun and Jungthirapanich, Chamnong. (2009b). *"Research Framework of Education Supply Chain, Research Supply Chain and Educational Management for the Universities"*, International Journal of the Computer, the Internet and Management (IJCIM), Thailand, Vol 17, No. SP1, pp.24.1-8 ISSN 0858-7027

Habib, M. and C. Jungthirapanich. (2010a).*"An Empirical Research of Educational Supply Chain for the Universities"*, The 5th *IEEE* International Conference on Management of Innovation and Technology, Singapore, E-ISBN: 978-1-4244-6566-8, Print ISBN: 978-1-4244-6565-1

Habib, Mamun. (2010b). *"An Empirical Research of ITESCM (Integrated Tertiary Educational Supply Chain Management) Model"* Editor, Management and Services, Sciyo.com, ISBN 978-953-307-118-3

Habib, M. and C. Jungthirapanich. (2010c). *"An Empirical Research of Integrated Educational Management for the Universities" The 2nd IEEE* International Conference on Information Management and Engineering, China, ISBN: 978-1-4244-5263-7

Habib, M. (2010d). *"An Empirical Research of ITESCM (Integrated Tertiary Educational Supply Chain Management) Model"* Management and Services, Sciyo.com, ISSN 978-953-307-118-3

Habib, M. and C. Jungthirapanich. (2009c). *"Research Framework of Educational Supply Chain Management for the Universities"*, IEEE International Conference on Engineering Management and Service Sciences EMS, China, ISBN: 978-1-4244-4638-4

Habib, Dr. Md. Mamun. (2011). *"An Exploratory Study of Supply Chain Management for Tertiary Educational Institutions"*, 2011 IEEE International Technology Management Conference (ITMC), San Jose, California, USA, ISBN 978-1-61284-950-8

Habib, M. (2010e). *"Supply Chain Management for Academia"* LAP Lambert Academic Publishing, Germany, ISBN 978-3-8433-8026-3

Habib, Dr. Md. Mamun. (2010f). *"Supply Chain Management: Theory and its Future Perspectives"*, International Journal of Business, Management and Social Sciences (IJBMSS), Vol. 1, No. 1

Habib, M.(2010g). "An Empirical Study of Tertiary Educational Supply Chain Management", International Conference on Knowledge globalization, Bangladesh, ISBN 978-984-33-1691-2

Habib, M. and C. Jungthirapanich. (2010h). *"An Empirical Study of Educational Supply Chain Management for the Universities"* INFORMS International Conference on Industrial Engineering and Operations Management (IEOM), Bangladesh, ISBN 978-984-33-0989-1

Habib, M. and C. Jungthirapanich. (2010i). *"International Supply Chain Management: Integrated Educational Supply Chain Management (IESCM) Model for the Universities"*, International Retailing: Text and Readings, S L Gupta, (Ed.), Excel Books, India, ISBN: 978-81-7446-859-8

Hay, R.D., (1990). Strategic Management in Non-Profit Organizations: An Administrator's Handbook, Quorum Books, Westport, CT

Handfield Robert B., Kannan Vijay R., Tan Keah Choon. (1998). *Supply Chain Management: "Supplier Performance and Firm Performance"*, International Journal of Purchasing and Materials Management, AZ USA, pp.2-9

Heskett, J., Ivie, R. and Glaskowsky, N. (1964). *Business Logistics, Management of Physical Supply and Distribution,* the Ronald Press Company, New York, NY

Heskett, J.L., Glaskowsky,N.A. Jr and Ivie, R.M. (1973). *Business Logistics*, 2nd ed., The Ronald Press, New York, NY, pp.14-21

Horvath, Laura. (2001). *"Collaboration: the key to value creation in supply chain management"*, Supply Chain Management: An International Journal, Vol. 6 No. 5, pp. 205-207

Houlihan, John B. (1988). *"International Supply Chains: A New Approach,"* Management Decision, Vol. 26, No. 3, pp. 13-19

Harwick, T. (1997). *"Optimal decision-making for the supply chain"*, APICS - The Performance Advantage, Vol.7 No. 1, pp.42-4

Inman, R.A. and Hubler J.H. (1992). *"Certify the Process – Not Just the Product"*, Production and Inventory Management Journal, USA, vol. 33, no. 4, pp. 11-14

Jones, Thomas and Daniel W. Riley. (1985). *"Using Inventory for Competitive Advantage through Supply Chain Management,"* International Journal of Physical Distribution and Materials Management, Vol. 15, No. 5, pp. 16-26

Kathawala, Yunnus and Khaled Abdou. (2003).*"Supply chain evaluation in the service industry: a framework development compared to manufacturing"*, Managerial Auditing Journal, Vol. 18 No. 2, pp.140-149

Lockamy, A. and Smith, W.I. (2000). *"Target costing for supply chain management: criteria and selection"*, Industrial Management & Data Systems, Vol.100 No. 5, pp. 210-8

Lau, Antonio K.W. (2007). *"Educational supply chain management: a case study"*, Emerald Group Publishing Limited, ISSN 1074-8121, Vol. 15 No.1, pp.15-27

La Londe, Bernard J. (1997). *"Supply Chain Management: Myth or Reality?"* Supply Chain Management Review, Vol. 1, spring, 1997, pp. 6-7

La Londe, Bernard J. and James M. Masters, *"Emerging Logistics Strategies: Blueprints for the Next Century,"* International Journal of Physical Distribution and Logistics Management, Vol. 24, No. 7, pp. 35-47

Lee, H.L. and Billington, C. *(1994)."Managing supply chain inventory: pitfalls and opportunities"*, Sloan Management Review, Vol. 33 No.3, pp.65-73

Lee Calvin B. (2002). *"Demand Chain Optimization – Pitfalls and Key Principles"*, USA, Nonstop Solution

Lummus, Rhonda and Robert, J. Vokurka. (1999). *"Defining supply chain management: a historical perspective and practical guidelines"*, Industrial Management & Data Systems", Vol.99 No.1, pp.11-17

Mentzer, John T. and et al. (2001). *"Defining Supply Chain Management"*, Journal of Business Logistics, Vol. 22 No. 2

Monczka, R. M. and Morgan, J.(1997). *"What's wrong with supply chain management"*, Purchasing, pp. 69-72

Monczka, Robert, Robert Trent, and Robert Handfield. (1994). *Purchasing and Supply Chain Management,* Cincinnati, OH: South-Western College Publishing, Chapter 8

Morgan J. and Monczka R.M. (1995). *Alliances for New Products,* Purchasing Journal, Vol 10, No. 1, pp. 103-109

Oliver, R.K. and Webber, M.D. (1992).*"Supply-chain management: logistics catches up with strategy"*, in Christopher, M. (Ed.), Logistics: The Strategic Issues, Chapman & Hall, London

O'Brien, Elaine M. and Kenneth R. (1996). *"Educational supply chain: a tool for strategic planning in tertiary education?"* Marketing Intelligence & Planning, Vol. 14 No. 2, pp.33-40

Ross, David Frederick. (1998). *"Competing Through Supply Chain Management"*, New York, NY: Chapman & Hall

Sampson, Scott E. (2000). *"Customer-supplier duality and bidirectional supply chains in service organization"*, International Journal of Service Industry Management, Vol. 11 No. 4, pp.348-364

Sandelands, E. (1994). *"Building supply chain relationships"*, International Journal of Physical Distribution & Logistics Management, Vol. 24 No. 3, pp.43-4

Scott, C. and Westbrook, R. (1991).*"New strategic tools for supply chain management"*, International Journal of Physical Distribution & Logistics Management, Vol. 21 No. 1, pp. 23-33

Sengupta, S. and Turnbull, J. (1996). *"Seamless optimization of the entire supply chain"*, IIE Solutions, Vol. 28, No. 10, pp.28-33

Stevenson, W.J. (2002). Operations Management, 7th ed., McGraw-Hill/Irwin, NY

Stevens, Graham C. (1989). *"Integrating the Supply Chains,"* International Journal of Physical Distribution and Materials Management, Vol. 8, No. 8, pp. 3-8

Tyndall, Gene, Christopher Gopal, Wolfgang Partsch, and John Kamauff. (1998). *"Supercharging Supply Chains: New Ways to Increase Value Through Global Operational Excellence"*, NY: John Wiley & Sons

Tan, K.C., Handfield, R.B. and Krause, D.R. (1998). *"Enhancing firm's performance through quality and supply base management: an empirical study"*, International Journal of Production Research, Vol. 36 No. 10, pp.2813-37

Tan, K.C. (2001). "*A framework of supply chain management literature*", European Journal of Purchasing and Supply Management, Vol.7 No.1, pp. 39-48

Talluri, Srinivas. (2002). "*Enhancing Supply Decisions through the Use of Efficient Marginal Cost Models*", The Journal of Supply Chain Management, UK, pp. 4-10

Watts, C.A., Kim, K.Y. and Hahn, C.K. (1992)."*Linking purchasing to corporate competitive strategy*", International Journal of Purchasing and Materials Management, Vol. 92, pp. 2-8

Wisner, J.D. and Tan, K.C. (2000). "*Supply chain management and its impact on purchasing*", Journal of Supply Chain Management, Vol.36 No.4, pp. 33-42

Weil, M. (1998). "*Customize the customer*", Manufacturing Systems,Vol.16 No. 4, pp.54-64

Part 2

Strategic and Tactical Issues in Supply Chain Management

2

Supply Chain Management Systems Advanced Control: MPC on SCM

Mohammad Miranbeigi and Aliakbar Jalali
Iran University of Science and Technology
Iran

1. Introduction

A supply chain is a network of facilities and distribution entities (suppliers, manufacturers, distributors, retailers) that performs the functions of procurement of raw materials, transformation of raw materials into intermediate and finished products and distribution of finished products to customers. Between interconnected entities, there are two types of process flows: information flows, e.g., an order requesting goods, and material flows, i.e., the actual shipment of goods (Figure 1). Key elements to an efficient supply chain are accurate pinpointing of process flows and timing of supply needs at each entity, both of which enable entities to request items as they are needed, thereby reducing safety stock levels to free space and capital. The operational planning and direct control of the network can in principle be addressed by a variety of methods, including deterministic analytical models, stochastic analytical models, and simulation models, coupled with the desired optimization objectives and network performance measures (Beamon, 1998).

The merit of model predictive control (MPC) is its applications in multivariable control in the presence of constraints. The success of MPC is due to the fact that it is perhaps the most general way of posing the control problem in the time domain. The use a finite horizon strategy allows the explicit handling of process and operational constraints by the MPC (Igor, 2008). In a recent paper (Perea et al., 2003), a MPC strategy was employed for the optimization of production/ distribution systems, including a simplified scheduling model for the manufacturing function. The suggested control strategy considers only deterministic type of demand, which reduces the need for an inventory control mechanism (Seferlis et al., 2004:Kapsiotis et al., 1992).

For the purposes of our study and the time scales of interest, a discrete time difference model is developed(Tzafestas, 1997). The model is applicable to multi echelon supply chain networks of arbitrary structure. To treat process uncertainty within the deterministic supply chain network model, a MPC approach is suggested (Wang et al., 2005:Chopra et al., 2004).

Typically, MPC is implemented in a centralized fashion (Wang et al., 2005). The complete system is modeled, and all the control inputs are computed in one optimization problem. In large scale applications, such as power systems, water distribution systems, traffic systems, manufacturing systems, and economic systems, such a centralized control scheme may not suitable or even possible for technical or commercial reasons (Sarimveis et al., 2008), it is useful to have distributed or decentralized control schemes, where local control inputs are computed using local measurements and reduced order models of the local dynamics. The

algorithm uses a receding horizon, to allow the incorporation of past and present control actions to future predictions (Camacho et al., 2004; Findeisen et al., 2007). As well as, further decentralized MPC advantages are less computational complication and lower error risk (Agachi, 2009:Towill, 2008).
So As supply chains can be operated sequentially, local Consecutive model predictive controllers applied to a supply chain management system consist of one plant, two warehouses, four distribution centers and four retailers. Also a move suppression term add to cost function, that increase system robustness toward changes on demands. Through illustrative simulations, it is demonstrated that the model can accommodate supply chain networks of realistic size under disturbances.

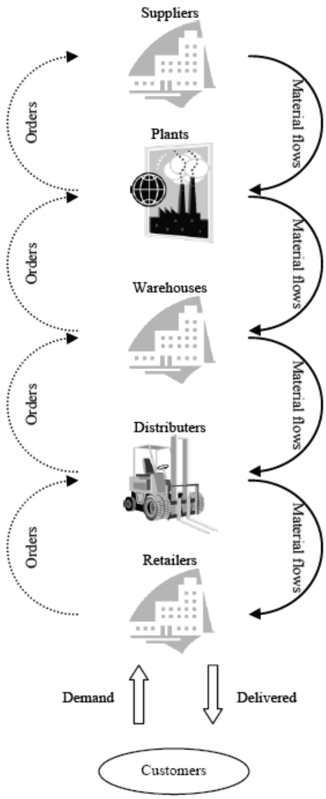


Fig. 1. Schematic of a multi echelon/multi product (A, B, C) supply chain network with process flows

2. Advanced control methods of supply chain management systems-literature review

The utilization of classical control techniques in the supply chain management problem can be traced back to the early 1950s when Simon applied servomechanism continuous-time theory to manipulate the production rate in a simple system involving just a single product. The idea was extended to discrete-time models by Vassian who proposed an inventory control framework based on the *z*-transform methodology. A breakthrough, however, was experienced in the late 1950s by the so-called "industrial dynamics" methodology, which was introduced by the pioneering work of Forrester. The methodology, later referred to as "system dynamics" used a feedback perspective to model, analyze and improve dynamic systems, including the production-inventory system. The scope of the methodology was later broadened to cover complex systems from various disciplines such as social systems, corporate planning and policy design, public management and policy, micro- and macro-economic dynamics, educational problems, biological and medical modeling, energy and the environment, theory development in the natural and social sciences, dynamic decision-making research, strategic planning and more. The book written recently by Sterman is an excellent source of information on the "system dynamics" philosophy and its various applications and includes special chapters on the supply chain management problem.

Forrester's work was appreciated for providing powerful tools to model and simulate complex dynamical phenomena including nonlinear control laws. However, the "industrial dynamics" methodology was criticized for not containing sufficient analytical support and for not providing guidelines to the systems engineers on how to improve performance. Motivated by the need to develop a new framework that could be used as a base for seeking new novel control laws and/or new feedback paths in production/inventory systems, Towill presented the inventory and order based production control system (IOBPCS) in a block diagram form, extending the work of Coyle. It was considered that the system deals with aggregate product levels or alternatively it reflects a single product. The system was subject to many modifications and improvements in subsequent years including extensions to discrete-time systems, thus leading to the IOBPCS family.

The designer has to decide on how the target stock will be set (fixed value or multiple of average sales) and select the three policies (demand policy, inventory policy and pipeline policy), in order to optimize the system with respect to the following performance objectives (Sarimveis et al., 2008):

a. Inventory level recovery.
b. Attenuation of demand rate fluctuations on the ordering rate.

The second objective aims at the reduction of the "bullwhip" effect. The term "bullwhip" was only recently introduced as mentioned in the introduction, but the phenomenon where a small random variation in sales at the marketplace is amplified at each level in the supply chain was already identified by the pioneering work of Forester in industrial dynamics. This was later postulated by Burbidge under the "Law of Industrial Dynamics". The utilization of control engineering principles in tackling the problem by providing supply chain dynamic modeling and re-engineering methodologies was soon recognized as reported by Towill.

The two performance objectives are conflicting. Thus, for each particular supply chain, the control system designer seeks for the best inventory level and ordering rate trade-off. A qualitative look at the two extremes scenarios (perfect satisfaction of each one of the two objectives) clearly shows that a compromise is needed to arrive at a well designed control system. If a fixed ordering rate is used then large inventory deviations are observed, since inventory levels follow any demand variation. This policy (known as Lean Production in manufacturing cites) obviously results in large inventory costs. On the other hand a fixed inventory level (known as Agile Production in manufacturing cites) results in highly variable production schedules and hence, large production costs.

Due to their dynamic and uncertain nature, production/inventory problems can be naturally formulated as dynamic programs. Dynamic programming is the standard procedure to obtain an optimal state feedback control law for stochastic optimal control problems.

MPC has now become a standard control methodology for industrial and process systems. Its wide adoption from the industry is largely based on the inherent ability of the method to handle efficiently constraints and nonlinearities of multi-variable dynamical systems. MPC is based on the following simple idea: at each discrete time instance the control action is obtained by solving *on-line* a finite-horizon *open-loop* optimal control problem, using the current state of the system as the initial state. A finite-optimal control sequence is obtained, from which only the first element is kept and applied to the system. The procedure is repeated after each state transition. Its main difference from stochastic dynamic programming and optimal control is that the control input is not computed a priori as an explicit function of the state vector. Thus, MPC is prevalent in the control of complex systems where the solution of the dynamic programming equations is computationally intractable due to the curse of dimensionality. However, when the optimal control problem is stochastic in nature, one can only obtain suboptimal solutions, due to the open-loop nature of the methodology (Sarimveis et al., 2008).

The significance of the basic idea implicit in the MPC has been recognized a long-time ago in the operations management literature as a tractable scheme for solving stochastic multi-period optimization problems, such as production planning and supply chain management, under the term rolling horizon. For a review of rolling horizons in operation management problems and interesting trade-offs between horizon lengths and costs of forecasts, we refer the reader to Sethi and Sorger and Chand et al. Kapsiotis and Tzafestas were the first to apply MPC to an inventory management problem, for a single inventory site. They included a penalty term for deviations from an inventory reference trajectory in order to compensate for production lead times. Tzafestas et al., considered a generalized production planning problem that includes both production/inventory and marketing decisions. They employed a linear econometric model concerning sales as a function of advertisement effort so as to approximate a nonlinear Vidale–Wolfe process. The dynamics of sales are coupled with an inventory balance equation. The optimal control problem is formulated as an MPC, where the control variables are the advertisement effort and the production levels. The objective function penalizes deviations from desired sales and inventory levels. Perea-Lopez et al. employed MPC to manage a multi-product, multi-echelon production and distribution network with lead times, allowing no backorders. They formulated the optimal control problem as a large scale mixed integer linear programming (MILP) problem, due to discontinuous decisions allowed in their model. In their formulation the demand is considered to be deterministic. They tested their formulation in a quite complex supply chain producing three products and consisting of three factories, three warehouses, four distribution centers and 10 retailers servicing 20 customers. They compared their centralized approach against two decentralized approaches. The first decentralized approach optimizes distribution only and uses heuristic rules for production/inventory planning. The second approach optimizes manufacturing while allowing the distribution network to follow heuristic rules. Through simulations, they inferred that the centralized approach exhibits superior performance (Sarimveis et al., 2008).

Seferlis and Gianellos developed a two-layered hierarchical control scheme, where a decentralized inventory control policy is embedded within an MPC framework. Inventory levels at the storage nodes and backorders at the order receiving nodes are the state variables for the linear state space model. The control variables are the product quantities transferred through the network permissible routes and the amounts delivered to the customers. Backorders are considered as output variables. Deterministic transportation delays are also included in the model. The cost function of the MPC consists of four terms, the first two being inventory and transportation costs, the third being a quadratic function that penalizes backorders at retailers and the last term being a quadratic move suppression term that penalizes deviations of decision variables between consecutive time periods. In order to account for demand uncertainty, they employed an autoregressive integrated moving average (ARIMA) forecasting model for the prediction of future product demand variation. Based on historical demand they performed identification of the order and parameters of the ARIMA model (Sarimveis et al., 2008).

PID controllers were embedded for each inventory node and each product. These local controllers are responsible for maintaining the inventory levels close to the pre-specified target levels. Hence, the incoming flows to the inventory nodes are selected as the manipulated variables for the PID controllers. This way a decoupling between inventory level maintenance and satisfaction of primary control objectives (e.g. customer satisfaction) is achieved, permitting the MPC configuration to react faster to disturbances in demand variability and transportation delays. However, tuning of the localized PID controllers requires a time consuming trial-and-error procedure based on simulations. In their experiments, assuming that demand is deterministic and performing a step change, they observed an amplification of set point deviations for upstream nodes (bullwhip). For stochastic demand variation, they noted that the centralized approach requires a much larger control horizon to achieve a comparable performance with their two-layered strategy.

Braun et al., developed a linear MPC framework for large scale supply chain problems resulting from the semiconductor industry. Through experiments, they showed that MPC can handle adequately uncertainty resulting from model mismatch (lead times) and demand forecasting errors. Due to the complexity of large scale supply chains, they proposed a decentralized scheme where a model predictive controller is created for each node, i.e production facility, warehouse and retailers. Inventory levels are treated as state variables for each node, the manipulated variables are orders and production rates, and demands are treated as disturbances. The goal of the MPC controller is to keep the inventory levels as close as possible to the target values while satisfying constraints with respect to production and transportation capacities. Their simulations showed that using move suppression (i.e. the term in the objective function that penalizes large deviations on control variables between two consecutive time instants), backorders can be eliminated. It is well known in the MPC community that the move suppression term has the effect of making the controller less sensitive to prediction inaccuracies, although usually at the price of degrading set point tracking performance. Through simulations, Braun et al. and Wang et al. justified further the significance of move suppression penalties as a means for increased robustness against model mismatch and hedging against inaccurate demand forecasts.

Wang et al. treated demand as a load disturbance and they considered it as a stochastic signal driven by integrated white-noise (the discrete-time analog of Brownian motion). They applied a state estimation-based MPC in order to increase the system performance and robustness with respect to demand variability and erroneous forecasts.

Assuming no information on disturbances, they employed a Kalman filter to estimate the state variables, where the filter gain is a tuning parameter based on the signal-to-noise ratio. Through simulations they concluded that when there is a large error between the average of actual demands and the forecast, a larger filter gain can make the controller compensate for the error sufficiently fast (Sarimveis et al., 2008).

Dunbar and Desa applied a recently developed distributed/decentralized implementation of nonlinear MPC to the problem of dynamic supply chain management problem, reminiscent of the classic MIT "Beer Game". By this implementation, each subsystem is optimized for its own policy, and communicates the most recent policy to those subsystems to which it is coupled. The supply network consists of three nodes, a retailer, a manufacturer and a supplier. Information flows (i.e., flows moving upstream) are assumed to have no time delays (lead times). On the other hand, material flows (i.e., flows moving downstream) are assumed to have transportation delays. The proposed continuous-time dynamic model is characterized by three state variables, namely, inventory level, unfulfilled orders and backlog for each node. The control inputs are the order rates for each node. Demand rates and acquisition rates (i.e., number of items per day acquired from the upstream node) are considered as disturbances. The control objective is to minimize the total cost, which includes avoiding backorders and keeping unfulfilled orders and inventory levels low. Their model demonstrates bidirectional coupling between nodes, meaning that differential equation models of each stage depend upon the state and input of other nodes. Hence, cycles of information dependence are present in the chain. These cycles complicate decentralized/distributed MPC implementations since at each time period coupled stages must estimate states and inputs of one another. To address this issue, the authors assumed that coupled nodes receive the previously computed predictions from neighboring nodes prior to each update, and rely on the remainder of these predictions as the assumed prediction at each update. To bound the discrepancy between actual and assumed predictions, a move suppression term is included in the objective function. Thus, with the decentralized scheme, an MPC controller is designed for each node, which updates its policy in parallel with the other nodes based on estimates regarding information for interconnected variables. Through simulations, they concluded that the decentralized MPC scheme performs better than a nominal feedback control derived in Sterman, especially when accurate forecasts regarding customer demand exist. However, both approaches exhibit non-zero steady-state error with respect to unfulfilled demands when a step increase is applied to the customer demand rate. Furthermore, the bullwhip effect is observed in their simulations (Sarimveis et al., 2008).

Based on the model of Lin et al., Lin et al. presented a minimum variance control (MVC) system, where two separate set points are posed. An ARIMA model is used as a mechanism to forecast customer demands. The system proved superior to other approaches such as the order-up-to-level policy, PI control in maintaining proper inventory levels without causing the "bullwhip" effect, whether the customer demand trend is stationary or not (Sarimveis et al., 2008).

Yildirim et al. studied a dynamic planning and sourcing problem with service level constraints. Specifically, the manufacturer must decide how much to produce, where to produce, when to produce, how much inventory to carry, etc., in order to fulfill random customer demands in each period. They formulated the problem as a multi-period stochastic programming problem, where service level constraints appear in the form of chance constraints. In order to obtain the optimal feedback control one should be able to solve the resulting stochastic dynamic program. However, due to the curse of dimensionality the problem is computationally intractable. Thus, in order to obtain a sub-optimal solution they formulated the problem as a static deterministic optimization problem. They approximated the service level chance constraints with deterministic equivalent constraints by specifying certain minimum cumulative production quantities that depend on the service level requirements. The rolling horizon procedure is applied on-line following the MPC philosophy, i.e. by solving the resulting mathematical programming problem at each discrete-time instance, applying only the first decision and moving to a new state, where the procedure is repeated. The authors compared their approach to certain threshold subcontracting policies yielding similar results.

Describing uncertainties in a stochastic framework is the standard practice used by the operations research community. For example, in the majority of papers reviewed so far, uncertainties concerning customer demands, machine failures and lead times were mostly described by probability distributions and stochastic processes. However, in many practical situations one may not be able to identify the underlying probability distributions or such a stochastic description may simply not exist. On the other hand, based on historical data or experience one can easily infer bounds on the magnitude of the uncertain parameters (Sarimveis et al., 2008).

Having realized this fact a long-time ago, the control engineering community has developed the necessary theoretical and algorithmic machinery for this type of problems, the so-called robust control theory. In this framework, uncertainties are unknown-but-bounded quantities and constraints dictated by performance specifications and physical limitations are usually hard, meaning that they must be satisfied for all realizations of the uncertain quantities. In the robust control framework, models can be usually "infected" with two types of uncertainty; exogenous disturbances (e.g. customer demands) and plant-model mismatch, that is, uncertainties due to modeling errors (Sarimveis et al., 2008).

The aim of this review paper was to present alternative control philosophies that have been applied to the dynamic supply chain management problem. Representative references were provided that can guide the reader to explore in depth the methodologies of his/her choice. The efforts started in the early 1950s by applying classical control techniques where the analysis was performed in the frequency domain. More recently, highly sophisticated optimal control methods have been proposed mainly based on the time domain. However, many recent reports state that the majority of companies worldwide still suffer from poor supply chain management. Moreover, undesired phenomena, such as the "bullwhip" effect have not yet been remedied. The applicability of control methodologies in real life supply chain problems is thus, naturally questioned.

It is true that in many methodologies that have been presented in this paper, the assumptions on which they are based are often not valid in reality. For example, lead times are not fixed and are not known with accuracy, as many models assume. Inventory levels should be bounded below by zero and above due to warehouse capacities, but these bounds are not always taken into account. The same happens with the production rates which are limited by the machinery capacities. Another limitation is that single stage systems are usually studied, assuming production of a single product or aggregated production. In real life systems, various products are produced with different production rates and different lead times, which, however, share common machinery and storage facilities. Horizontal integration is often represented by considering the supply chain stages in a raw, while interconnections between different level and same level stages are ignored. Finally, raw material costs which may be variable, labor costs and inventory costs are rarely taken explicitly into account. From the above discussion, it is evident that despite the considerable advances that have occurred throughout the years in controlling supply chain systems, there is still plenty of room for further improvements. Elimination of the above limitations will lead to new methodologies of more applicability. Therefore, dynamic control of supply chain systems remains an open and active research area. Among the alternative methodologies that have been presented in this review paper, we would like to draw the attention of the reader to the MPC framework which has become extremely popular in the engineering community, as it proved successful in facing problems similar to the ones mentioned above. Among other advantages, the MPC framework can easily incorporate bounds on the manipulated and controlled variables and leads to the formulation of computationally tractable optimization problems (Sarimveis et al., 2008).

3. MPC for multi echelon supply chain management system

Supply chains are complicated dynamical systems triggered by customer demands. Over the past decade, supply chain management and control has become a strategic focus of leading manufacturing companies. This has been caused by rapid changes in environments in which the companies operate, characterized by high globalization of markets and ever increasing customer demands for higher levels of service and quality. Proper selection of equipment, machinery, buildings and transportation fleets is a key component for the success of such systems. However, efficiency of supply chains mostly depends on management decisions, which are often based on intuition and experience. Due to the increasing complexity of supply chain systems (which is the result of changes in customer preferences, the globalization of the economy and the stringy competition among companies), these decisions are often far from optimum. Another factor that causes difficulties in decision making is that different stages in supply chains are often supervised by different groups of people with different managing philosophies. From the early 1950s it became evident that a rigorous framework for analyzing the dynamics of supply chains and taking proper decisions could improve substantially the performance of the systems. Due to the resemblance of supply chains to engineering dynamical systems, control theory has provided a solid background for building such a framework. During the last half century many mathematical tools emerging from the control literature have been applied to the supply chain management problem. These tools vary from classical transfer function analysis to highly sophisticated control methodologies, such as MPC and neuro dynamic programming.

In this work, a discrete time difference model is developed. The model is applicable to multi echelon supply chain networks of arbitrary structure, that DP denote the set of desired products in the supply Chain and these can be manufactured at plants, P, by utilizing various resources, RS. The manufacturing function considers independent production lines for the distributed products. The products are subsequently transported to and stored at warehouses, W. Products from warehouses are transported upon customer demand, either to distribution centers, D, or directly to retailers, R. Retailers receive time varying orders from different customers for different products. Satisfaction of customer demand is the primary target in the supply chain management mechanism. Unsatisfied demand is recorded as backorders for the next time period. A discrete time difference model is used for description of the supply chain network dynamics. It is assumed that decisions are taken within equally spaced time periods (e.g. hours, days, or weeks). The duration of the base time period depends on the dynamic characteristics of the network. As a result, dynamics of higher frequency than that of the selected time scale are considered negligible and completely attenuated by the network (Perea, 2007).

Plants P, warehouses W, distribution centers D, and retailers R constitute the nodes of the system. For each node, k, there is a set of upstream nodes and a set of downstream nodes, indexed by (k', k''). Upstream nodes can supply node k and downstream nodes can be supplied by k. All valid (k', k) and/or (k, k'') pairs constitute permissible routes within the network. All variables in the supply chain network (e.g. inventory, transportation loads) valid for bulk commodities and products. For unit products, continuous variables can still be utilized, with the addition of a post-processing rounding step to identify neighbouring integer solutions. This approach, though clearly not formally optimal, may be necessary to retain computational tractability in systems of industrial relevance.

A product balance around any network node involves the inventory level in the node at time instances t and $t-1$, as well as the total inflow of products from upstream nodes and total outflow to downstream nodes. The following balance equation is valid for nodes that are either warehouses or distribution centers:

$$\begin{aligned} & y_{i,k}(t) = y_{i,k}(t-1) + \sum_{k'} x_{i,k',k}(t - L_{k',k}) - \sum_{k''} x_{i,k,k''}(t), \\ & \forall k \in \{W, D\}, \qquad t \in T, \qquad i \in DP \end{aligned} \tag{1}$$

where $y_{i,k}$ is the inventory of product i stored in node k; $x_{i,k',k}$ denotes the amount of the i-th product transported through route (k', k); $L_{k',k}$ denotes the transportation lag (delay time) for route (k', k), i.e. the required time periods for the transfer of material from the supplying node to the current node. The transportation lag is assumed to be an integer multiple of the base time period.

For retailer nodes, the inventory balance is slightly modified to account for the actual delivery of the i-th product attained, denoted by $d_{i,k}(t)$.

$$\begin{aligned} & y_{i,k}(t) = y_{i,k}(t-1) + \sum_{k'} x_{i,k',k}(t - L_{k',k}) - d_{i,k}(t), \\ & \forall k \in \{R\}, \qquad t \in T, \qquad i \in DP. \end{aligned} \tag{2}$$

The amount of unsatisfied demand is recorded as backorders for each product and time period. Hence, the balance equation for back orders takes the following form:

$$\begin{aligned} & BO_{i,k}(t) = BO_{i,k}(t-1) + R_{i,k}(t) - d_{i,k}(t) - LO_{i,k}(t), \\ & \forall k \in \{R\}, \qquad t \in T, \qquad i \in DP. \end{aligned} \tag{3}$$

where $R_{i,k}$ denotes the demand for the i-th product at the k-th retailer node and time period t. $LO_{i,k}$ denotes the amount of cancelled back orders (lost orders) because the network failed to satisfy them within a reasonable time limit. Lost orders are usually expressed as a percentage of unsatisfied demand at time t. Note that the model does not require a separate balance for customer orders at nodes other than the final retailer nodes (Sterman et al, 2002).

MPC is a model based control strategy that calculates at each sampling time via optimization the optimal control action to maintain the output of the plant close to the desired reference. In fact, MPC stands for a family of methods that select control actions based on online optimization of an objective function. MPC has gained wide acceptance in the chemical and other process industries as the basis for advanced multivariable control schemes. In MPC, a system model and current and historical measurements of the process are used to predict the system behavior at future time instants. A control relevant objective function is then optimized to calculate a sequence of future control moves that must satisfy system constraints. The first predicted control move is implemented and at the next sampling time the calculations are repeated using updated system states (illustrated in Figure 2). MPC represents a general framework for control system implementation that accomplishes both feedback and feed forward control action on a dynamical system. The appeal of MPC over traditional approaches to control design include (1) the ability to handle large multivariable problems, (2) the explicit handling of constraints on system input and output variables, and (3) its relative ease of use. MPC applied to supply chain management relies on dynamical models of material flow to predict inventory changes among the various nodes of the supply chain. These model predictions are used to adjust current and future order quantities requested from upstream nodes such that inventory will reach the targets necessary to satisfy demand in a timely manner (Wang et al, 2007). The control system aims at operating the supply chain at the optimal point despite the influence of demand changes. The control system is required to possess built in capabilities to recognize the optimal operating policy through meaningful and descriptive cost performance indicators and mechanisms to successfully alleviate the detrimental effects of demand uncertainty and variability. The main objectives of the control strategy for the supply chain network can be summarized as follows: (i) maximize customer satisfaction, and (ii) minimize supply chain operating costs.

The first target can be attained by the minimization of back orders (i.e. unsatisfied demand) over a time period because unsatisfied demand would have a strong impact on company reputation and subsequently on future demand and total revenues. The second goal can be achieved by the minimization of the operating costs that include transportation and inventory costs that can be further divided into storage costs and inventory assets in the supply chain network. Based on the fact that past and present control actions affect the future response of the system, a receding time horizon is selected. Over the specified time horizon the future behavior of the supply chain is predicted using the described difference model (Eqs. (1)–(3)). In this model, the state variables are the product inventory levels at the storage nodes, y, and the back orders, BO, at the order receiving nodes. The manipulated (control or decision) variables are the product quantities transferred through the network's permissible routes, x, and the delivered amounts to customers, d. Finally, the product back orders, BO, are also matched to the output variables. The inventory target levels (e.g. inventory setpoints) are time invariant parameters. The control actions that minimise a performance index associated with the outlined control objectives are then calculated over the receding time horizon. At each time period the first control action in the calculated sequence is implemented. The effect of unmeasured demand disturbances and model mismatch is computed through comparison of the actual current demand value and the prediction from a stochastic disturbance model for the demand variability. The difference that describes the overall demand uncertainty and system variability is fed back into the MPC scheme at each time period facilitating the corrective action that is required.

The centralized mathematical formulation of the performance index considering simultaneously back orders, transportation and inventory costs takes the following form:

$$\begin{aligned}J_{total} = &\sum_{t}^{t+P} \sum_{k\in\{W,D,R\}} \sum_{i\in DP} \left\{ w_{y,i,k}(y_{i,k}(t) - y_{s,i,k}(t))^2 \right\} + \sum_{t}^{t+M} \sum_{k\in\{W,D,R\}} \sum_{i\in DP} \left\{ w_{x,i,k',k}(x_{i,k',k}(t))^2 \right\} \\ &+ \sum_{t}^{t+P} \sum_{k\in\{R\}} \sum_{i\in DP} \left\{ w_{BO,i,k}(BO_{i,k}(t))^2 \right\} + \sum_{t}^{t+M} \sum_{k\in\{W,D,R\}} \sum_{i\in DP} \left\{ w_{\Delta x,i,k',k}(x_{i,k',k}(t) - x_{i,k',k}(t-1))^2 \right\}.\end{aligned} \tag{4}$$

The performance index, J, in compliance with the outlined control objectives consists of four quadratic terms. Two terms account for inventory and transportation costs throughout the supply chain over the specified prediction and control horizons(P , M). A term penalizes back orders for all products at all order receiving nodes (e.g. retailers) over the prediction horizon P. Also a term penalizes deviations for the decision variables (i.e. transported product quantities) from the corresponding value in the previous time period over the control horizon M. The term is equivalent to a penalty on the rate of change in the manipulated variables and can be viewed as a move suppression term for the control system. Such a policy tends to eliminate abrupt and aggressive control actions and subsequently, safeguard the network from saturation and undesired excessive variability induced by sudden demand changes. In addition, transportation activities are usually preferred to resume a somewhat constant level rather than fluctuate from one time period to another.

However, the move suppression term would definitely affect control performance leading to a more sluggish dynamic response. The weighting factors, $w_{y,i,k}$, reflect the inventory storage costs and inventory assets per unit product, $w_{x,i,k',k}$, account for the transportation cost per unit product for route (k',k) .Weights $w_{BO,i,k}$ correspond to the penalty imposed on unsatisfied demand and are estimated based on the impact service level has on the company reputation and future demand. Weights $w_{\Delta x,i,k',k}$, are associated with the penalty on the rate of change for the transferred amount of the i-th product through route (k',k) . Even though, factors $w_{y,i,k}$, $w_{x,i,k',k}$ and $w_{BO,i,k}$ are cost related that can be estimated with a relatively good accuracy, factors $w_{\Delta x,i,k',k}$ are judged and selected mainly on grounds of desirable achieved performance.

The weighting factors in cost function also reflect the relative importance between the controlled (back orders and inventories) and manipulated (transported products) variables. Note that the performance index of cost function reflects the implicit assumption of a constant profit margin for each product or product family. As a result, production costs and revenues are not included in the index.

But in this paper, a consecutive decentralized formulation will used, namely centralized cost function divided to decentralized cost functions for each stage(warehouse, distribution center, retailer):

$$\begin{aligned} J_1 = &\sum_{t}^{t+P} \sum_{i \in DP} \left\{ w_{y,i,k} (y_{i,k}(t))^2 \right\} \\ &+ \sum_{t}^{t+M} \sum_{i \in DP} \left\{ w_{x,i,k',k} (x_{i,k',k}(t))^2 \right\} \\ &+ \sum_{t}^{t+M} \sum_{i \in DP} \left\{ w_{\Delta x,i,k',k} (x_{i,k',k}(t) - x_{i,k',k}(t-1))^2 \right\}, \quad k \in W \end{aligned} \tag{5}$$

$$\begin{aligned} J_2 = &\sum_{t}^{t+P} \sum_{i \in DP} \left\{ w_{y,i,k} (y_{i,k}(t))^2 \right\} \\ &+ \sum_{t}^{t+M} \sum_{i \in DP} \left\{ w_{x,i,k',k} (x_{i,k',k}(t))^2 \right\} \\ &+ \sum_{t}^{t+M} \sum_{i \in DP} \left\{ w_{\Delta x,i,k',k} (x_{i,k',k}(t) - x_{i,k',k}(t-1))^2 \right\}, \quad k \in D \end{aligned} \tag{6}$$

$$
\begin{aligned}
J_3 = & \sum_{t}^{t+P} \sum_{i \in DP} \left\{ w_{y,i,k} (y_{i,k}(t))^2 \right\} \\
& + \sum_{t}^{t+M} \sum_{i \in DP} \left\{ w_{x,i,k',k} (x_{i,k',k}(t))^2 \right\} \\
& + \sum_{t}^{t+P} \sum_{i \in DP} \left\{ w_{BO,i,k} (BO_{i,k}(t))^2 \right\} \\
& + \sum_{t}^{t+M} \sum_{i \in DP} \left\{ w_{\Delta x,i,k',k} (x_{i,k',k}(t) - x_{i,k',k}(t-1))^2 \right\}, \quad k \in R.
\end{aligned} \tag{7}
$$

Therefore by this implementation, As supply chains can be operated sequentially, i.e., stages update their policies in series, synchronously, each node by a decentralized model predictive controller optimizes for its own policy, and communicates the most recent policy to those nodes to which it is coupled. In fact, MPC's of retailers (with Eqs. (1),(5)) only will optimized for its own policy and then will sent its optimal inputs to upstream joint nodes to those nodes which it is coupled (distribution centers), as measurable disturbances. Also model predictive controllers of distribution centers (with Eqs. (1),(6)) only will optimized for its own policy and then will sent its optimal inputs to upstream joint nodes to those nodes which it is coupled (warehouse centers), as measurable disturbances. Finally, model predictive controllers of warehouses (with Eqs. (2),(3),(7)) will optimized for its own optimal inputs.

Two types of sequential decentralized MPC can be used. In first method, each node completely by a decentralized MPC optimizes for its own policy. At each time period, the first decentralized MPC action in the calculated sequence is implemented until MPC process complete.

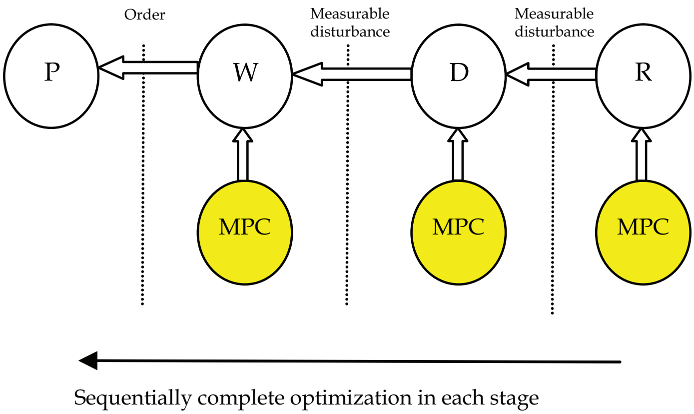


Fig. 2. Procedure of first consecutive decentralized MPC

In fact, local decentralized model predictive controllers corresponding to retailers will done for regulating inventory level in R and then will sent its MPC optimal inputs at long prediction horizon to upstream joint nodes to those nodes which it is coupled (distribution centers), as measurable disturbances. Also model predictive controllers corresponding to distribution centers will optimized and then will sent its optimal inputs to upstream joint nodes to those nodes which it is coupled (warehouse centers), as measurable disturbances. Finally, model predictive controllers corresponding to warehouses will optimized for its own optimal inputs by local method. In fact decentralized model predictive controllers, sequentially operate (Figure 2).

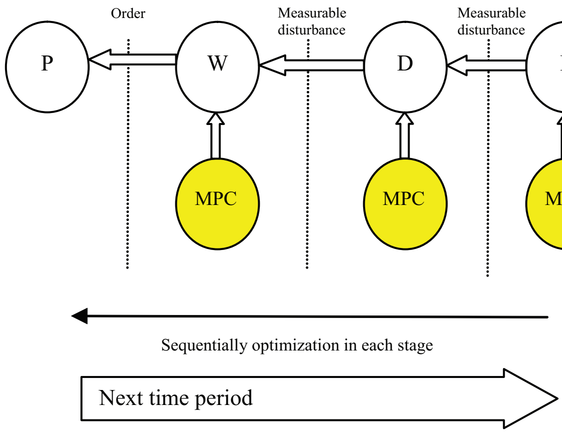


Fig. 3. Procedure of second consecutive decentralized MPC

4. Simulations

A four echelon supply chain system is used in the simulated examples. The supply chain network consists of one production nodes, two warehouse nodes, four distribution centers, and four retailer nodes (Figure 4). All possible connections between immediately successive echelons are permitted. One product family consist of 12 products is being distributed through the network. Inventory setpoints, maximum storage capacities at every node, and transportation cost data for each supplying route are reported in Table 1.

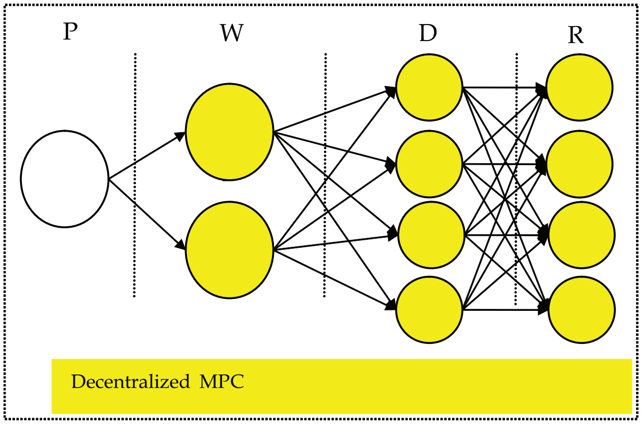


Fig. 4. MPC framework in a multiechelon supply chain management system

Echelon	**W**	**D**	**R**
Max inventory level	1400	500	150
Inventory setpoint	320	220	35
Transportation cost (move suppression cost)	P to W 0.5	W to D 1	D to R 1
Inventory weights	1	1	1
Back order weights	-	-	1
Delays	2	3	2

Table 1. Given values of supply chain

A prediction horizon of 25 time periods and a control horizon of 20 time periods were selected and was considered $LO_{i,k} = 0$ for every times. So each delay was replaced by its 4th order Pade approximation (after system model transform to continues time model and then return to discrete time model). In this part, two method of consecutive decentralize MPC that beforehand was stated, applying to large scale supply chain to constant demands equal 4. The simulated scenarios lasted for 70 time periods. As demand is constant, both method have equal response to constant demand that is presented in figure 5 (average inventory levels in each echelon). The move suppression term would definitely affect control performance leading to a more sluggish dynamic response.

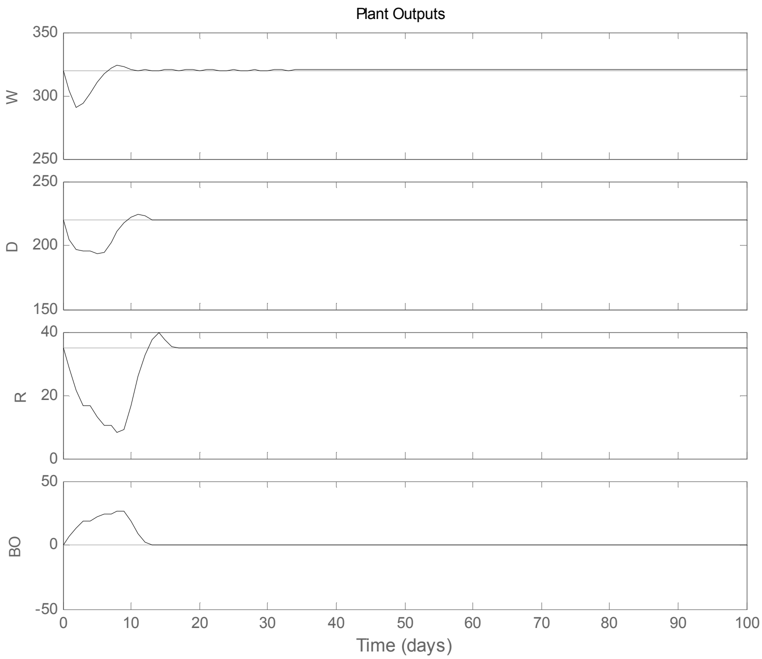


Fig. 5. Discrete time dynamic response to a 4 unit constant demand for networks with different transportation delays L = [2 3 2] (first and second method)

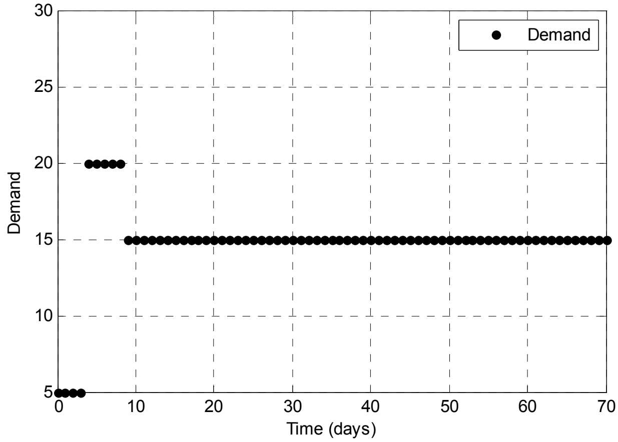


Fig. 6. Discrete pulsatory customer demand

In fact, if suddenly demand changed, the first method can not predict this changes and has not efficiency. Instead second method by online demand prediction in its formulation is efficient. As second method by online demand prediction in its formulation is rather efficient to first method, in this part, second decentralized MPC method applied to the supply chain network with pulsatory variations of customer demand that are seeing in figure 6, once with no move suppression term (Figure 7), and once with move suppression term (Figure 8).

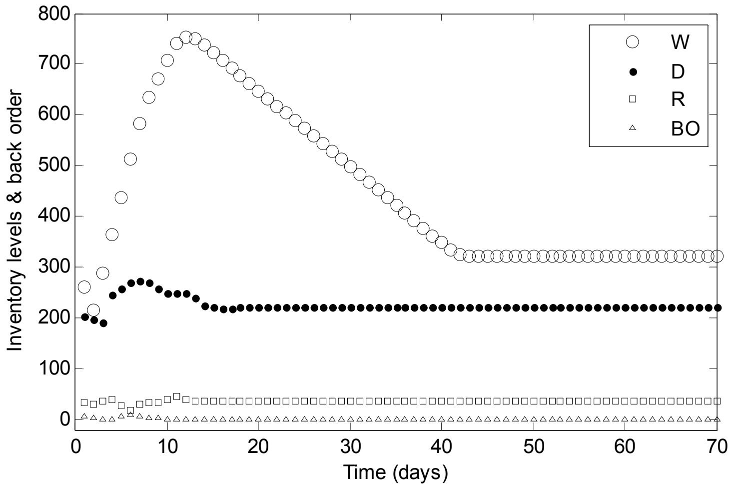


Fig. 7. Inventory levels control by second method of consecutive decentralized MPC toward discrete pulsatory demand with without move suppression effect

Also second decentralized MPC method applied to the supply chain network with pulsatory variations of customer demand that are seeing in figure 9, once with no move suppression term (Figure 10), and once with move suppression term (Figure 11).

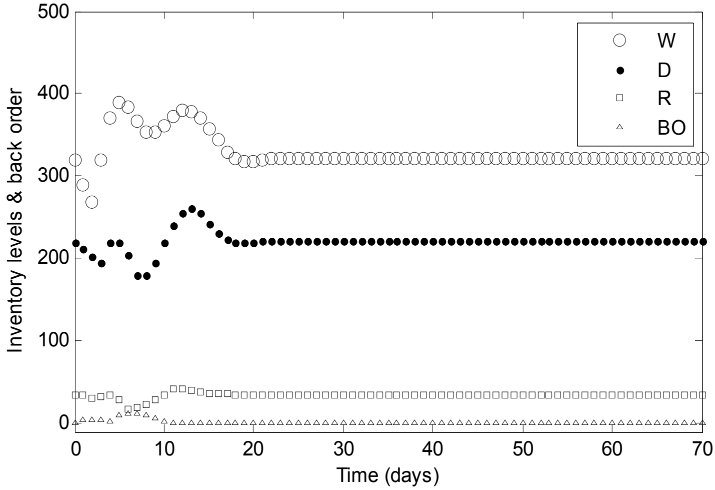


Fig. 8. Inventory levels control by second method of consecutive decentralized MPC toward discrete pulsatory demand with move suppression effect

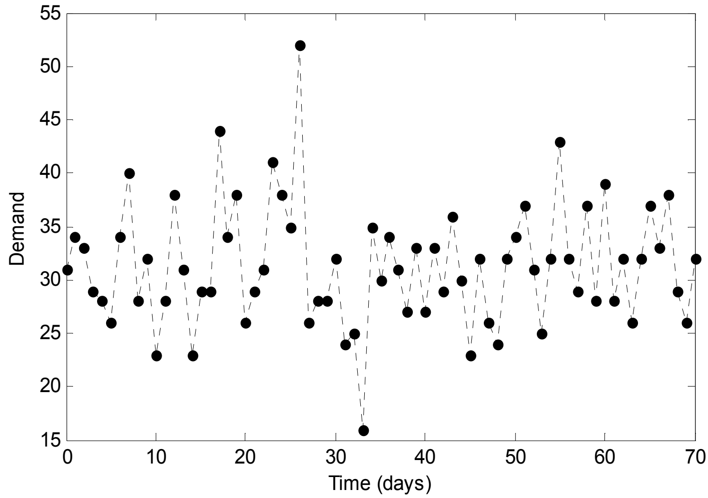


Fig. 9. Discrete stochastic demand of gamma distribution

Therefore by using of move suppression, amplitude of variation of outputs will be decreased. So move suppression term increased system robustness toward changes on demands (Figure 11).

5. Conclusion

Supply chain management system is a network of facilities and distribution entities: suppliers, manufacturers, distributors, retailers. The control system aims at operating the

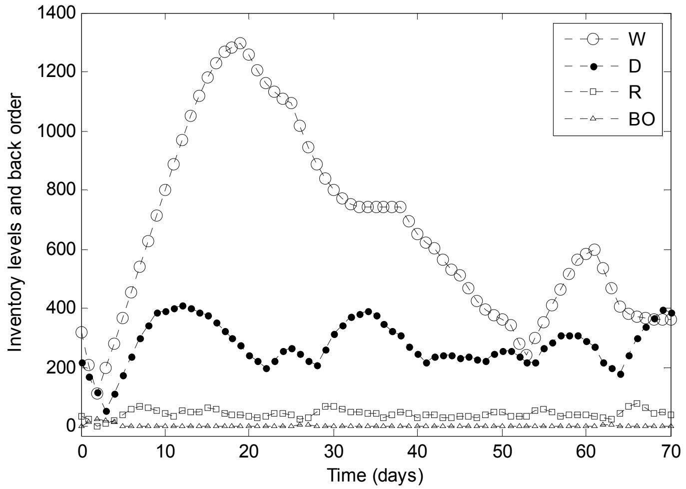


Fig. 10. Inventory levels control by second method of consecutive decentralized MPC toward discrete stochastic demand of gamma distribution without move suppression effect

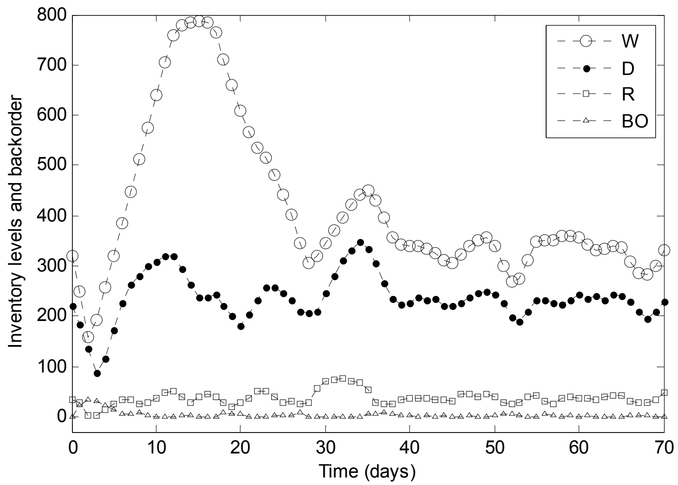


Fig. 11. Inventory levels control by second method of consecutive decentralized MPC toward discrete stochastic demand of gamma distribution with move suppression effect

supply chain at the optimal point despite the influence of demand changes. As supply chains can be operated sequentially, local Consecutive model predictive controllers applying to a supply chain management system consist of four echelon. Two types of sequential decentralized MPC used. In first method, each node completely by a decentralized model predictive controller optimized for its own policy, and in second method, decentralized model predictive controllers in each stage are updated in each time period. As second method by online demand prediction in its formulation is rather efficient to first method, in this part, second decentralized MPC method applied to the supply chain network with pulsatory variations of customer demand. Also second decentralized MPC method applied to the supply chain network with pulsatory variations of customer demand. In fact, if suddenly demand changed, the first method can not predict this changes and has not efficiency. Instead second method by online demand prediction in its formulation is efficient. Also a move suppression term add to cost function, that increase system robustness toward changes on demands.

6. References

Agachi, P. S.; Nagy, Z. K. & Cristea, M. V. & Imre, A. (2009). *Model Based Control,* WILEY-VCH Verlag GmbH & Co.

Beamon, B. M. (1998). Supply chain design and analysis: models and methods. *International Journal of Production Economics*, Vol. 55, pp. 281.

Camacho, E. F.; Bordons, C. (2004). *Model Predictive Control,* Springer.

Chopra, S.; Meindl, P. (2004). *Supply Chain Management Strategy, Planning and Operations*, Pearson Prentice Hall Press, New Jersey, pp. 58-79.

Findeisen, R.; Allgower, F.; Biegler, L., T. (2007). *Assessment and future directions of nonlinear model predictive control*, Springer.

Igor, S. (2008). Model predictive functional control for processes with unstable poles. *journal of control,* Vol 10, pp. 507-513.

Kapsiotis, G.; Tzafestas, S. (1992). Decision making for inventory/production planning using model-based predictive control. *Parallel and distributed computing in engineering systems*, Elsevier, pp. 551–556, Amsterdam.

Perea, E.; Ydstie, B. E. (2003). Model predictive control strategy for supply chain optimization. *Computers and Chemical Engineering*, Vol. 27, pp. 1201.

Perea, E. (2007). Modeling and classical control theory for supply chain management. *Computers and Chemical Engineering*, Vol. 24, pp. 1143-1149.

Sarimveis, H.; Patrinos, P.; Tarantilis, D.; Kiranoudis, T. (2008). Dynamic modeling and control of supply chain systems: A review. *Computers and Research*, Vol. 35, pp. 3530 – 356.

Seferlis, P.; Giannelos, N. F. (2004). A two layered optimization based control sterategy for multi echelon supply chain network. *Computers and Chemical Engineering*, Vol. 28, pp. 799–809.

Sterman, J. D. (2002). *Business Dynamics Systems Thinking and Modelling in A Complex World*, Mcgraw Hill Press, pp. 113-128. pp. 799–809.

Towill, R. (2008). Dynamic analysis of an inventory and order based production control system. *Int J. Prod. Res*, Vol. 20, pp. 671-687.

Tzafestas, S.; Kapsiotis, G. (1997). Model based predictive control for generalized production planning problems. *Computers in Industry*, Vol. 34, pp. 201–210.

Wang, W.; Rivera, R. (2005). A novel model predictive control algorithm for supply chain management in semiconductor manufacturing. *Proceedings of the American control conference*, vol. 1, pp. 208–213.

Wang, W.; Rivera, R.; Kemp, K. G. (2007). Model predictive control strategies for supply chain management in semiconductor manufacturing. *Int. J. Production Economics*, vol. 107, pp. 56–77.

3

Supply Chain Control: A Perspective from Design for Reliability and Manufacturability Utilizing Simulations

Yan Liu and Scott Hareland
Medtronic, Inc.
United States

1. Introduction

Product quality and reliability are essential in the medical device industry. In addition, predictable development time, efficient manufacturing with high yields, and exemplary field reliability are all hallmarks of a successful product development process.

One challenge in electronic hardware development normally involves understanding the impact of variability in component and material properties and the subsequent potential impact on performance, yield, and reliability. Over-reliance on physical testing and characterization of designs may result in subsequent yield issues and/or post-release design changes in high volume manufacturing. Issues discovered later in the product cycle make development time unpredictable and do not always effectively eliminate potential risk. Using hardware testing to verify that the embedded system hardware and firmware work under the worst case conditions in the presence of variation is potentially costly and challenging. As a result, improving predictability early in design with a virtual environment to understand the influence of process corners and better control of distributions and tails in components procured in the supply chain is important. The goal is to ensure that design works in the presence of all specified variability and to ensure the component designed is appropriately controlled during purchasing/manufacturing. This is achieved by establishing a clear link between the variability inherent in the supply chain on the performance, yield, and reliability of the final design. This will lay the groundwork for managing expectations throughout the entire supply chain, so that each functional area is aware of its responsibilities and role in the overall quality and reliability of the product.

In this chapter, a methodology is outlined that utilizes electrical simulations to account for component variability and its predicted impact on yield and quality. Various worst-case circuit analysis (WCCA) methods with the advantages, assumptions and limitations are introduced in Section 2. A simulation based flow is developed in Section 3 to take advantage of the best qualities of each method discussed to understand design, reliability, and yield in relation to how the product is used and how the effects of variability in the supply chain influence the outcome. Furthermore, predictive yield estimation is enabled using a computationally efficient Monte Carlo analysis technique extending results of worst case analysis with actual component parameter distributions obtained from the supply chain is discussed in Section 4. Transfer functions are built upon simulation-based design of experiments and realistic distributions applied to the various input parameters using statistically based data analysis. Building upon simulations to statistically predict real-world performance allows creating a virtual operations line for design yield analysis, which allows effective design trade-offs, component selection, and supply chain control strategies.

2. Worst-case circuit analysis methods

Worst-case circuit analysis (WCCA) is a method to ensure the system will function correctly in the presence of allowed/specified variation. WCCA quantitatively assesses the performance that takes into consideration the effect of all realistic, potential variability due to component and IC variability, manufacturing processes, component degradation, etc. so as to ensure robust and reliable circuit designs. Modeling and simulation-based worst-case circuit analysis enables corners to be assessed efficiently, and allows design verification at a rigorous level by considering variations from different sources.

2.1 Sensitivity analysis

An initial approach for understanding the primary sources of variability usually starts with a sensitivity analysis study which is a method to determine the effects of input parameter variation on the output of a circuit by systematically changing one parameter at a time in the circuit model, while keeping the other parameters constant (Figure 1). Sensitivity is defined as follows:

$$\text{Sensitivity} = \Delta \text{ output} / \Delta \text{ parameter} \tag{1}$$

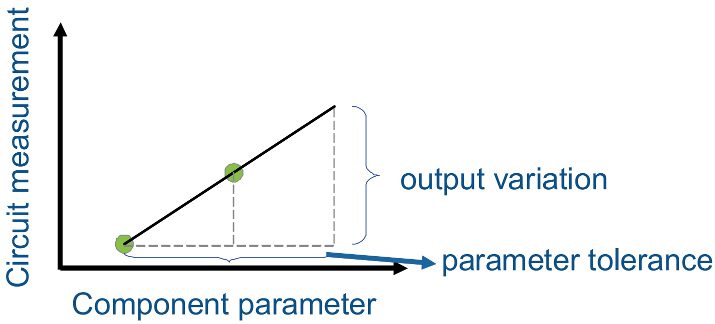


Fig. 1. Sensitivity analysis: circuit output changes due to variation of the input

If the output variation is reasonably linear with the variation of the component parameter across its entire tolerance range, sensitivity can be multiplied by the tolerance range of the component parameter to determine the output variation due to this tolerance. Two important attributes in the sensitivity analysis are the magnitude and polarity/direction. When the input increases, the polarity/direction is positive if the output increases, and is negative if the output decreases. Because of the huge potential number of simulation variables (e.g. m components with n parameters each), sensitivity analysis can be used to investigate one factor at a time (OFAT) to provide an initial triage of those parameters requiring subsequent evaluation. For typical designs, there are multiple outputs that need to be understood, so separate sensitivity analysis and subsequent treatment is usually employed, which is discussed in Section 3 and Section 4. The real-world is rarely as simple as textbook-like examples.

In each case, as one parameter is varied, all others are held at their nominal conditions. This approach assumes that all variables are independent and there are no interactions among them. While this technique is much less sophisticated than other formal methods, it provides an effective means of reducing the subsequent analysis and complexity, potentially by several orders of magnitude. Figure 2 shows one example of a sensitivity analysis result. A few top critical input factors that dominate output response are identified from sensitivity analysis with 74 parameters varied within the specified limits. A large number of other factors that are insignificant are eliminated from subsequent analysis by performing this important sensitivity analysis step. Subsequent simulations or physical testing can then focus limited resources on the factors with the greatest importance.

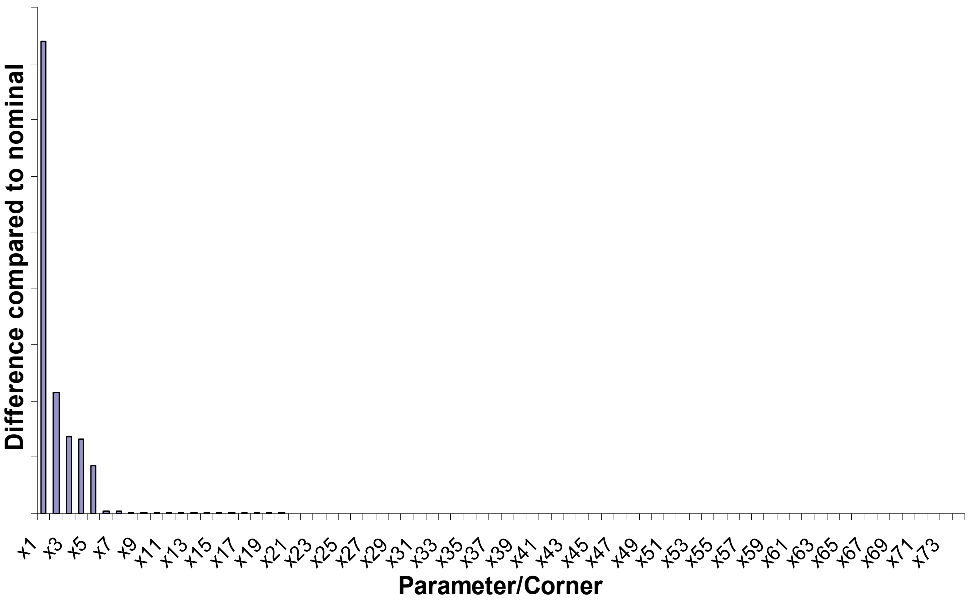


Fig. 2. Top five critical factors identified from sensitivity analysis

2.2 Extreme value analysis (EVA)

Extreme value analysis is a method to determine the actual worst case minimum or maximum circuit output by taking each component parameter to their appropriate extreme values. The EVA method decomposes the simulations into two steps for a circuit with n input variables.

First 2n sensitivity simulations are run, where each component parameter is simulated separately at its minimum and maximum (Figure 3). The results of the sensitivity simulations are analyzed, and the magnitude of change on the output due to each individual input variation can be ranked in a Pareto chart (Figure 2). Parameters that make the most influence can be identified as critical factors. Knowing critical parameters from sensitivity analysis provides information to narrow down the list of variables and provides information for component selection and control in case needed.

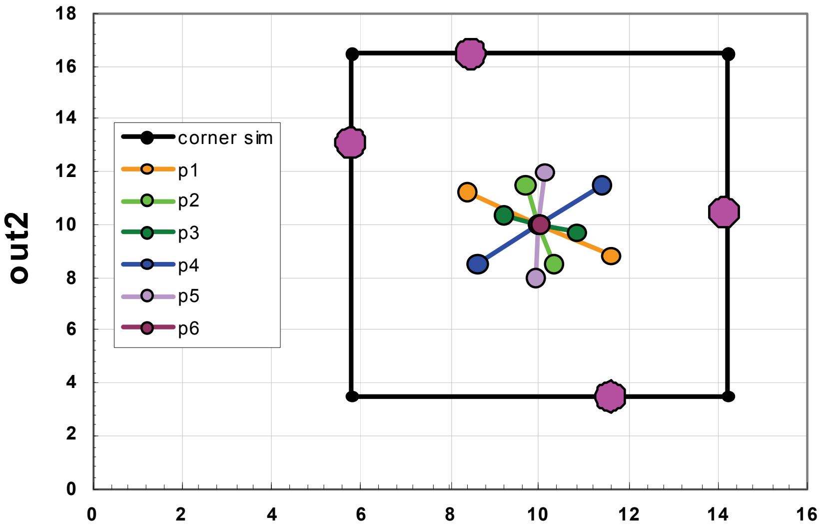


Fig. 3. Sensitivity analysis: output sensitivity to all inputs (2n 'quick' simulations)

Next, for each output measurement, two simulations are run that combine critical input parameters at either low spec limit and/or upper spec limits. Thus, this method requires only 2n+2 simulations so this method can be efficiently used on large number of outputs.
EVA is a commonly used worst case analysis method and the easiest one to apply (Reliability Analysis Center, 1993). It is also a more conservative method compared to root-sum-squared analysis or Monte Carlo analysis. One limitation of EVA is the assumption that critical factors are independent of one another, and the polarity determined from sensitivity doesn't change between the nominal and the worst case scenarios. EVA can be an effective and efficient way of performing worst case analysis. In other situations where interactions exist among input parameters or when the very conservative nature of EVA is too prohibitive for design, other methods such as design of experiments or circuit level Monte Carlo simulations can be used instead.

2.3 Root-sum-squared (RSS) analysis

As EVA targets the worst case corners which can be very conservative, Root-Sum-Squared analysis provides a statistically realistic estimation. Assuming an output Y can be approximated by n inputs x_1 to x_n.

$$Y = \sum_{i=1}^{N} a_i X_i \tag{2}$$

Variance of Y is

$$Var(Y) = \sum_{i=1}^{N} a_i^2 Var\left(X_i\right) + 2\sum_{i<j} a_i a_j Cov\left(X_i, X_j\right) \tag{3}$$

Assuming correlation between inputs are zero, the covariance of x_i and x_j is zero. The variance of Y is

$$Var(Y) = \sum_{i=1}^{N} a_i^2 Var\left(X_i\right) \tag{4}$$

When there are no interactions among input variables, a practical Root-Sum-Squared analysis method calculates the root-sum-square of the tolerances. Using RSS, the standard deviation of the output measurement is determined as follows (Reliability Analysis Center, 1993):

$$\sigma_Y = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial Y}{\partial x_i} \sigma_{Xi} \right)^2} \tag{5}$$

where σ_{Xi} is the standard deviation of the i[th] input parameter.
Assuming the output follows a normal distribution, the worst case performance limits of the output measurement can be approximated as mean ± $m\sigma_Y$ depending on the worst case criteria. Compared to EVA, RSS provides more realistic, less conservative worst case predictions. The limitation is that it is not a "true" worst case analysis. In addition, it assumes component parameters have normal distributions that are described by a mean and a standard deviation. Due to these limitations, RSS is not as widely applied compared to EVA, especially in critical reliability applications.

2.4 Monte Carlo simulations

The Monte Carlo method is an algorithm that utilizes random sampling of input parameters to compute a statistical output result. Monte Carlo simulations in this Section refer to circuit simulations with electronic design software programs. Circuit level Monte Carlo analysis takes into account process variation, mismatch, and/or other design and component variables. For each iteration, a circuit is constructed by selecting a set of component parameters using statistical distributions, and then the circuit is simulated and the results are captured. After the simulations are completed, the result is a statistical distribution of the output. The Monte Carlo method requires a statistical distribution for each actual part tolerance distributions in the circuit, which is used to create the component model. The parameter distributions are not limited to normal distributions and can be extended to any real data distribution that can be described mathematically. This is particularly effective if the output variation is NOT linear with the variation of the component parameter across its entire tolerance range. Thus, the Monte Carlo simulation method is the most accurate method to provide a realistic variability evaluation. However, the Monte Carlo approach requires running a large number of analysis iterations, which is computationally expensive, especially when simulating complex circuit functionality consistent of many integrated circuits and discrete components. Due to this reason, it is challenging to use Monte Carlo simulations to provide a "true" worst-case result, and it is more practical to use it to estimate mean and standard deviation of the output based upon a practical number of Monte Carlo samples.

When using Monte Carlo simulations to estimate yield for cases where the probably of failure is small, the number of needed iterations can be very large. To obtain a yield estimate with $(1-\varepsilon)100\%$ accuracy and with $(1-\delta)100\%$ confidence when the probability of failure is p, the required number of iterations is

$$N(\varepsilon,\delta) \approx \frac{\log\left(\delta^{-1}\right)}{p\varepsilon^{2}} \tag{6}$$

Thus, for 90% accuracy ($\varepsilon = 0.1$) and 90% confidence ($\delta = 0.1$), roughly 100/p samples are needed (Date et al., 2010; Dolecek et al., 2008). Other modified methods such as Importance Sampling, are developed for variance reduction and thus to accelerate convergence with reduced number of runs (Zhang & Styblinshi, 1995).

Nowadays many simulation platforms have built-in Monte Carlo algorithms and algorithms to facilitate variability analysis. Circuit level Monte Carlo simulations can be very time consuming. Due to the size and complexity of today's systems, it is more practical and efficient to partition the Electrical systems into smaller functional blocks/circuits and perform simulation based WCCA or yield predictions on the circuit block level, or to perform simulations at the system level with abstract block behavioral models to improve speed.

2.5 Monte Carlo analysis based on empirical modeling

Instead of running circuit level Monte Carlo simulations requiring a large number of runs and computational expense, Monte Carlo analysis based on a transfer function that mathematically describes the relationship between the input variables and the outputs can be used. This transfer function can be an analytical design model or an empirical model generated from design of experiments (Maass & McNair, 2010).

$$Y = f\left(x_1, x_2, \ldots, x_i\right) \tag{7}$$

Using design of experiments (DOE) methodologies, factorial experiments are conducted and influence of input variables on outputs are analyzed from a statistical point of view. Furthermore, response surface methodology (RSM) focuses on optimizing the output/response by analyzing influences of several important variables using a linear function or (first-order model) or a polynomial of higher degree (second-order model) if curvature exists (Montgomery, 2009).

One advantage of DOE and RSM is finding the worst case in situations where interactions exist among input variables, which sensitivity analysis and EVA may not take into account. In addition, Monte Carlo analysis based on transfer functions generated from DOE or RSM can greatly improve computation efficiency compared to Monte Carlo circuit simulations by replacing large number of random samples to a limited number of corner simulations. However, the accuracy of transfer functions is based on how well it represents real behavior. These methods work well if the assumptions are valid that a linear or quadratic function accurately describes the relationship between inputs and the output. Otherwise, circuit level Monte Carlo simulations for yield estimations are more accurate, though more computationally expensive. In addition, when the number of factors is large, the number of runs required for a full factorial design could be too large to be realistic. In such cases, fractional factorial design can be used with fewer design points. However, design knowledge is needed to make judgment and assumptions, as some or all of the main effects could be confounded with interactions (Montgomery, 2009). Low resolution designs with fractional factorial design are thus more useful for screening critical factors rather than to be used to generated an empirical model.

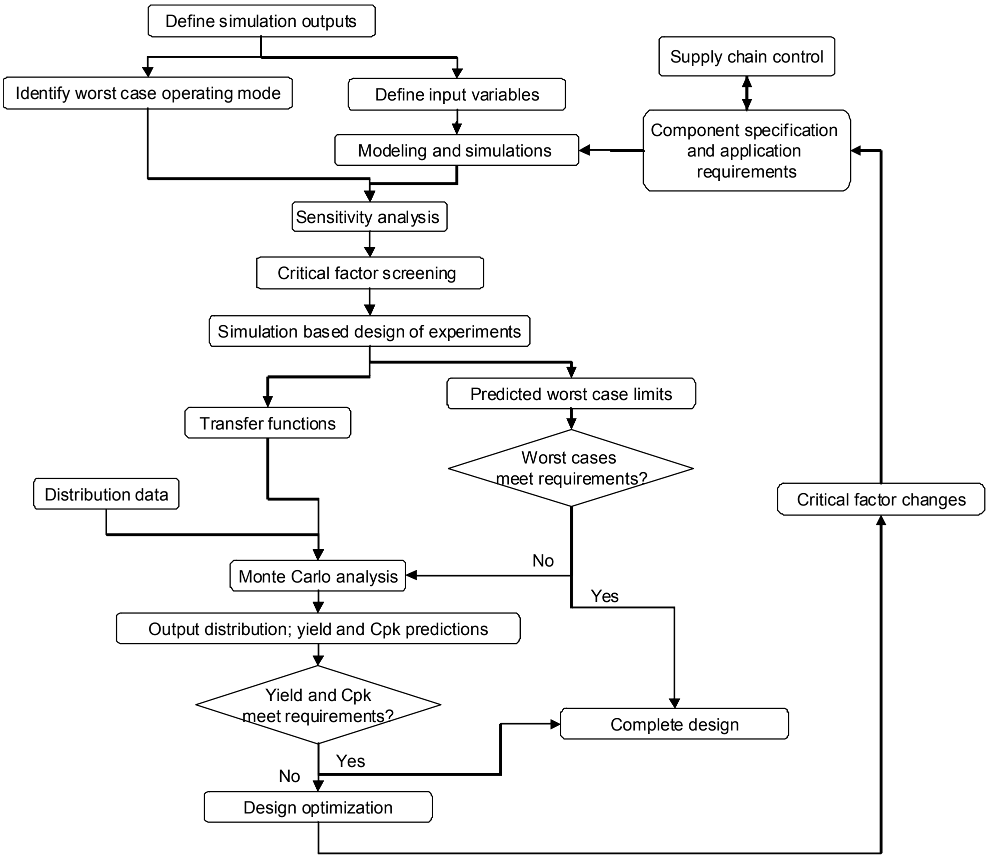


Fig. 4. Simulation-based worst-case circuit analysis and yield prediction flow

3. Simulation flow for WCCA and yield predictions

As different methods have different assumptions, advantages, and limitations, a simulation based WCCA and yield prediction method has been utilized. The simulation-based WCCA flow, shown in Figure 4, describes how the methods discussed in Section 2 are used in different scenarios to estimate the worst case limits and to develop the transfer functions needed to understand design, reliability, and yield in relation to how the product is used and how the effects of variability in the supply chain impact design success. This method provides a flow to effectively narrow down critical factors and a conservative estimation of worst case limits, while taking advantage of the best qualities of different methods for the optimal accuracy and computational efficiency.

The process begins with the following key elements:

- Identify output signals to monitor and potential input factors to analyze
- Generate and validate circuit models (component and IC models) that support worst case analysis
- Determine component tolerances and ranges
- Determine worst case operating modes

WCCA requires that the components in the circuit have specifications that include the minimum and maximum for important component parameters, which are integrated into the component models needed to support WCCA simulations. Using component or subsystem specification limits as tolerance limits could be conservative, as the specification limits can be wider than actual distributions. This is mainly to ensure requirement consistency at different hierarchy levels. Setting worst-case limits at or beyond the specification limits helps ensure conservative simulations that are most likely to capture the worst-case behavior of the system.

Simulations start with sensitivity analysis to determine the impact of each component parameter variance on each output signal. At this step, 2n simulations are performed for sensitivity analysis in a circuit with n component parameters for each output. This is more efficient to screen and to identify critical factors if there are a large number of component parameters in the circuit that are suspected to impact the design outputs.

From the sensitivity analysis, k critical factors are identified according to the impact on the output changes. One example of identified critical factors is shown in a Pareto chart in Figure 2. In this example, 74 parameters were varied within the specified limits in the sensitivity analysis and the first a few top critical factors that dominate are identified from this screening and will be used in subsequent treatments. Note that it is possible that a potential critical parameter might be left out if the impact shown is negligible, as the sensitivity analysis is only performed with one parameter varied and others are held at their nominal conditions. In such cases, design knowledge may need to be applied and design of experiments can be used instead to screen and determine if the suspected parameters have critical impact on outputs.

With the critical factors identified for each corresponding output, worst case limits can be determined using the component specifications and other additions due to aging or environmental (e.g. radiation) exposure. If the critical factors are independent of one another based on design knowledge, EVA can be applied to determine the worst case design performance limits for that output. Two simulations are run with EVA that combine critical input parameters at either low spec limit and/or upper spec limits. If interactions among input parameters are not negligible, simulation corners can be designed based on DOE and RSM to address interactions. With a full factorial design of two-level k critical factors, 2^k simulations are run based on the worst-case limits for each of the critical parameters. A transfer function is then generated that describes the relationship between the output and critical inputs in a linear or quadratic equation. Worst case limits can be determined based on the generated empirical methods and simulations can be used to confirm the results.

The derived transfer function can be further used for yield estimates via Monte Carlo analysis, which is illustrated in details in Section 4. If an accurate transfer function is not easily derived and simulation speed is permitted, circuit level Monte Carlo simulation is preferred to estimate output distribution and yield.

One major application of worst-case circuit analysis is to determine design trending through sensitivity analysis, and determine design capability limits and design margin. Figure 5 illustrates the results of worst case analysis and predicted distributions.

Besides design verification, another major application for WCCA is to determine component level worst case electrical use conditions, which can only be driven by simulations with WCCA. Understanding worst case use conditions is critical in reliability engineering to assess component reliability relative to capability data obtained from critical component reliability testing and modeling.

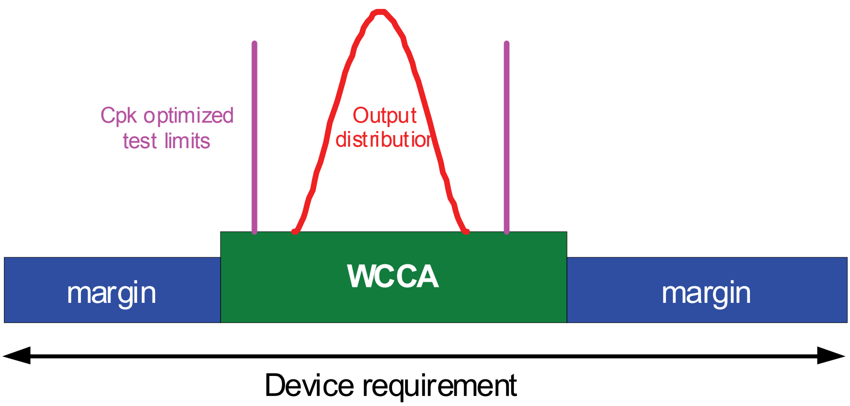


Fig. 5. Simulation and analysis outputs

Design for reliability approaches integrate reliability predictions into the hardware development process, thus improving design decisions and ensuring product reliability early in the life cycle. The objective is to capture quality / reliability issues earlier in the design cycle, and utilize quantitative reliability predictions based on simulated use conditions to drive design decisions. Use of simulations provides not only nominal use conditions, but also the variations in use conditions due to different operating modes and underlying component variability. Understanding use conditions related to design and variance is critical to create a virtual field use model for reliability predictions and to ensure design for reliability early in development. Based on the predictions, operating modes or component parameters that contribute to circuit overstress or premature wearout will be captured earlier to drive design and supply chain changes. On the other hand, some component parameters drift over time due to aging or exposure to certain environments (e.g. medical radiation), which may result in product failure at some point. Integrating these aging effects in simulations can help capture how the system functions when experiencing "faults." This fault condition analysis helps to understand design capability limits, to prevent/alleviate certain failure mechanisms, and to help put the right controls in supply chain.

The simulation based WCCA / variability method developed in this chapter can be very conservative. The probability that all component parameters shift simultaneously to the worst case limits is extremely small. In addition, using the specification limits as tolerance limits make the results even more conservative, as some of the component specifications may have much wider limits than what the components actually perform to.
However, the intent of using specification limits is to ensure that specification ranges at lower levels are consistent with higher level design requirements, and to highlight the potential risk and extracted critical component parameters if inconsistency exists. Using actual distribution data to start with will leave unanalyzed regions at risk if the distribution drift but still meet specification.
The fact that with a conservative WCCA method and data the circuit still meets requirements provides great confidence of the design quality. Otherwise, limits used in the component models can always be revisited, and more detailed analysis such as Monte Carlo analysis can be performed to get a better idea of the circuit behavior that includes variation.
In general, WCCA should be performed early in the project, during the design phase of a project as an integral part of hardware verification. When the analysis results indicate the circuit does not work in the worst case, there are several options:

- Change the circuit design
- Select different components
- Change requirement for a component
- Screen critical component parameters in manufacturing
- Perform a less conservative WCCA and estimate the distribution and Cpk

If opportunities are found that critical component parameters need to have a tighter range, controls should be put in place to get the new component level requirements implemented in supply chain.
WCCA originated in the days when design was based on standard components and circuit boards. Thus design consisted of selecting the correct components and connecting them together correctly. The components were small ICs, discrete semiconductors, and passive components. The purpose of worst case circuit analysis was to ensure that the design would work correctly in the presence of all allowed variation, as specified in vendor datasheets of the standard parts. If the design didn’t work at the worst case scenario, a different component will be selected or the circuit design will be changed. With more custom or semi-custom components nowadays, design optimization (in terms of design margin) is more emphasized as part of the design process.

4. Application of computationally efficient Monte Carlo techniques

Worst-case circuit analysis (WCCA) provides confidence that designs are robust against all potential design and manufacturing variability, due in major part to the variation inherent in all electronic components and assemblies. WCCA evaluates the design against various performance and reliability metrics in the presence of this variation. WCCA is capable of understanding the effect of parametric variation on design performance, establishing quantified metrics that identify and quantify the critical features necessary for design success (and margin), and demonstrating performance at the extreme limits of variation. By successfully analyzing a circuit using the WCCA methodologies, a high level of confidence can be demonstrated that circuits will perform as anticipated, even under these extreme conditions. To our knowledge, no experimental approach to design verification can make equivalent claims of design robustness relative to WCCA.

If a circuit is robust against these worst-case measures, it is safe to assume that high levels of design margin have been achieved. Yet, it is important to also understand more realistic levels of design margin, in order to further optimize designs that can trade-off design margin against other metrics such as performance or component cost. It is not always judicious to design for maximum design margin at the expense of these other metrics, after all, why pay extra for a ±1% resistor when a ±5% resistor will do just as well in a certain application. Rather, we would like to demonstrate a balance between design margin and other business and performance factors. Other analysis methods, such as Monte Carlo based simulation, can give more realistic estimates of real-world performance, yet it is hampered by two major tool limitations in a circuit simulation environment: 1) computational expense and 2) inflexibility in many simulation platforms in being able to accurately reflect real-world distributions using non-normal distribution functions.

In our improved methodology, called extended WCCA (EWCCA), we build the transfer functions based upon the WCCA methodology and apply more realistic distributions to the various input parameters using statistically based data analysis. This maintains the accuracy of circuit simulation while also providing the flexibility to evaluate various parametric distributions of critical inputs in a computationally efficient manner. The WCCA method provides the simulated design performance over a wide range of permitted (by specification) variability while the EWCCA method simply leverages those data to build transfer functions and utilize real-world distributions to make estimates of realistic performance. The results can be analyzed extremely rapidly using readily available software tools to virtually simulate the design performance of hundreds of thousands of units in a matter of seconds. This combination of accuracy and computational efficiency drives the real power in EWCCA towards predictive yield, real-world design margin, and reliability margin, while preserving the robust design analysis from the WCCA methodology.

4.1 Methodology

Extended worst-case circuit analysis (EWCCA) builds upon the WCCA simulation based approach where variability is simulated in order to predict performance and reliability margin as well as identify critical features for control. During the evaluation of a design under WCCA, all of the parameters are set at either a lower specification limit (LSL) or an upper specification limit (USL) and may also include variation due to aging or radiation exposure. By setting component (IC or discrete) specifications at their limits, a sensitivity of the relevant output parameters are observed via simulation. The parameters with the greatest influence on the outputs are quantified and captured as critical features. Once the top n critical features are identified, a simulation based design of experiments (DoE) is executed using the n critical features as experimental inputs while the simulation provides the virtual experimental output. Using a full 2^n factorial design based simulation set permits the development of a transfer function model between the inputs and the outputs as shown in Figure 6. Of course, design of experiments is capable of utilizing more efficient, smaller sample, data input combinations, such as central-composite or Box-Behken for example. Regardless of the design of experiments approach that is taken, the primary aim is to leverage the simulation capabilities to perform the experiment, rather than taking the time, expense, and energy to replicate the experiment using physical hardware.

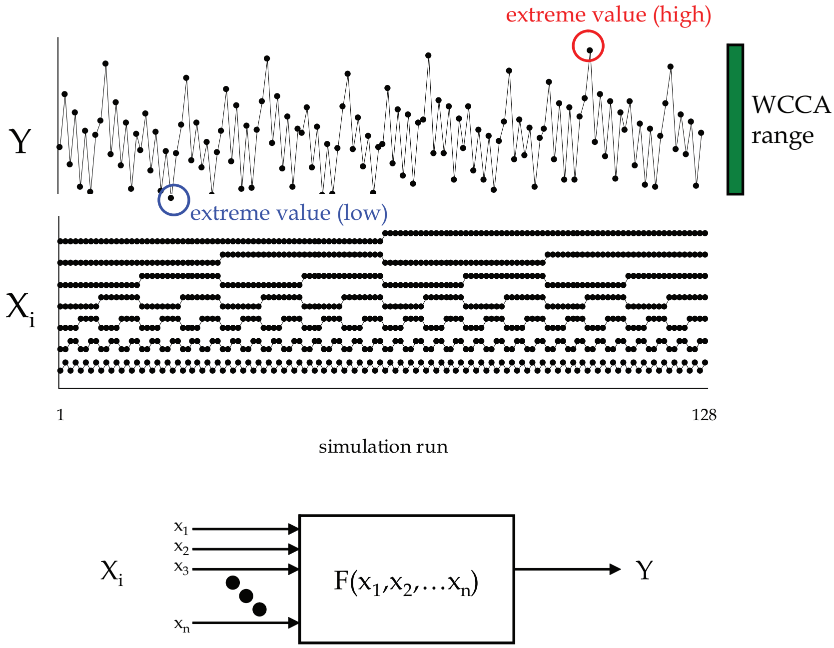


Fig. 6. Variation in inputs (Xi's) leading to observable output (Y). Relationship between Xi's and Y creates a transfer function F(x1,x2,…xn)

Using standard statistical analysis software, it is relatively straightforward to generate a linearized model that relates the observed outputs (*Y*'s) to the *n* critical design inputs (*X*'s). Since the simulated worst-case circuit analysis was built upon a 2^n factorial experiment, all of the pieces are available to develop a linearized model which can be used for rapid, and accurate, calculations suitable for predicting real-world circuit behavior. For each of the critical features identified during the WCCA, either the lower-specification limit (LSL) or the upper-specification limit (USL) was used in the 2^n factorial design. Here, for each input variable, the LSL is coded as a '-1' and the USL is coded as a '+1' during the model generation and analysis. Uncoded (actual) X_i values can also be used to generate models. In either situation, the end result should be the same, it's simply a matter of how one arrives at the end state.
A first-order model assumes that only the critical parameters identified in the WCCA sensitivity analysis have a significant effect on the outputs, while ignoring the potential interactions between terms. In general, a first order model takes the form:

$$Y = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + ...\alpha_n X_n + \varepsilon \quad (8)$$

where *Y* is the observed output given the various input parameters (X_i's). The Y can be a performance metric, such as charge time, to assess design rigor or it may be a component use condition, such as dissipated power, that will be used to estimate reliability of the component. The α_i terms are simply the model coefficients and ε is a term accounting for the

coefficient terms	model term	first order model	second order
offset	α_0	36.5971	36.5971
x_1	α_1	4.1113	4.1113
x_2	α_2	1.1109	1.1109
x_3	α_3	0.6841	0.6841
x_4	α_4	-0.8081	-0.8081
x_5	α_5	-0.0279	-0.0279
x_6	α_6	-0.0299	-0.0299
x_1* x_2	β_{12}		0.1257
x_1* x_3	β_{13}		0.0772
x_1* x_4	β_{14}		-0.0918
x_1* x_5	β_{15}		-0.0007
x_1* x_6	β_{16}		-0.0052
x_2* x_3	β_{23}		0.0211
x_2* x_4	β_{24}		0.0209
x_2* x_5	β_{25}		-0.0026
x_2* x_6	β_{26}		0.0003
x_3* x_4	β_{34}		-0.0141
x_3* x_5	β_{35}		-0.0008
x_3* x_6	β_{36}		-0.0002
x_4* x_5	β_{45}		-0.0018
x_4* x_6	β_{46}		0.0012
x_5* x_6	β_{56}		0.0004

Table 1. Design of experiments simulation analysis results showing transfer function of simulation output vs. model parameters and input variables (X_i)

residual error in the model. In general, for the WCCA results, a first order model provides a reasonably good prediction of the 'true' simulated outputs. It is relatively simple with software to create an improved version of the model that takes into account second-order effects, e.g. first-order interactions between all of the terms. While slightly more complex in form, it is a simple matter to generate such a second-order model and subsequently improve the predictive nature of the linearized model. The general form of a second-order model has the form:

$$Y = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + ...\alpha_n X_n + \beta_{12} X_1 X_2 + ...\beta_{1n} X_1 X_n + ...\beta_{ij} X_i X_j + ... + \varepsilon \quad (9)$$

where Y is again the observed output given the various input parameters (X_i's), the α_i terms reflect the first order model coefficients (which may be different than the α_i's generated using only the first order model, and the β_{ij} terms relate to interaction terms between the respective X_i's. By including the interaction terms, the model is better able to predict the 'true' response of the design. In Figure 7, a comparison of the predictive nature of both a first-order and a second-order model are shown relative to the 'true' simulated response of the predicted output of a hardware circuit block. While the first-order model demonstrates very good agreement, the second-order model improves the accuracy without making the model overly burdensome. The goal is to demonstrate that the 1st or 2nd-order models accurately reflect the more computationally expensive simulation output. In this example, the critical factors for this design output Y identified via WCCA are x_1, x_2, x_3, x_4, x_5, and x_6. Recall that parameters x_7-x_{96} were determined to have only minor impact on the predicted output (Y), and are thus treated as part of the error term (ε) in equation () above.

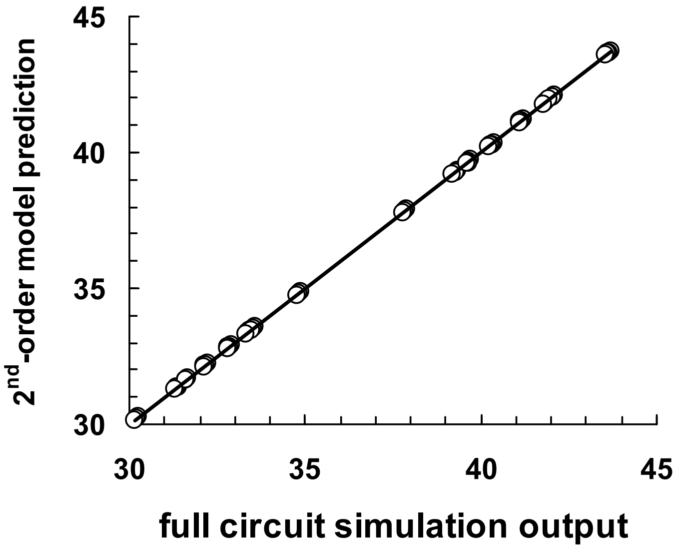


Fig. 7. Comparison of a 1st-order and a 2nd-order model predictive relative to the 'true' simulation output result. In this case, a WCCA result predicting high voltage FET power dissipation is illustrated. While the 1st-order model shows good predictive behavior, the addition of the 2nd-order terms greatly improves the predictability of the model

With a linearized model, it is now possible to leverage the computational efficiency of the approach and work to understand the predictive performance and yield of the design relative to real-world component variation. While the WCCA process was developed to guarantee performance at the limits of component specs many real-world distributions will not be at their worst-case limits, but will be represented more accurately by a statistical distribution. Many distributions are not accurately represented with the traditional normal distribution, but are rather more complicated.

4.2 Modeling distributions

There are many methods for modeling distribution functions in various statistical packages, and some very complicated distributions can be generated when the proper techniques are used. Not only can relatively standard normal, lognormal, and Weibull distribution functions be obtained, but models of bi- or multi-model distributions can be generated as well. Here, the algorithms necessary to select a random variable X from either a normal, lognormal, or Weibull distribution in Excel is shown in Table 2.

In order to create a data set corresponding to a particular distribution, the above functional models are repeatedly applied to create a data set. A flowchart for this method is shown in Figure 8.

distribution	functional model	notes
normal	= NORMINV(RAND(),μ,σ)	RAND() is the random number generator in Excel where (0<RAND()<1) and the expression NORMINV(probability,μ,σ) is a function that returns the inverse of the normal cumulative distribution function for the specified mean (μ) and standard deviation (σ)
lognormal	= EXP(NORMINV(RAND(),μ,σ)	
Weibull	= α*[(-LN(RAND()))]1/β	

Table 2. Models for different distribution types suitable for use in the Excel spreadsheet program

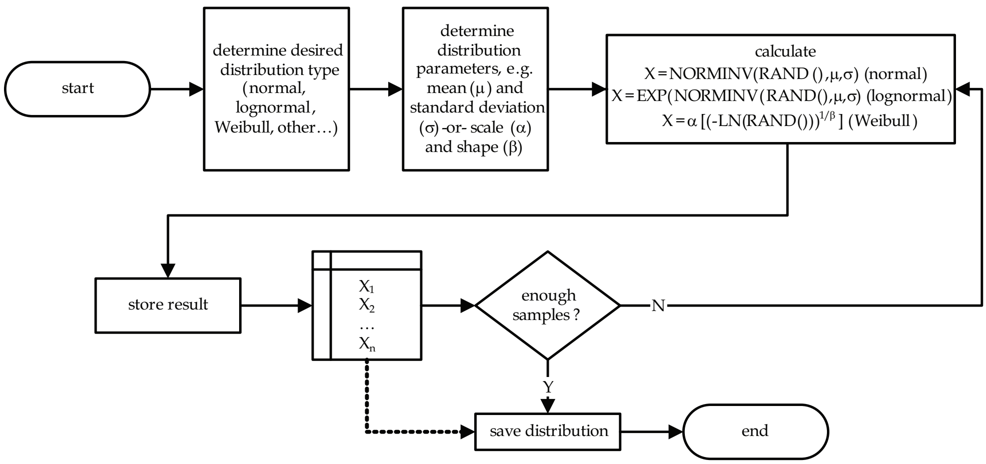


Fig. 8. Algorithm for calculating random variables reflective of a statistical distribution

4.3 Bi- and multi-modal distributions

It is relatively straightforward to create bi- and multi-modal distributions using these distribution functions and some additional random number manipulation. If one is dealing with a distribution that is bimodal, statistical properties for the two distributions can be separated and then combined again to form a random distribution of variables that, in turn, will recreate the statistical behavior of the original bimodal distribution during Monte Carlo modeling.

One example of a common bimodal distribution can be observed in many commercial off the shelf (COTS) components such as capacitors where tolerance levels are specified. Because a supplier can usually charge a little more for components with higher tolerances, it is not uncommon to order a batch of ±10% components and find that some of the ±5% components were removed from the distribution, and presumably sold as higher cost parts to another customer, as shown in Figure 9.

All of the ±10% capacitors meet the specifications, but there now becomes a more multi-modal distribution that should be understood. The different distributions can be separated in order to parameterize the data set. An analysis of the multi-lot distribution shows that approximating the component parameters received from the supplier can be reflected with three separate distributions.

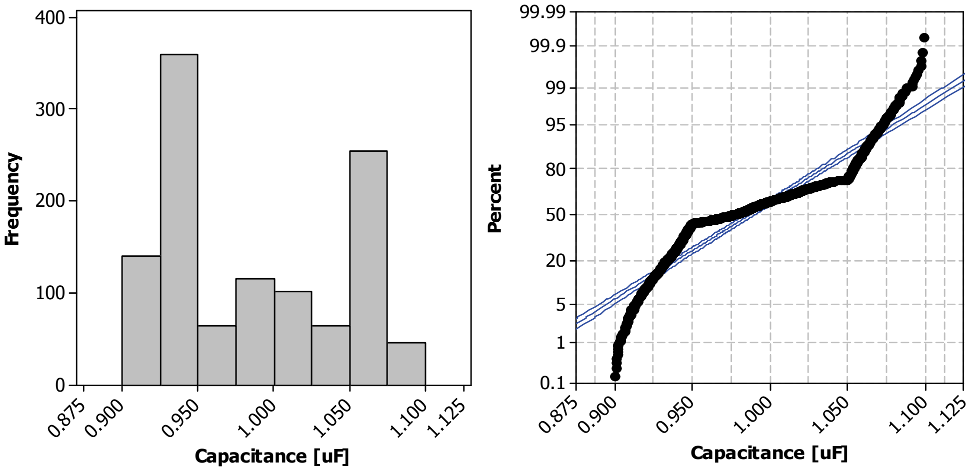


Fig. 9. Incoming data for +/-10% caps where some of the +/-5% caps were removed and used for other applications. The resulting distribution of capacitance values is multi-modal

The presence of bi- or multi-modal distributions should raise some level of speculation unless there is a clear underlying cause. These distributions imply that there is more than one type of behavior occurring in the overall population. These differences in behavior can be seen in the resulting distribution function, but they can also signify potential differences in failure modes, failure rates, and overall reliability of the component. With this disclaimer, it is very important to realize that multi-modal distributions are generally not desirable in a highly controlled, high reliability manufacturing environment, even if all parameters meet specification. Great care and a lot of work need to be performed to justify use of components with 'odd' behavior.

With that disclaimer, we will set out to replicate bi- (and by extension multi-) modal distributions for subsequent statistical Monte Carlo analysis. Decomposition of the full distribution shown in Figure 9 reveals the existence of about three separate distributions that can statistically describe the total distribution. The extracted distributions are:

At this juncture, perfect accuracy is not required. The intent is to be able to statistically model the distribution, not claim perfect equivalency. In order to create a model for this multi-modal distribution using our algorithms described above, we will make a data set of random variables of selected from each of the three populations. The process is outlined in Figure 10. Here, the three data sets (n=3) is assumed and each population is modeled per the parameters in Table 3. The repeated calling of the random variable φ will select a randomly generated parameter from sub-population 1 45% of the time, from sub-population 2 30% of the time, and sub-population 3 the remaining 25% of the time. As the number of samples increases, the subsequent modeled population provides a statistical representation of the real-world distribution function, even in the case of complex, multi-modal distributions.

distribution	type	mean	variance	fraction of total
sub-population 1	normal	0.933	0.01367	~0.45
sub-population 2	normal	1.003	0.02484	~0.30
sub-population 3	normal	1.064	0.0115	~0.25

Table 3. Distribution parameters for the multi-model distribution seen in Figure 9

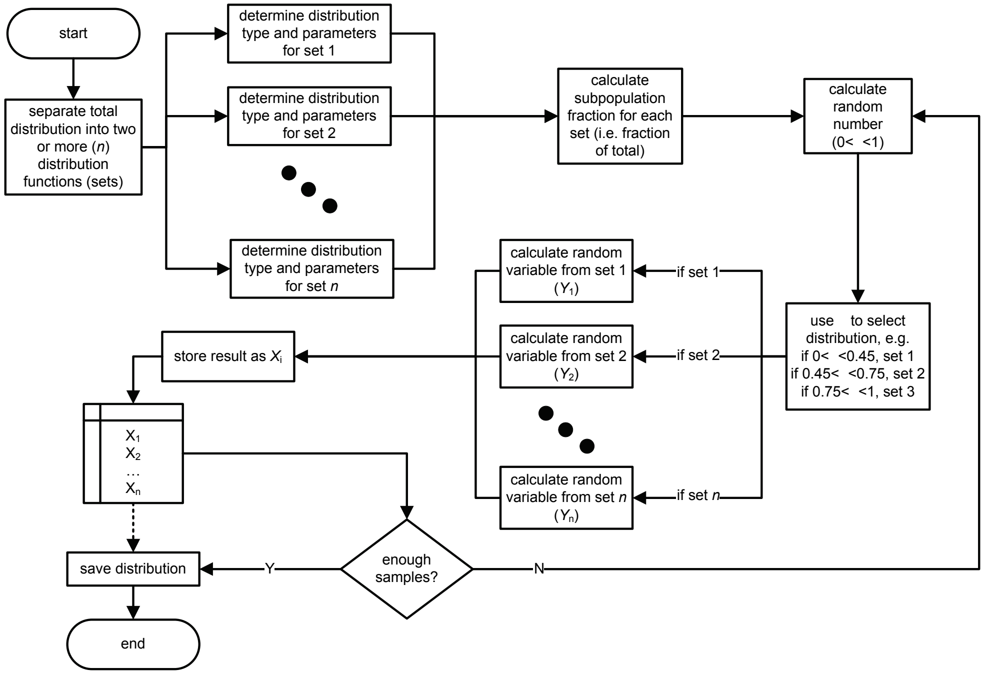


Fig. 10. Algorithm for handling bimodal (extendable to multi-modal) distributions

The final modeled results are shown in Figure 11. The agreement between the original data distribution and the modeled data set shows the ability of this mixing algorithm to accurately model more complex distributions.

4.4 Monte Carlo analysis

Now that we have some basic tools for modeling distributions, we can link the methods together to perform Monte Carlo analysis of our transfer functions, obtained from the linearized models built upon the 2^n factorial simulation results of the WCCA, and real-world parametric distributions from incoming component variability analysis. The basic flow is illustrated in Figure 12. The linearized models were built upon simulations where the critical features were investigated at their upper and lower specification limits (USL and LSL, respectively.). Depending upon the type of model generated, coded vs. uncoded models… In the linearized model, these reflect input variables codes with permissible

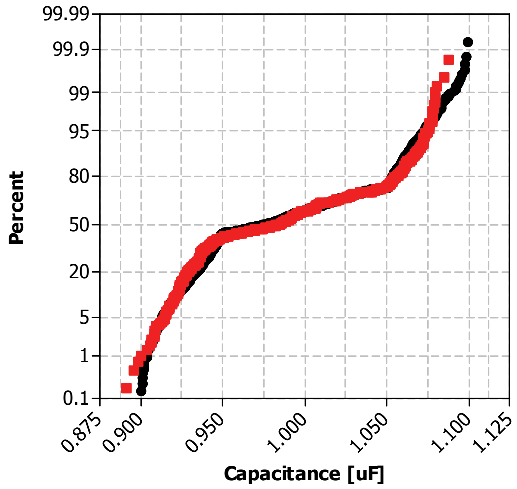


Fig. 11. Comparison of original data set and the bi-modal modeled distribution using two independent distributions and a mixing ratio

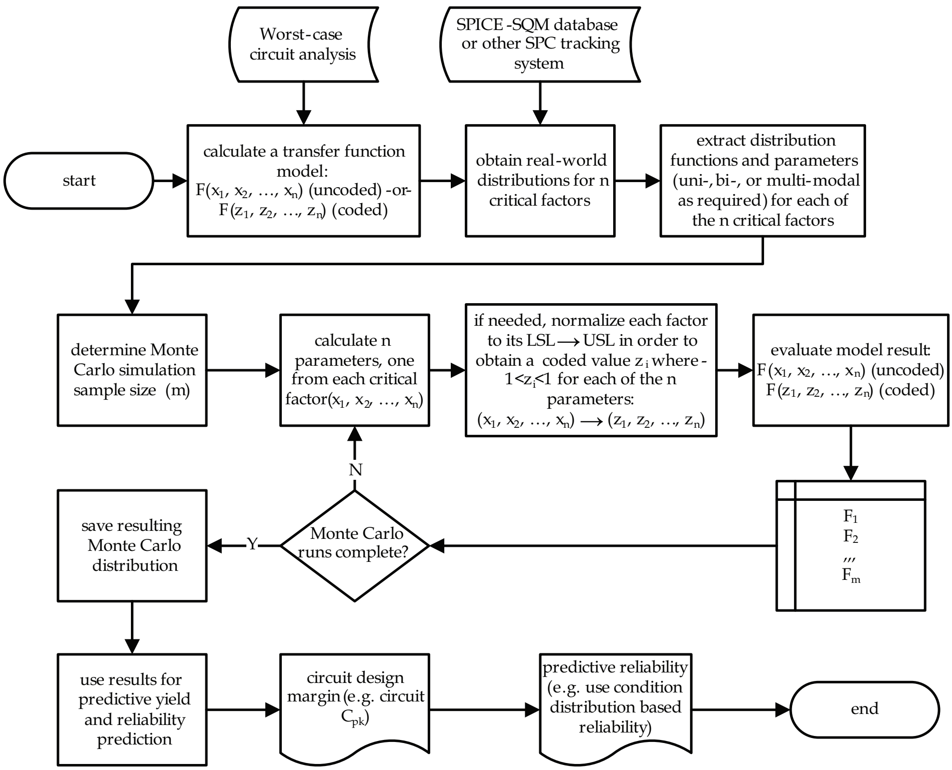


Fig. 12. Integrated extended worst-case circuit analysis flow

values ranging from (-1 at the LSL, 0 at nominal, and +1 at the USL). Any continuous value between -1 and +1 would reflect some point of the distribution that meets specification.
In this example, a predictive Monte Carlo run is repeatedly performed to estimate the effect of the randomly selected input variables (x_1-x_n) on the circuit output (Y). Additional studies could be taken to determine if six critical parameters was sufficient or if fewer parameters would still provide results with sufficient accuracy.
Based upon the WCCA, a linearized model using coded inputs based upon the 2^n simulation results was extracted as:

$$\begin{aligned} Y = 36.6 + 4.1x_1 + 1.1x_2 + 0.68x_3 - 0.81x_4 - 0.028x_5 - 0.03x_6 + 0.13x_1 \cdot x_2 \\ +0.077x_1 \cdot x_3 - 0.092x_1 \cdot x_4 - 0.0007x_1 \cdot x_5 - 0.005x_1 \cdot x_6 + 0.021x_2 \cdot x_3 \\ +0.021x_2 \cdot x_4 - 0.0026x_2 \cdot x_5 + 0.0003x_2 \cdot x_6 - 0.014x_3 \cdot x_4 - 0.0008x_3 \cdot x_5 \\ -0.0002x_3 \cdot x_6 - 0.0018x_4 \cdot x_5 + 0.0012x_4 \cdot x_6 + 0.0004x_5 \cdot x_6 \end{aligned} \quad (10)$$

The excellent fit between the linearized, second-order model and the more computationally expensive simulation results were shown in Figure 7.
For each of the critical component parameters, real distributions were obtained from in-house test or vendor supplied test data. A summary of the distributions is shown in Figure 13. The minimum and maximum values on each of the corresponding x-axes are the relevant LSL and USL for each of the distribution parameters.

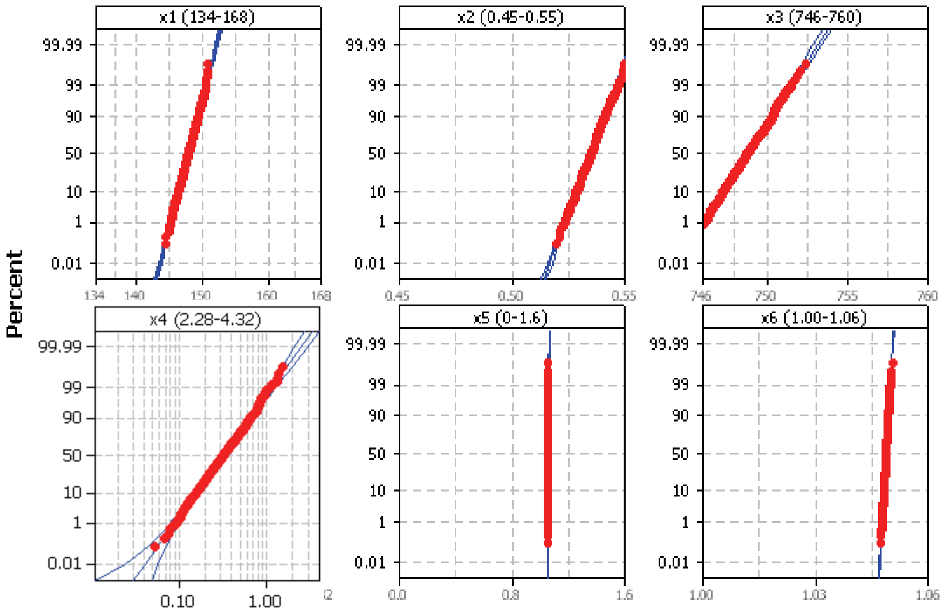


Fig. 13. Modeled distributions for the critical parameters determined from the worst-case circuit analysis. All distributions reflect realistic distributions seen via the supply chain procurement process. The limits of each graph show the specification limits for the component parameter. Some components have very high Cpk, while others go through extensive screening to maintain in-spec compliance

Using the distributions and the 2nd-order linearized model, a Monte Carlo run was performed using over 10,000 data points, essentially modeling the electrical performance of 10,000 circuits built in a high volume manufacturing facility. The results were summarized and statistically analyzed using Minitab software, and a summary of the results is shown in Figure 14. The real-world results, simulated from distributions in our Monte Carlo model, permit us to estimate the yield of this circuit to be an effective $C_{pk} = 5.2$ at the ±20% requirement level and 2.0 at a tighter ±10% level.

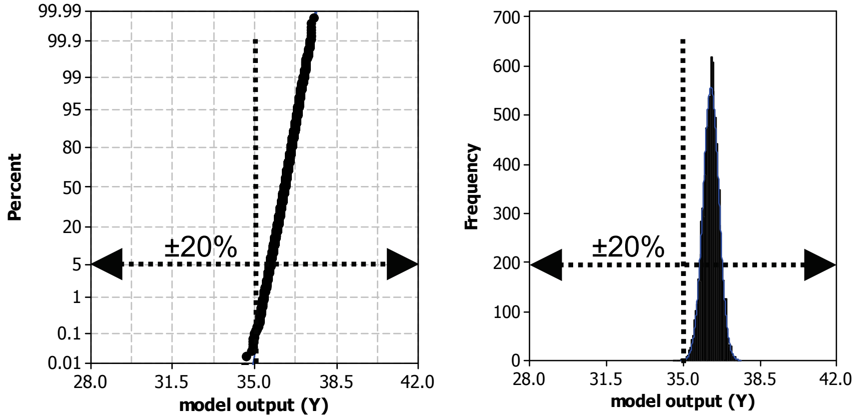


Fig. 14. Monte Carlo simulated output given the variability of the critical inputs. The target design point is Y=35, and the permitted variation is specified to be Y=35±20%. Worst-case circuit analysis indicates a maximum variation from 29.9 to 43.4. The real-world variation based upon the statistical model demonstrates a statistically well-behaved output with a representative Cpk=5.2. Both graphs contain the same simulation data

Given these predicted output distributions, it is possible to not only demonstrate the design margin, but also to predict the yield of the design and process. Once this estimate is available, it becomes possible to compare the simulation results to end-of-line test data in order to determine the initial accuracy of the simulations. If deviations or differences are observed to be significant, it is suggested that the difference is understood in order to either improve the simulation accuracy (maybe requiring more accurate discrete component or integrated circuit simulation models) or look for the impact of test hardware or test execution.

One of the main benefits of having a statistical estimation of the critical output distribution is being able to understand how variations in incoming components and materials impact the end of line performance. This can drive appropriate control plans and monitoring strategies around the most critical parameters first and then expanding the scope of the incoming material control plans as time and resources allow. In addition, a statistical estimation of end of line performance is also crucial for being able to proactively control the quality and reliability of manufactured products. The simulation-based statistical model as well as the on-going test data collected for the purposes of statistical process control will help identify tested units that violate the statistical expectations for performance, even if they meet the end of line specification. Essentially, this means that even though a unit meets specification, if it does not fit the expectations for performance based upon the statistical picture of the design and process, it should be suspected of potentially not meeting the same performance expectations over time compared to the statistically well-behaved units. This situation is illustrated in Figure 15, where a statistical distribution based upon both simulation (line) and end-of-line test data (symbols) are compared against a tested unit that meets specification but differs from the statistical model of the output distribution (the outlier near 31.5). An essential part of any control strategy, whether it is in incoming supply chain component and material procurement or end-of-line unit performance, should involve close scrutiny of statistical outliers in order to maintain the quality and reliability of products that the customers will see.

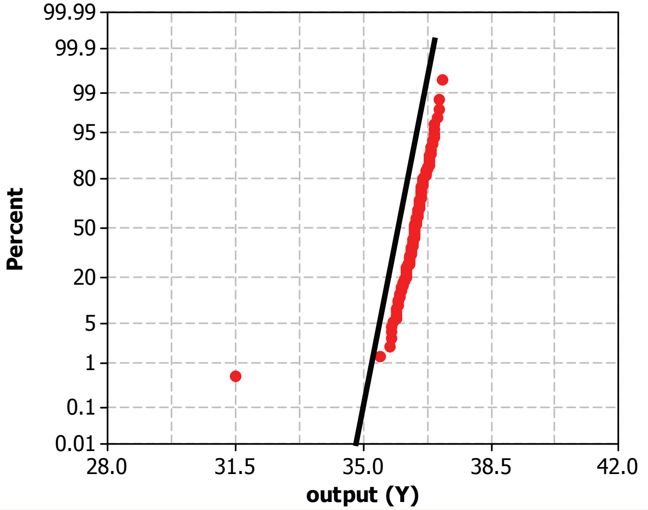


Fig. 15. Example of an in-spec, but out of control data point (at Y~31.5) compared to the simulated distribution prediction (line) and the cumulative end-of-line test data (symbols). This statistical anomaly should be treated as suspect unless convincing data proves otherwise

Figure 16 shows one example of simulated worst case limits and distributions versus the actual manufacturing test data distribution of 305 samples. In this case, one output parameter for an Implantable Cardioverter Defibrillator (ICD) was simulated with models built for each IC, discrete components, and the tester. Simulations were first conducted at a smaller block level to sweep more than 70 initial component parameters with specified variations at a faster speed, compared to simulating the entire ICD. From the sensitivity analysis results 5 critical parameters were identified. Full factorial design is conducted to address potential interactions among the critical component parameters. Thirty-two simulations were run at the device level with models of all hardware included. A transfer function was built to describe the relationship between output and the 5 identified critical input parameters. Monte Carlo analysis was performed to generate the distribution of the output based on the transfer function. This way the computation efficiency is much higher compared to running Monte Carlo simulations for the entire parameter set of 70+ components for this ICD output. It is demonstrated from Figure 16 that the simulated distribution matches well with the actual product manufacturing data. In this particular case, the simulated worst case limits are within the manufacturing test requirements, which indicate design margin. It also accurately showed that the distribution for this output is highly skewed toward the lower end of the requirement, which leaves less design margin at the lower limit side compared to the higher limit which is advantageous in this scenario.

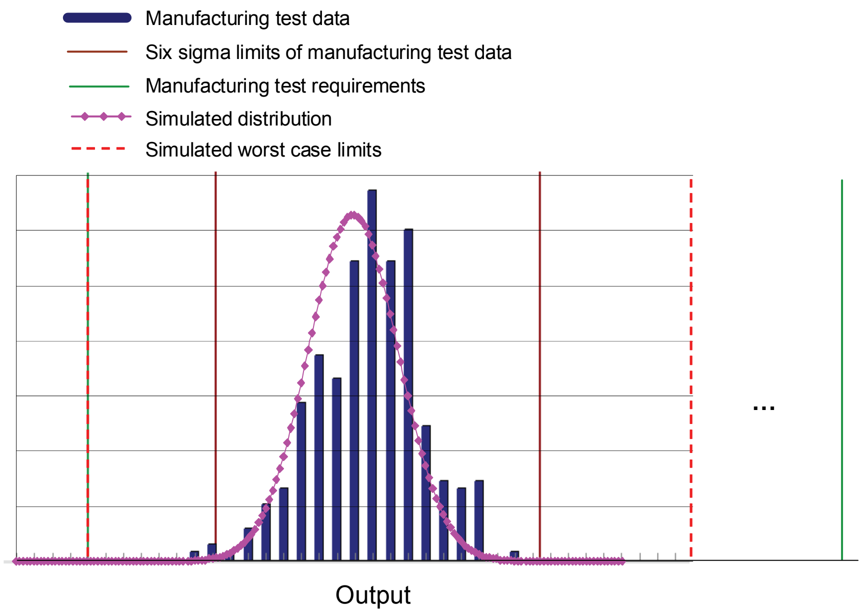


Fig. 16. A device output distributions from Monte Carlo analysis and manufacturing test. Simulated worst case limits are shown in red dashed line

While the generalized method of EWCCA was demonstrated here using electrical circuit simulation, any experimental or simulation based analysis method can be treated in this fashion to understand both the worst-case anticipated variation in a design: electrical, thermal, or mechanical, etc. as well as realistic variation which can be modeled accurately and computationally efficiently using the methods described in this paper.

5. Conclusion

Increased focus on product quality is requiring electrical designers to more effectively understand design margin. Fully understanding design margin provides designers the data to effectively make design trade-offs. These trade-offs may include rationale for component selection and manufacturing yield. This requires better understanding the influence of corners and better control of distribution tails. However, assessing the impact of corners or parameter shift is difficult to achieve in lab testing. Furthermore, using hardware testing to verify that system hardware works under all conditions in the presence of variation is very challenging, as the number of units tested cannot represent all the possible variations. This information can be provided proactively through worst-case circuit analysis to ensure the design works correctly in the presence of all specified variability.

This chapter provides an overview of different WCCA/variability analysis methods with the pros and cons for each method introduced. In addition, a simulation based flow for WCCA and yield predictions is developed to address different scenarios to allow extended analysis for yield estimation.

Worst-case circuit analysis is a demonstrated method that provides clear understanding of design margin. The extended worst-case circuit analysis builds upon these findings to create mathematically simple transfer functions which can be used to simulate a virtual high volume manufacturing line that reflects real-world variability of incoming components and processes. The application of the EWCCA technique provides predictive yield and permits the use of realistic performance outputs, component stresses (use conditions) for use in subsequent reliability analysis, and helps create opportunities to balance design margin against a variety of other factors, including reliability and economic considerations.

The benefits of simulation-based WCCA and yield predictions include rigorous identification of critical features to properly select components and define control strategies, understanding component use conditions, evaluation of design and manufacturing trade-offs, enabling predictive reliability, implementing design for reliability and manufacturability, and establishing meaningful component limits based upon design capability. In instances where inconsistencies exist between component tolerance and higher level design requirements, early, proactive solutions can be implemented in design, component selection, control requirements, or test requirements.

In summary, with the disciplined use of simulation-based variability analysis and enabled predictive reliability analysis, product development can further improve time-to-market and reduce reliability issues, including those resulting from supply chain sources. Limits of circuit / component use conditions, insight into design margin, predictions on reliability and yield, and recommendations on critical control parameters can be provided to design and supply chain to improve design performance and yield. Identified critical features in simulations from a design for reliability and manufacturability perspective are used to drive supply chain decisions to build robust designs in an efficient way.

6. Acknowledgement

The authors want to sincerely thank Don Hall for developing discrete component models, Eric Braun and Rob Mehregan for the support of simulation environment and circuit models, Joe Ballis, Bill Wold, Roger Hubing, Lonny Cabelka, Tim Ebeling, Jon Thissen, and Anthony Schrock for circuit design consultation, Tom Lane, Brant Gourley, Jim Avery, Mark Stockburger, James Borowick and Leonard Radtke for the advice and support on this study as part of the Electrical Design for Reliability and Manufacturability project.

7. References

Date, T.; Hagiwara, S.; Masu, K. & Sato, T. (March 2010). Robust Importance Sampling for Efficient SRAM Yield Analysis, *Proceedings of 2010 11th International Symposium on Quality Electronic Design (ISQED)*, pp. 15 – 21, ISBN 978-1-4244-6454-8, San Jose, California, USA, March 22-24, 2010

Dolecek, L.; Qazi, M.; Shah, D. & Chandrakasan, A. (November 2008). Breaking the Simulation Barrier : SRAM Evaluation through Norm Minimization, *Proceedings of*

IEEE/ACM International Conference on Computer-Aided Design, pp. 322-329, ISBN 78-1-4244-2819-9, San Jose, California, USA, November 10-13, 2008

Maass, E. & McNair, P. D. (2010). *Applying Design for Six Sigma to Software and Hardware Systems*, Pearson Education, Inc., ISBN 0-13-714430-X, Boston, Massachusetts, USA

Montgomery, D. C. (2009). *Design and Analysis of Experiments*, John Wiley and Sons, Inc., ISBN 978-0-470-12866-4, Hoboken, New Jersey, USA

Reliability Analysis Center, Sponsored by the Defense Technical Information Center (1993). *Worst Case Circuit Analysis Application Guidelines,* Rome, New York, USA

Zhang, J. C. & Styblinshi, M. A. (1995). *Yield and Variability Optimization of Integrated Circuits*, Kluwer Academic Publishers, ISBN 0-7923-9551-4, Norwell, Massachusetts, USA

4

Supply Chain Event Management System

Bearzotti Lorena[1], Fernandez Erica[2,3],
Guarnaschelli Armando[2,3], Salomone Enrique[2] and Chiotti Omar[2,3]
[1]Universidad Nacional Andrés Bello, Campus Los Castaños 7 Norte 1348 Viña del Mar,
[2]INGAR- CONICET, Avellaneda 3657 Santa Fe,
[3]CIDISI – UTN FRSF, Lavaise 610, Santa Fe,
[1]Chile
[2,3]Argentina

1. Introduction

The *Supply Chain Management* (SCM) can be defined as the set of proposals used to efficiently integrate suppliers, manufacturers and warehouses, such that the product is produced and distributed in the right quantity and at the right time, minimizing the total cost and satisfying the required service level (Simchi-Levi et al., 1999). To this aim, enterprises in a Supply Chain (SC) perform collaborative business processes (Soosay et al., 2008). Particularly, collaborative planning processes allow each enterprise to obtain production and/or distribution schedules synchronized with schedules of the other SC members (Derrouiche et al., 2008).

In this chapter, a *schedule* is defined as a set of orders, where each order represents a supply process (production or distribution) that assigns materials to a place, states the required resources, the time period during which each resource is required and its required capacity. The execution of a schedule implies performing the operations defined in the supply process each order represents.

As result of the uncertainty inherent in any supply process (Kleindorfer & Saad, 2005) disruptive events arise. The problems they cause during a schedule execution occur on a daily basis, and affect not only the organization where they are produced but also propagate throughout the SC (Lee et al., 1997; Radjou et al., 2002). That is, these disruptive events may affect the schedules and their synchronization.

In this chapter a *disruptive event* is defined as a significant change in the order specifications or planned values of resource availability. These changes could be: rush or delay in the start or end date of the order, changes in the amount specified by the order, change in the expected future availability of a resource, and change into the current level of a resource regards to its planned value. They can be produced by changes that can take place into the enterprise or outside the enterprise. For example, an equipment breakdown, breakage of materials, change of material specification, weather conditions, traffic congestion, etc.

The occurrence of disruptive events is a fact well known to the planning task, and therefore planning systems generate schedules including buffers (material, resource capacity and time) to be robust and flexible, thus the schedule can be adapted to conditions occurring during implementation (Van Landeghem & Vanmaele, 2002; Adhitya et al., 2007; Wang &

Lin, 2009; Bui et al., 2009; Liu & Min, 2008). The occurrence of disruptive events during the schedule execution requires an adequate response. If the effect cannot be mitigated, an exception occurs. In this work an *exception* is defined as a deviation from the schedule that prevents the fulfillment of one or more orders that requires re-planning.

Supply Chain Event Management (SCEM) is defined as an event-based business process whereby significant disruptive events are recognized in time, reactive actions are quickly triggered, the flow of information and material are adjusted and key employees are immediately notified. The goal of SCEM is to enable the SC to respond to disruptive events avoiding the need to re-plan the operations of the SC. To support this business process, a new generation of event-based information systems, known as SCEM Systems (Masing, 2003; Zimmermann, 2006), has been proposed. This proposal emphasizes the necessity of exception-based management of the SC, supporting short term logistic decisions, avoiding complex cycles of re-planning, aimed at reducing the gap between the planning system and the execution of the schedules generated by it.

In this chapter a proposal to systematically address the problem of disruptive event management in SC is described. Both academic and industrial researchers (Zimmermann, 2006, Radjou et al., 2002) have identified this problem as not being adequately covered by state of the art solutions in the SCEM systems. Moreover, the ability to automatically detect disruptions and repair them locally without affecting coordinated and coexistent schedules within a SC, is recognized to be a major competitive advantage in next generation of SCM systems.

2. SCEM system classification

From the view point of their automation levels, SCEM systems can be classified in the following types:

Monitoring system: Planned as an extension of traditional Tracking and Tracing Systems (Szirbik et al., 2000; Kärkkäinen et al., 2003) they allow the user monitoring planed events to detect disruptive events.

Alarm system: Can systematically detect deviations in the schedule and notify the key employee (Hoffmann et al., 1999; Speyerer & Zeller, 2004; Teuteberg & Schreber, 2005; Zimmermann, 2006).

Decision support system: Can detect deviation and find a solution that minimizes the disturbance impact on the SC. The solution will be proposed to the human decision-maker to make the final decision (Cauvin et al., 2009; Adhitya et al., 2007).

Autonomous corrective system: Able to detect a disruptive event, verify the feasibility of the current schedule or look for a solution to repair the schedule and implement it if one exists.

From the view point of their monitoring strategy, the SCEM systems can be classified in the following types:

Order focus: The monitoring task is centred on the orders. As disruptive event captures any significant change *i* to the specification of an order, ΔO_i. These include: rush or delay in the start or end date of the order, changes in the carrying amount of the order, cancellation of order, new order.

Order and Resource focus: The monitoring task is centred on the orders and resources associated with an order. As disruptive event captures any significant change in the planned value of the resource *j*, ΔR_j, which produces significant change *i* to the specification of an order, ΔO_i. To infer the change in the order specification, a change propagation function is used, which can be represented as in equation (1):

$$\Delta O_i = \mathrm{f}(\Delta R_j,\ \text{for all } j),\ \text{where} \quad (1)$$
$$\Delta R_j: \text{change of the resource } j$$

Order, Resource and environment focus: The monitoring task is centred on the orders, resources associated with them and environmental variables. As disruptive event captures any significant change *i* to the specification of an order, ΔO_i, any significant change *j* in the planned value of a resource, ΔR_j, and significant change regards to the expected in the environmental variable *h*, ΔE_h, which may produce significant changes to the specification of an order or a resource. To infer these changes, propagation functions are used, which can be defined as in equation (2):

$$\Delta O_i = \mathrm{f}(\Delta E_h,\ \text{for all } h),$$
$$\Delta R_j = \mathrm{f}(\Delta E_h,\ \text{for all } h), \quad (2)$$
$$\text{where: } \Delta E_h = \text{change of the environment variable h}$$

A propagation function can be defined as follow:
- *Based on data*: through relevant data fault propagation patterns are detected and inference rules to specify cause-effect relationships are defined based on them.
- *Based on the structure of the supply process*: a deterministic model is defined to capture and propagate disruptive events based on the structure of the supply process.
- *Based on the availability profile*: a deterministic model is defined to capture and propagate disruptive events based on the availability profile of a resource.
- *Based on the structure of the supply process and probabilistic data*: a probabilistic model is defined to capture and propagate disruptive events based on the structure of the supply process and statistical data updated periodically.

3. Proposed SCEM System

This chapter presents a SCEM system that from the view point of its automation level it can be classified as autonomous corrective system, and from the view point of its monitoring strategy can be classified as order, resource and environment focused.
Figure 1 graphically represents a model of main components of a system proposed for management a SC. The SCEM system is composed by the Control Subsystem, the Monitoring Subsystem, and the Feasibility Management Subsystem.
In this architecture, the SCEM system receives from the Planning System a *schedule* and notifies it if an *exception* has occurred; from the Execution System receives *execution data* and send it a *solution* (repaired schedule) if it is necessary to mitigate the effect of a disruptive event.
Following, the three main components of the SCEM system, Control Subsystem, Monitoring Subsystem, and Feasibility Management Subsystem are described.

3.1 Control subsystem

This subsystem, graphically represented in Figure 2, is responsible for providing the functionality to control a schedule. Each member (node) of a SC has a Control Subsystem responsible for requesting monitoring function (*Request schedule Monitoring)* to the Monitoring Subsystem providing the access to updated data from the Execution Systems. It also interacts with the Feasibility Management Subsystem requesting the feasibility verification and repairing (*Request Feasibility Schedule Check*) when a disruptive even is detected and engaging in collaborative repair (*Request Collaboration to other Control System*) when requested. It is responsible for send solution to the Execution System received from the Feasibility Management Subsystem and notifying exception to the Planning System for re-planning.

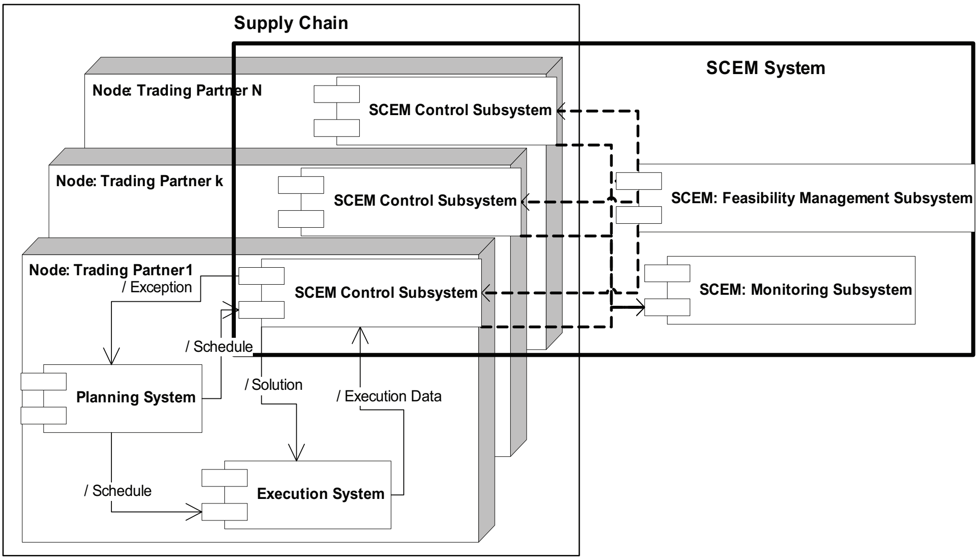


Fig. 1. Model of main components of a SC management system

3.2 Feasibility management subsystem

This Subsystem is responsible of providing functionalities for verifying the feasibility of a schedule when a disruptive event has occurred, and to repair a disrupted schedule requesting the collaboration of other Control Subsystems if it is necessary. To perform these functionalities appropriate decision making models, such as mathematical programming, heuristic programming, etc., are required.

The functional model of the Feasibility Management Subsystem is graphically represented in Figure 3. This Subsystem receives the disruptive event notification, sent by the Control Subsystem, and analyzes the impact of it on a schedule. If the feasibility is damaged, it searches for strategies to repair the schedule.

Sometimes, in order to restore feasibility in a damaged schedule it is necessary to propagate changes towards either customer or providers orders. These changes are feasible only if the customer's and provider's schedules are analyzed together with the damaged schedule, to ensure synchronicity and execution feasibility. That is, the solution to a schedule disruption, if found, must consider all schedule synchronization and should be executable and expressed in a common representation. To this aim, a request for collaboration is sent to the Control Subsystem. The solution to the schedule disruption only introduces changes within planned buffers.

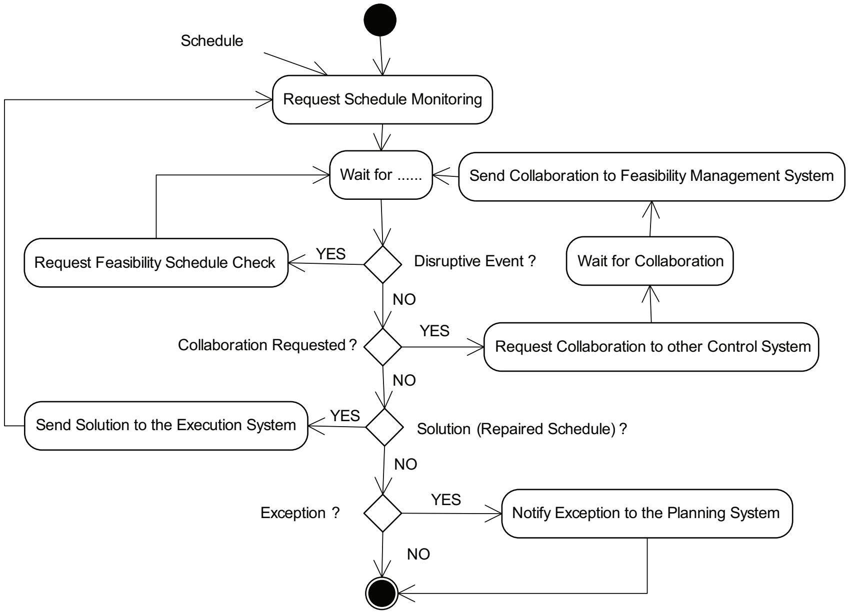


Fig. 2. Functional model of the control subsystem

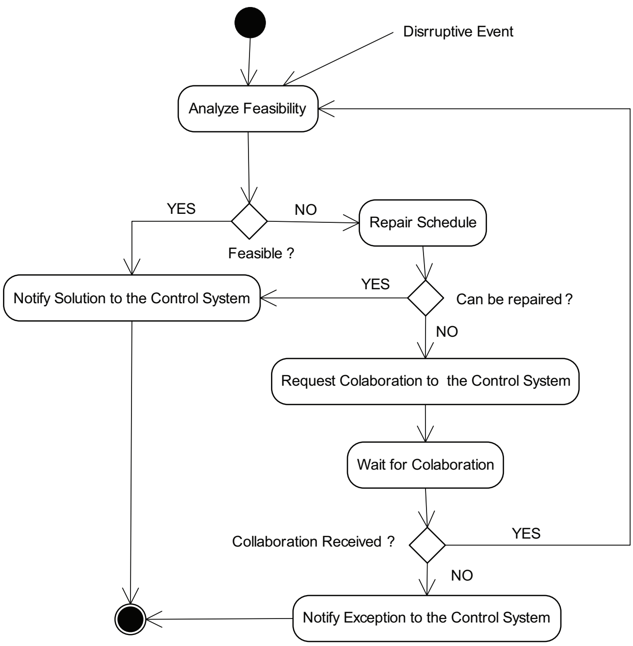


Fig. 3. Functional model of the feasibility manager subsystem

The Feasibility Management Subsystem performs these functions using a model based on a reference model for disruptive event management able to describe on going execution schedules of any kind, systematically capturing the planned buffers on critical resources and orders in a way suitable to perform feasibility analysis and repair processes. The reference model is described following.

3.2.1 Reference model for management of disruptive events

A reference model for management of disruptive event has been presented in (Guarnaschelli et al., 2010). It is relevant to emphasize that an instance of this reference model is a self-contained description of the feasibility of an execution schedule that can be automatically transformed into a Constraint Satisfaction Problem (CSP). This CSP, checks the feasibility of the execution schedule, and also gives the possibility of identifying slacks in order to device a repair mechanism with minimum modifications, as the one presented here. Following the two main modeling views of this reference model are described.

3.2.1.1 The supply process orders

Whenever a disruptive event occurs it is important to track its origin and delimit its propagation, to be able to attenuate its effects or even eliminating them. To do this any ongoing execution schedule, a *Schedule* and the possible sources and propagation paths of a disruptive event, is described as a net of *Resources* and *Supply Process Orders* linking them. This representation is proposed not only because it can show the origin and propagation of a disruptive event, but also allows monitoring and controlling disruptive events and possible exceptions at their origin, communicating disruptions (repair solutions) and exceptions to the proper receptor. The receptor is the Control Subsystem, which has control of the resources and involved supply process orders. Using this representation the disruption propagation and impact can be assessed as different SCs and different business partners in a single SC are represented as supply process orders and resources having different Control Subsystems.

Figure 4 presents an UML class diagram representation of a general supply process. Linked supply processes define a net of resources and supply process orders. In the class diagram, a supply process is defined, through a *SupplyProcessOrder*, which is composed by a set of *DimensionRequirements* imposed to every *FeasibilityDimension* of the resources assigned for the execution of the supply process order. When two supply process orders belong to different business partners, or even to different SCs their relation is captured by the association class *RelatedSPO*, which implies relationships between the two supply process orders, such as same *orderQuantity*, same timing, etc.

Some supply process orders, can be cancelled in favor of the feasibility of execution of other supply process orders, and there can be special supply process orders called spare, that are only executed in case of emergency, for example an supply process order using a 3PL (third party logistics provider).

In a typical SC, a disruptive event can cause different kind of losses, amongst them service level diminishment of the node causing the exception and in general for the whole SC. But it might not affect the totality of the ongoing execution schedule of the related nodes, but instead a set O of *Supply Process Orders* (SPO). Every $SPO \in O$ is related to a set of resources required for its fulfillment (*assignedResources* set) belonging to any of the affected nodes. Whatever the disruptive event, if the information required is on hand, it is possible to trace its origin to the unavailability of one of the related resources or to a change in one supply process order.

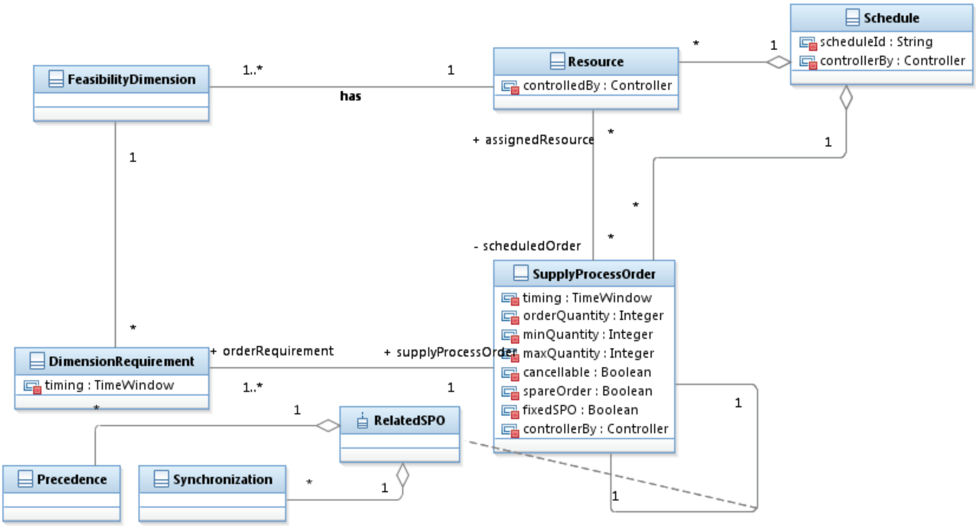


Fig. 4. UML class diagram of a general supply process order

3.2.1.2 The resources

In order to assess the availability of a resource, the feasibility of its schedule and to evaluate the effects of disruptive events, it is necessary to describe the resources. A possible attempt is to classify resources by types as in (Hoffmann et al., 1999), but this has the drawback that resources in a SC can be quite diverse, a more generic and extensible characterization is needed.

As the purpose is to model the availability of resources and the feasibility of its scheduled supply process orders, the characterization of resources by introducing the concept of feasibility dimensions is proposed (Figure 5).

A *FeasibilityDimension* is a characteristic of a resource describing its capability to fulfill a requirement from a supply process order. The availability of the resource is therefore conditioned by them and every requirement for the resource should be expressible in terms of its feasibility dimensions.

Two types of feasibility dimensions are defined, *CapacitatedDimension* and *StateBased Dimension*. Each one of them has an *AvailabilityProfile* that describes its intrinsic and planned availability in a given *Horizon*.

Every *SupplyProcessOrder* has a set of requirements over the resources assigned for its fulfillment. These requirements should be expressed according to the availability of each resource, which is expressed in feasibility dimensions. The concept of *DimensionRequirement* to define all the possible uses of resources is introduced, in correspondence with each type of feasibility dimension. Therefore there are two types of requirements *StateBased Requirement* and *CapacityRequirement*.

3.3 Monitoring subsystem

This Subsystem is responsible of providing functionalities for monitoring a schedule. The execution of a schedule implies performing the operations defined in the supply process

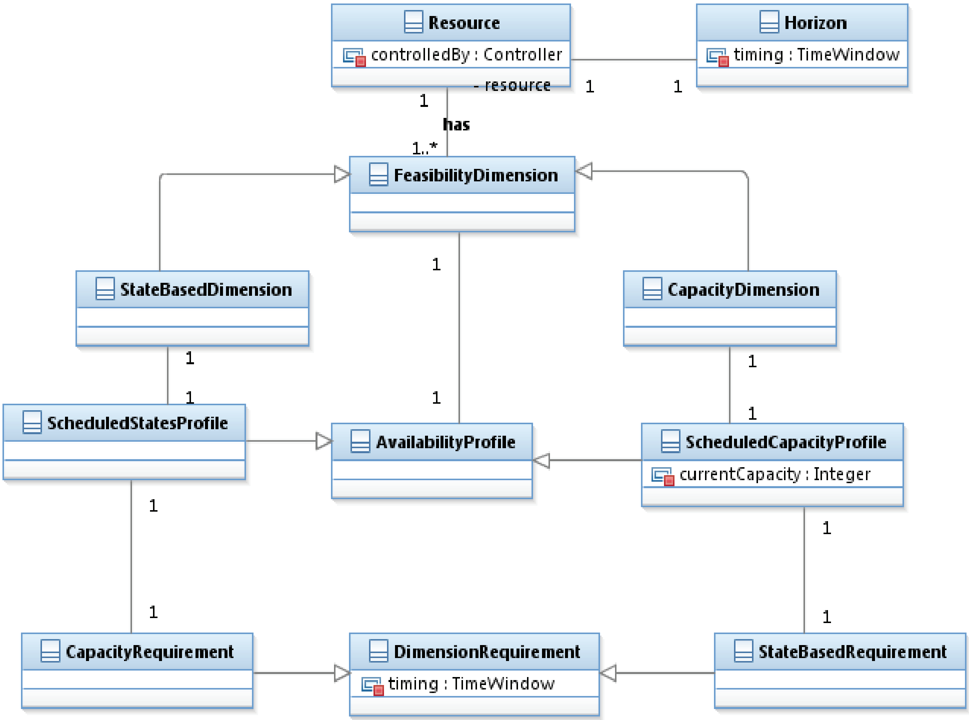


Fig. 5. Feasibility dimension of a resource

each order represents and is feasible if both the order requirements and the availability of the resources take their planned values. The monitoring function implies detecting relevant disruptive events in real time (Knickle & Kemmeler, 2002). To perform this functionality four main monitoring activities have to be carried out during the execution of a schedule, which are described following.

Monitoring changes on expected future availability of a resource: The objective is to capture significant changes of the planed value of the future availability of a resource.

Monitoring order progress: The objective is to monitor on going execution orders to proactively predict if a disruptive event affects the order expected completion. This implies to capture significant changes on any variable measuring the order progress or having a predictive relationship with this progress. Typically, they are variables in the execution environment that are used as predictors of potential disruptions.

Monitoring current status of resource feasibility: The objective is to capture significant changes on the current value of any attribute of a resource that is critical to grant its feasibility.

Monitoring current status of resource feasibility: The objective is to capture significant changes on the current value of any attribute of a resource that is critical to grant its feasibility.

Monitoring order specification changes: The objective is to capture independent changes of the order specification values, i.e., start time, quantity or end time. By independent, we mean original modifications to the order specification, not as derived consequence of adjusting the order in response to other disruptive events.

The functional model of the Monitoring Subsystem is graphically represented in Figure 6. The Monitoring Subsystem has the ability of systematically generating the structure for capturing changes that can take place into the enterprise or outside the enterprise and may affect a supply process order or a resource. Using a cause-effect model propagates these changes to infer advancement or delay in the start or end date of the order, changes in the amount specified by the order, change into the availability of a resource, or change into the current level of a resource regards to its planned value, and analyzes if these changes can produce a disruptive event. The cause-effect model is developed based on the supply process structure and statistical data, and can be modeled using Bayesian Network, Petri Net, decision tree, etc. In this way, the Monitoring Subsystem can proactively notify the Control Subsystem a disruptive event affecting an order or a resource has occurred.

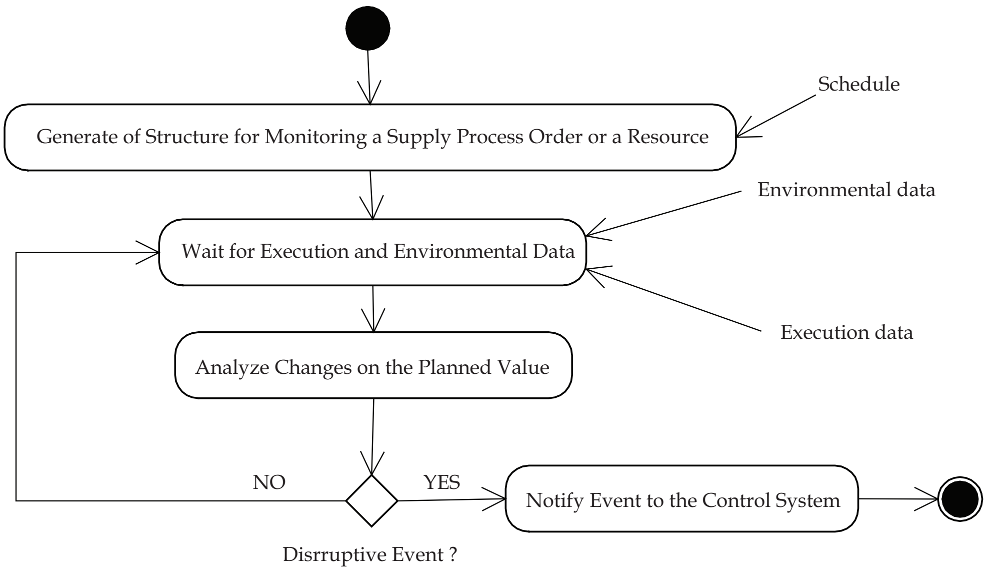


Fig. 6. Functional model of the monitoring subsystem

3.3.1 Reference model for monitoring orders and resources

A reference model for monitoring orders has been presented in (Fernández et al., 2010). In this chapter the reference model is extended for monitoring orders and resources. An instance of this reference model is a self-contained description of the monitoring structure of an order or a resource, which can be automatically transformed into a particular cause-effect model. The UML class diagram in Figure 7 presents the monitoring reference model which has a monitoring network structure based on a *cause_effect* relationship among *Variables*. These variables represent *AttributeVariable* (resource or order specifications) or *Environment Variable* affecting a resource or a supply process order specification.

The monitoring structure has a set of milestones. Each *Milestone* defines a point where a set of variables will be observed. Each *Variable* of the monitoring structure has one *State* that can be: *ObservedState* or *EstimatedState*. When the state is *ObservedState*, the *Variable* is observed and its value is given. When the state is *EstimatedState*, the *Variable* value is estimated from the value of other variables using the *cause_effect* relationship network. To perform this task, the *MonitoringStructure is_analysed_by* a *MonitoringStructureAnalyzer*. A variable has an observation policy. An *ObservationPolicy* defines the mode, the recurrence and the updating time of the observed variable.

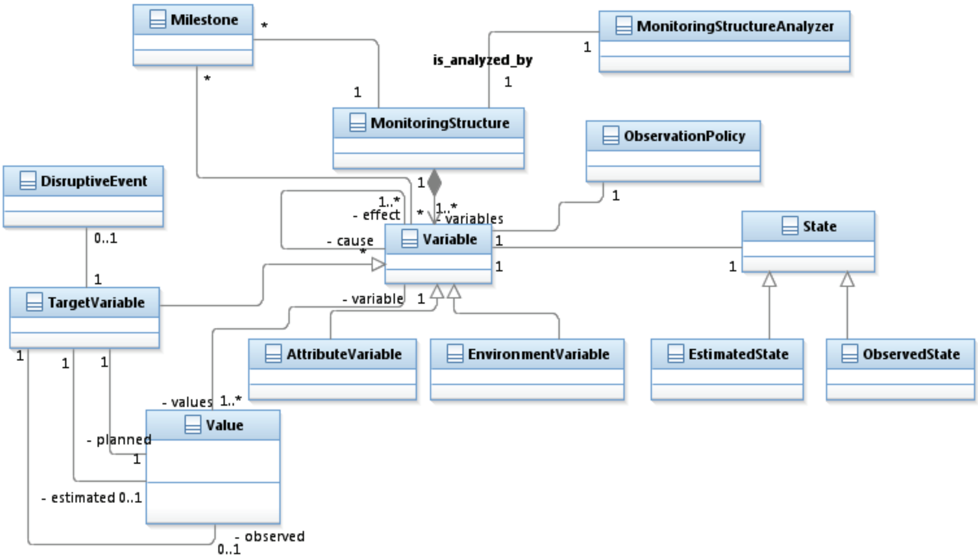


Fig. 7. Reference model for monitoring orders and resources

The *TargetVariable* has a planned *Value* that is an order specification (for example, amount, end time, etc.) or a resource parameter (for example, geographical positions planned, production rate planned of the machine, etc.). Also, the target variable must have an estimated *Value* which is defined by a *MonitoringStructureAnalyzer* or an observed *Value* which is a given value of a variable in the monitoring structure.

The *TargetVariable* is used to evaluate if a disruptive event can occur. This is done by evaluating conditions between the estimated/observed value and the planned one. When the disruption condition is verified, a *DisruptiveEvent* is reported.

3.3.1.1 Monitoring changes on expected future availability of a resource

Figure 8 presents the UML class diagram associated with this activity. Every resource has a scheduling horizon during which it will be monitored. Each *AvailabilityProfile has_assigned* a *MonitoringStructure.*

The *ScheduledCapacityProfile* is defined by an ordered set of *AvailableCapacityItem*. Each *AvailableCapacityItem* has two *TimeMilestone* (*itemStartTime* and *scheduleStart* attributes) that define a time period where the capacity bounds will be observed to evaluate modifications of its planned values.

The monitoring structure has a set of *TargetVariable*. This is, for each *AvailableCapacityItem* there are two target variables (one for each capacity bound).

The Monitor is responsible for observing the capacity bounds at each milestone associated with a *AvailableCapacityItem*. It gets the observed value of each capacity bound and inserts them to the *MonitoringStructure*. Each target variable (*minTargetVariable* and *maxTargetVariable*) has a planned *Value* that is the planned maximum or minimum capacity bound. The Monitor uses each target variable and comparing its planned and observed values to evaluate a possible *DisruptiveEvent*.

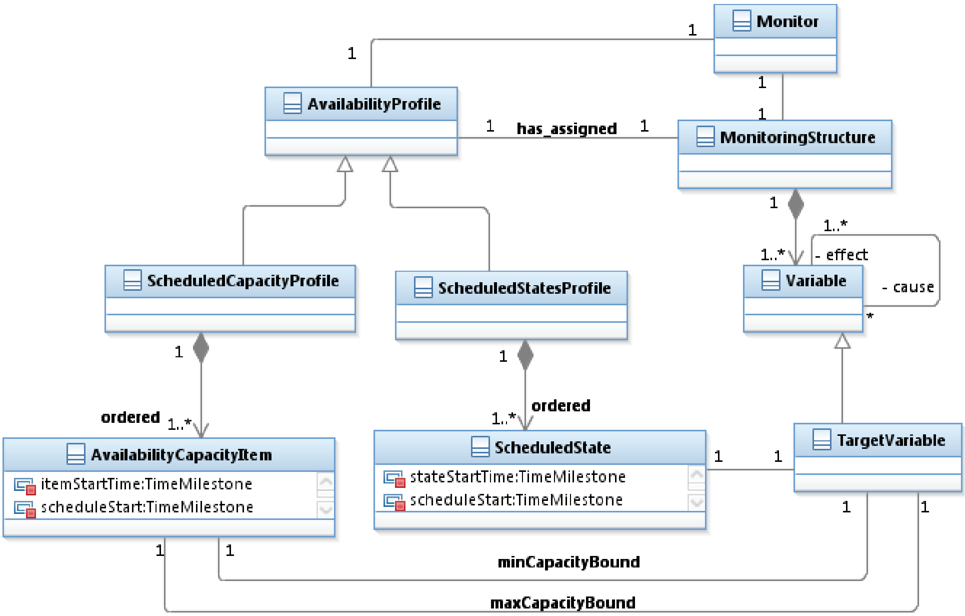


Fig. 8. UML class diagram for the Monitoring future availability of a resource

The *ScheduledStatesProfile* is defined by an ordered set of states, *ScheduledState*. Each *ScheduledState* has two *TimeMilestone* (*stateStartTime* and *scheduleStart* attributes).
The monitoring structure associated with *ScheduledStateProfile* has a target variable for each *ScheduledState*. The Monitor is responsible for observing the specified state at each milestone. It gets the observed value of each *ScheduledState* and inserts it to the *MonitoringStructure*. The target variable has a planned *Value* that is a parameter of the state. It uses the target variable and comparing its planned and observed values to evaluate a possible *DisruptiveEvent*.
For both dimensions, once the schedule start milestone is activated, the monitor will capture any change in the planned availability values and when the change is assessed as significant, according to a threshold, the disruptive event is concluded.

3.3.1.2 Monitoring order progress

Figure 9 presents the UML class diagram associated with this activity. The monitoring structure associated with this activity in general will depend on the type of process since complex cause-effect relationship among variables may be introduced to improve the predictive capabilities of a disruptive event.
Each *SupplyProcessOrder* that is part of a schedule has a *SupplyProcess*. Each *SupplyProcess* *has_a_set_of* milestones defining its *MonitoringStructure*. A *Milestone* can be a *TimeMilestone* (absolute time or related to another milestone) or a *StateMilestone* (state to be reached by the

supply process). Each *Milestone* has a set of *Variables* associated that allows representing *Environment* variables affecting the supply process or resources *Attributes*.

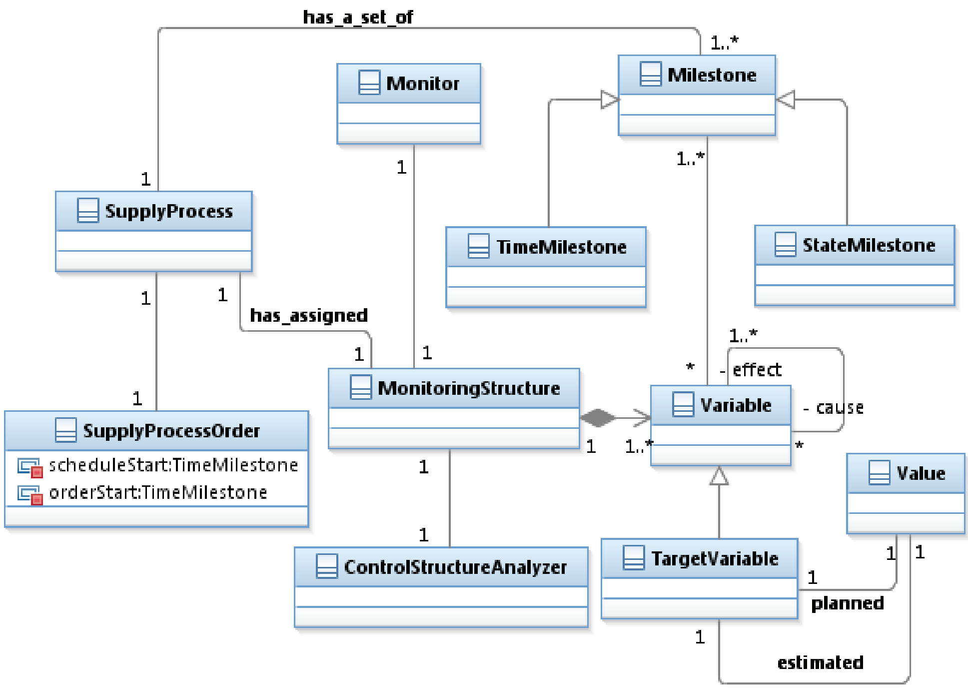


Fig. 9. UML class diagram of the *Monitoring order progress*

Each *SupplyProcess has_assigned* a *MonitoringStructure* based on a *cause_effect* relationship among *Variables* associated with all milestones, which allows predicting if a disruptive event at the last milestone can occur.

Each *Variable* associated with a *Milestone* has one *State* that can be: *ObservedState* or *EstimatedState*. The state of a variable can be changed on the same milestone. After the value of a variable whose state was estimated is known (evidence), the variable changes to observed state. The branch of the monitoring structure (cause_effect relationship sub-net) that predicted its value is no longer necessary and can be eliminated.

The *Monitor* is responsible for observing the variables at each *Milestone*. It starts with the initial milestone, gets the value of each observed *Variable* and inserts them to the *MonitoringStructure*. The *MonitoringStructureAnalyzer* using the *MonitoringStructure* (cause_effect relations net) evaluates the impact of these variable values on current and next milestones until the last milestone. Particularly, it defines an estimated *Value* for the *TargetVariable*. The *TargetVariable* has a planned Value that is an order parameter (for example, amount planned, end time planned, etc.). Following, to predict if a disruptive event can occur, the *Monitor* uses the *TargetVariable* comparing its planned and estimated values. Based on a decision criterion, it predicts if a disruptive event can occur, if so, it reports the *DisruptiveEvent* and the monitoring process ends; if not, the monitoring process follows. To this aim, the *Monitor* defines the next *Milestone* where the variables have to be

observed. The monitoring structure is initially defined for each supply process, but it is dynamically explored each time a milestone is reached. That is, the *Monitor*, depending on the results generated by the *MonitoringStructureAnalyzer*, can extend its monitoring strategy to another milestone including other observed variables, eliminating those that are not necessary or exploring different branches of the control structure.
Unless a specific structure is designed for the process, a default structure is generated having two milestones: supply process order start and supply process order end, two target variables: corresponding to the order end time planned and order amount planned, and one observed variable indicating a measure of the order progress. This measure is used to infer estimated values for the target variables and anticipate a disruptive event.

3.3.1.3 Monitoring current status of resource feasibility

Figure 10 presents the UML class diagram associated with this activity. The monitoring structure associated with this activity defines a target variable for each feasibility dimension associated with a resource. For each *AvailableCapacityItem* and *ScheduledState* there is a target variable which has a planned value that represents an expected value of the corresponding feasibility dimension of the resource. The planned value is calculated through the projected profile for each feasibility dimension. This is, for each supply process order there is a set of requirements over the resources assigned for its fulfillment. These requirements are expressed according to the resource's availability, which is expressed in feasibility dimensions.

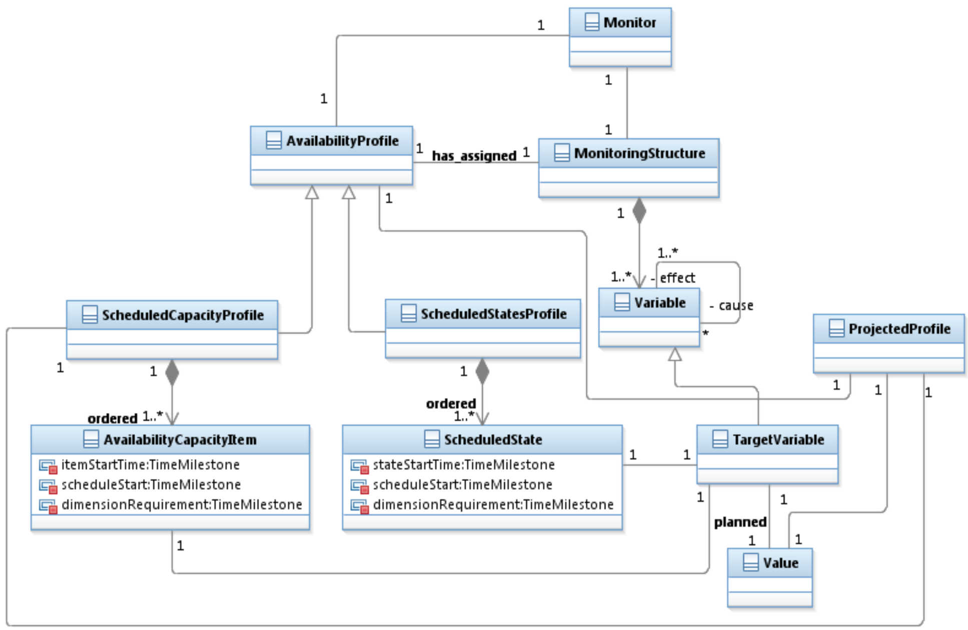


Fig. 10. UML class diagram of the Monitoring current status of resource feasibility

The *Monitor* has a milestone for each dimension requirement where the current value is observed and compared against the planned value to evaluate the occurrence of a disruptive event in that dimension.

3.3.1.4 Monitoring order specification changes

Figure 11 presents the UML class diagram associated with this activity. The monitoring structure associated with this activity defines three *TargetVariables* for each *SupplyProcess Order*. Each Variable has a planned value and an observed value. The planned value corresponds to an order specification (start time, end time or quantity). By default, the Monitor has two milestones to evaluate if a disruptive event may occur in an order. These are: schedule start, order start. Once the schedule start milestone is activated, the monitor will capture any change in the planned values for the order target variables (i.e., changes in the order specification) and when the change is assessed as significant, according to a threshold, the disruptive event is concluded. When the order start milestone is activated, the actual start time will be observed and compared with the planned value to evaluate a possible disruptive event. After this milestone, this activity finishes.
Following the principles of the model driven architecture (Mellor et al., 2004), through a model-to-model transformation, from an instance of the monitoring reference model, a monitoring model can be automatically derived.

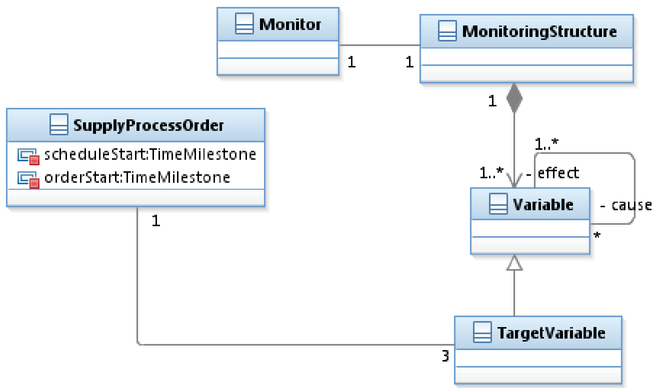


Fig. 11. UML class diagram of the Monitoring order specification changes

4. Case study: A commodity chemical supply chain

As illustrative example a case study presented in (Guarnaschelli et al., 2010) is used. In this supply chain Urea is produced in the factory located at Bahía Blanca, Argentina, warehoused in the factory warehouse, *FWBahiaBlanca* and distributed to three distribution centers *Urea-DCSanLorenzo* at San Lorenzo, Argentina; *Urea-DCUruguay*, at Montevideo, Uruguay; and *Urea-DCBrasil*, at Rio Grande, Brazil. The distribution centers are sourced by means of dedicated ships through fluvial and maritime routes. Table 1 presents the average trip times in hours.

	Urea-DCSanLorenzo	*Urea-DCUruguay*	*Urea-DCBrasil*
FWBahiaBlanca	96	144	168
Urea-DCUruguay	-	-	60

Table 1. Average trip times in hours

Distribution schedules for a horizon of 33 days are generated by a Distribution Resource Planning system. Product availability in *FWBahiaBlanca* is considered to be unlimited, this means that stock, demand and supply is managed for each distribution center attending constraints regarding to: Ships routes and availability, loading dock availability at factory warehouse, and inventory size and safety stocks constraints at each distribution center.
The schedule defines the replenishments to each distribution center, which imply coordination and timing for the resources implied by them. Using the reference model (Section 3.2.1) replenishments are modeled as transfers from *FWBahiaBlanca* to each distribution center, using the corresponding ship, loading dock and inventory resource at distribution center, like the supply process *transfer-Urea-BahiaBlanca-DCBrasil-26* depicted in Figure 12. This figure also shows how the implied resources are modeled.
Ships are coordinated with regards to its capacity and geographical position. A *stateBasedDimension* defines every geographical position along the scheduling horizon of every ship resource. The successive *stateBasedDimension* along the scheduling horizon defines the *ScheduledStatesProfile* for the corresponding ship resource.
Inventory resources modeled with a single *CapacityDimension*, only have a maximum capacity constraint (Table 2) captured by *availableCapacityItems* in the *scheduledCapacityProfile*.

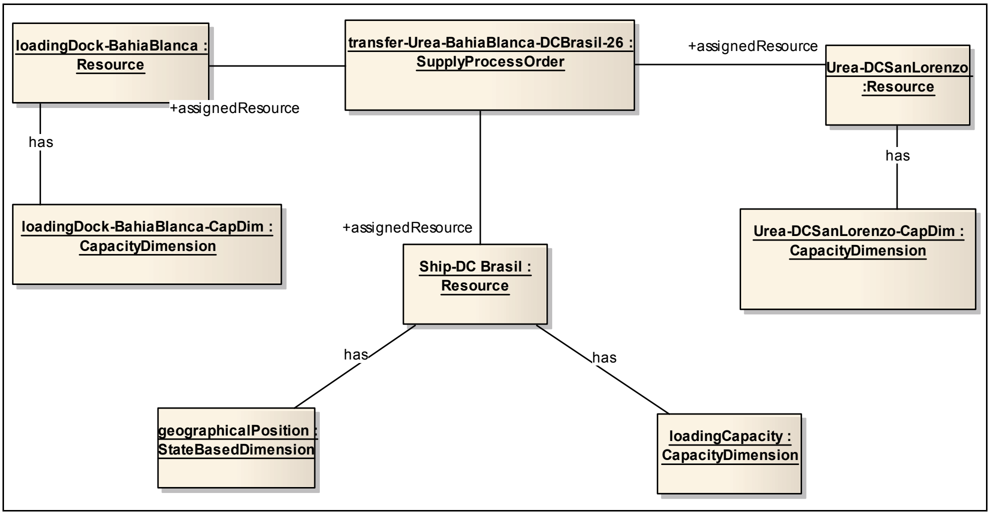


Fig. 12. A transfer-Urea-BahiaBlanca-DCBrasil-26 supply process order

The loading dock acts as a renewable resource, requirements it attends are of type *Renewable*.
Each distribution center has a list of Supply Process Orders (SPO) (transfer orders) to serve, which for this example are set together as a daily shipment for each of the 33 days. Each SPO imposes a *CapacityRequirement* on the corresponding inventory resource.

	Urea-DCSanLorenzo	*Urea-DCUruguay*	*Urea-DCBrasil*
Maximum capacity	30,000	20,000	20,000

Table 2. Maximum capacity of distribution centers in tons

In this schedule, the shipments from each distribution center have the following scheduling/ rescheduling policy: Each order has a time window for its dispatch, if it was originally scheduled for day d, in case of a repair procedure it cannot be dispatched outside the week that contains day d. Some orders allow quantity modifications but they cannot exceed 10% of the original value. Table 3 presents minimum and maximum shipment size in tons.

	Urea-DCSanLorenzo	*Urea-DCUruguay*	*Urea-DCBrasil*
minimum	953	393	705
maximum	2150	696	1147

Table 3. Minimum and maximum shipment size (*orderQuantity*) in tons

The replenishments to the distribution centers, that is transfer orders, are scheduled with a specific timing in the scheduling horizon, but, in case a of a repair procedure, their timing specification can be changed as long as resources capacities (inventories and ship capacity) and states (geographical position of ships) allow these changes. Transfer quantities are only limited by ships capacities (all of them have a storage capacity of 17000 tons). At Bahía Blanca ships are loaded at a constant rate of 1000 tons/hour. And in distribution centers ships are downloaded at a constant rate of 250 tons/hour in San Lorenzo and Uruguay, and at 425 tons/hour in Brasil.
In exceptional situations the supply from Bahia Blanca to Brasil can be done by a third party logistics provider that by contract provides a transportation capacity of 17000 tons with a delivery time of 7 days. This optional process is modeled as a *spareOrder* (also cancelable) that requires for its execution resources *loadingDock-BahiaBlanca* to load Urea and *Urea-DCBrasil* to download Urea.

4.1 Predicting and detecting disruptive events

The monitoring function performs four main activities during the execution of a schedule (Section 3.3). These are: monitoring order specification changes, monitoring current status of resource feasibility, monitoring order progress and monitoring changes in the expected future availability of a resource. The monitoring structure is generated using the reference model for monitoring orders and resources (Section 3.3.1).
In this supply process, the navigation conditions of the ship can be unfavorable due to the weather conditions (storms, winds, etc.). These unfavorable weather conditions are more frequent in the winter season and can produce a delay in the ship arrives to the port. The delay can be increased if in the arrival port or in the intermediate ports there are unfavorable weather conditions or the port is congested. This prevent to carry out unload operations. The *Ship-DCBrasil* can carry orders to ports on Uruguay and Brasil. I.e., it is not a dedicated ship to an order. Therefore, this ship that has to carry Urea an order requires from Bahía Blanca to Rio Grande, may need to go through an intermediate port to meet the requirements of orders of Montevideo. It can be see in Table 1 the ship is in transit 144 hours from Bahia Blanca to Montevideo and 60 hours from Montevideo to Rio Grande. The *MonitoringStructure* (Section 3.3.1.2) for monitoring the progress of this maritime transport order is graphically represented in Figure 13. The total navigation time of the ship will be of 204 hours. The milestones set contains:
depart_of_the_BahiaBlanca_port:StateMilestone, arrival_to_intermediate_position_1:StateMilestone, arrival_to_intermediate_position_2:StateMilestone, arrival_to_Montevideo_port:StateMilestone, arrival_to_intermediate_position_3:StateMilestone, arrival_to_RioGrande_port:StateMilestone.

In Figure 14 a graphic representation of a Bayesian network of this *MonitoringStructure* is graphically represented. It is composed by discrete nodes and continuous nodes. The discrete nodes (the states are represented in braces) are the following: *season:DiscreteNode* {winter, non_winter}, *navigation_condition:Discrete Node* {favorable, neutral, unfavorable} and *weather_conditions_at_port:DiscreteNode* {favorable, unfavorable}, *delay_in_departure:Discrete Node* {[0-0.5),[0.5-2),[2-6),[6-24),[24-48),[48-inf)} and has a Gamma distribution. The continuous nodes are the following: *delay_in_transit:ContinuousNode*, *delay_in_position :ContinuousNode*, *delay_in_intermediate_port:ContinuousNode* and *delay_in_arrival:Continuous Node*. The node function is *estimated_delay_in_arrival:FunctionNode*.
The decision criteria used by the Comparator establishes that the ship is delayed when its probability is greater than a threshold. In this example, the threshold has been defined equal to 24 hours.

4.2 Disruptive event in the case study

To illustrate the capabilities of the Feasibility Manager Subsystem in the case study a scenario generated due to a disruptive event notified by the Monitoring Subsystem is considered. The disruptive event is an unexpected increase in demand at *Urea-DC-Uruguay* has occurred.
The supply chain of this example shares the Urea market with another provider and its supply chain. At Uruguay the distribution center of the competitor temporarily runs out of stock, this obligates its clients to supply from *Urea-DCUruguay*. As a result shipments scheduled from day 10 to 19 are duplicated and now their *orderQuantity* (without possibility of negotiating order quantities) are incremented as shown in Table 4:

Supply Process Order	*orderQuantity*	*new orderQuantity*
shipment-Urea-DCUruguay-10	668	1500
shipment-Urea-DCUruguay-11	589	1500
shipment-Urea-DCUruguay-12	481	1500
shipment-Urea-DCUruguay-13	628	1500
shipment-Urea-DCUruguay-14	693	1500
shipment-Urea-DCUruguay-15	656	1000
shipment-Urea-DCUruguay-16	502	1000
shipment-Urea-DCUruguay-17	683	1000
shipment-Urea-DCUruguay-18	649	1000
shipment-Urea-DCUruguay-19	509	1000

Table 4. Unexpected changes in *orderQuantity* of SPOs in tons

Simulating the effects of this event on *Urea-DCUruguay* inventory (*CapacityDimension : Urea-DCUruguay-capDim*), an important infeasibility clearly appears as seen in Figure 15, looking at the curve named "Exception".
The Feasibility Manager Subsystem returns the following results: A set of 10 SPOs are modified (within planned buffers) in order to restore feasibility (Table 4). In Figure 15 is visible how the solution of the mechanism is closely related to the original schedule. The second Urea transfer is put forward and the other modifications consisted in slightly reducing some orders quantities in order to restore feasibility preserving most of the original schedule.

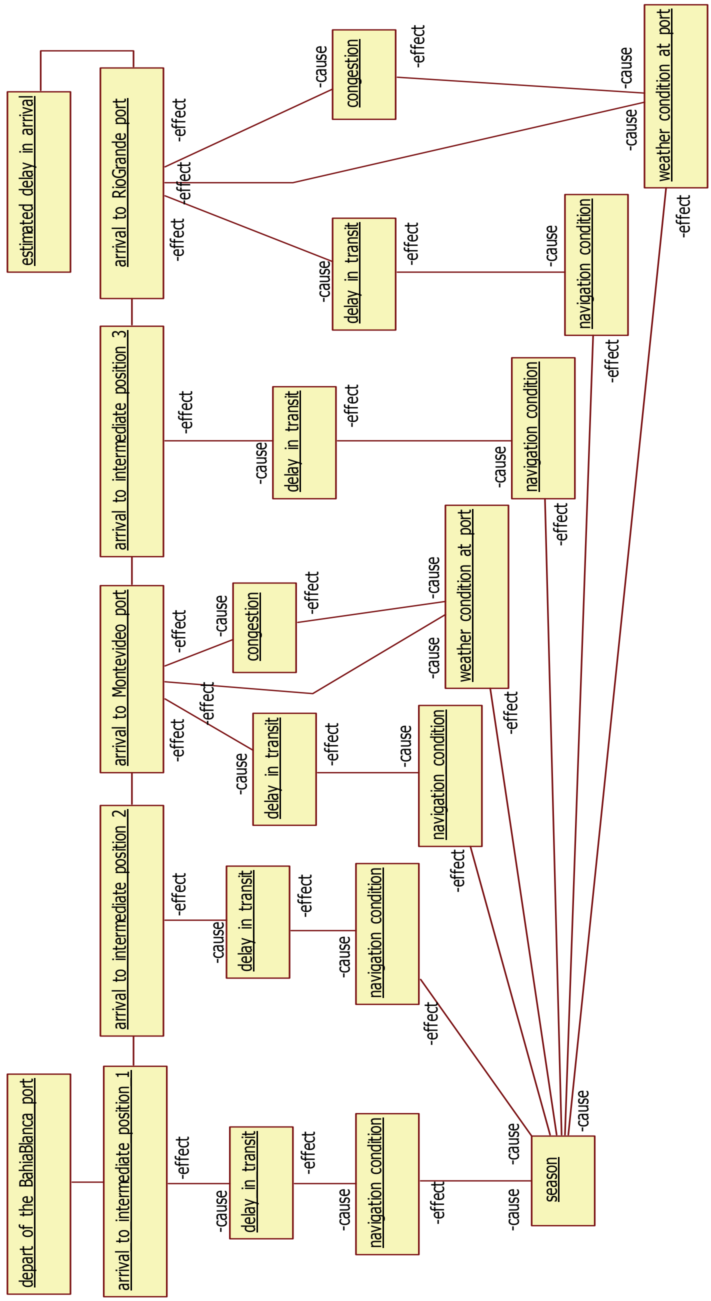


Fig. 13. *MonitoringStructure* of a marine transport order

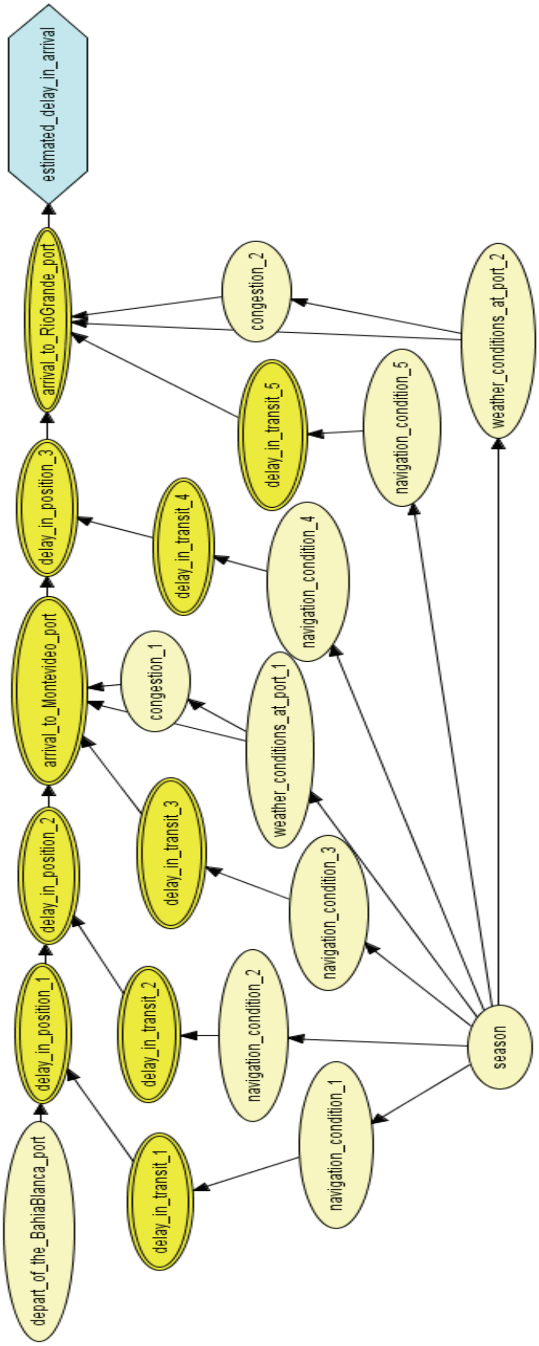


Fig. 14. Monitoring structure based on Bayesian Network

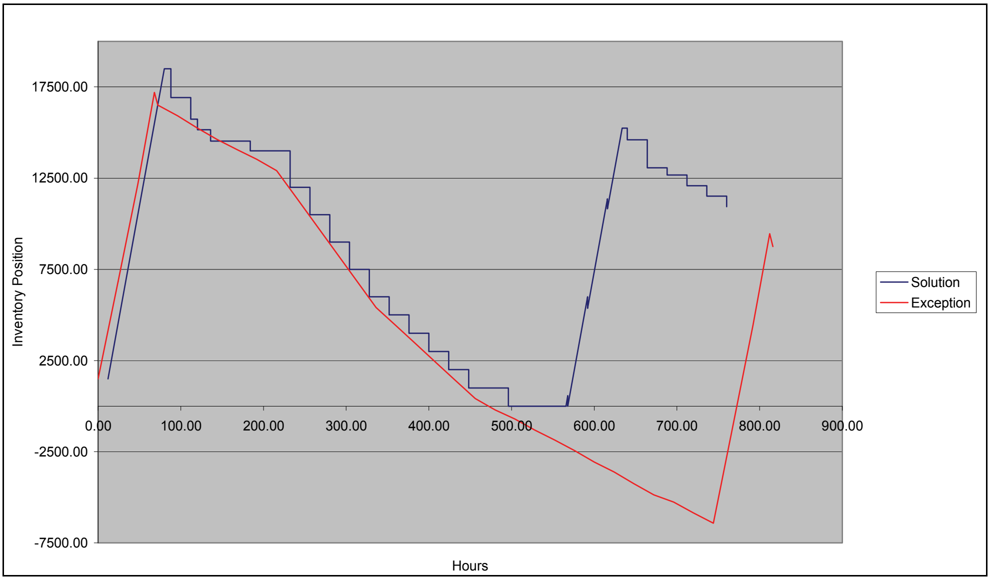


Fig. 15. *Urea-DCUruguay* projected available inventory (exception and solution)

5. SOA-based implementation of the SCEM system

Service oriented computing and architecture is the technology chosen to enact the SCEM business process in (Fernández et al., 2010 and Guarnachelli et al., 2010). It provides a way to create software artifacts that supports requirements on heterogeneity and autonomy that arise on current supply chain management practices. It provides a way to capture business requirements and processes and software artifacts delivered using Service-Oriented Architecture (SOA) (Papazoglou et al., 2007) are tied to them. The collaborative nature of this proposal for SCEM is benefited by adopting SOA technologies as it promotes few coarse grained interactions between service providers and consumers. Additionally a SOA architecture definition is platform independent allowing its implementation on business partners with diverse co-existent technologies.

Using the methodology for SOA development (Arsanjani et al., 2008), to support the functionalities of the SCEM business process three participants have been proposed: Controller, Monitor and Feasibility Manager. Following, the collaborative SCEM business process has been defined (Fernández et al., 2010) (Guarnachelli et al., 2010). The business process defines the necessary collaboration among participants (messages) and the tasks each them has to perform to provide the SCEM functionalities to any SC implementing it. These participants define the components of the SCEM system architecture presented in Section 3.

To identify all the capabilities and services required to enact the SCEM business process, a standard modeling technique (SOMA) (Arsanjani et al., 2008) was followed. The service model has been designed starting with the capabilities each participant in the business process has to provide to enact the collaboration. After that, the services exposing these capabilities were defined.

In this proposal a document-centric approach to support the access to service operations has been adopted, therefore for each operation defined in a service there is an associated

document containing all the information required to provide the service. These documents are specified using the *messageType* artifact from the SOAML specification. (OMG, 2009).
In order to define the messages and its information content in a consistent and complete way, we use the reference model described in Section 3.3.1. This model provides self-contained descriptions of any on-going execution schedule of supply process orders with all the information required to assess its feasibility.

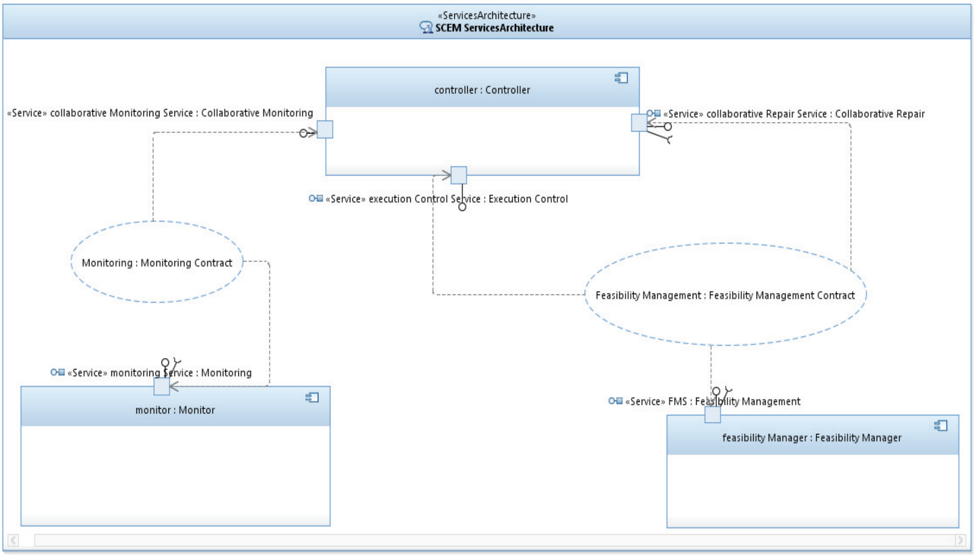


Fig. 16. SCEM service architecture

Fig. 17. The monitoring and feasibility management contracts

The architecture resulting from organizing the participants and services through specific service contracts including the collaboration choreographies is represented in Figure 16.

In order to specify how compatible requests and services are connected by service channels, service contracts Feasibility Management and Monitoring are defined (Figure 17).
These contracts contain all the metadata regarding the description about the SCEM SOA based solution services that is: the purpose and function of their operations, defined in service identification; the messages that need to be exchanged in order to engage the operations, defined in the service interface specification and the data models used to define the structure of the messages, defined in the service data model.
The choreographies required by the collaboration among the participants in these contracts were described using UML sequence diagrams specifying the asynchrony of operation calls, and the logic and sequence in which operations are used.

6. Conclusion

In this chapter a proposal to systematically address the problem of disruptive event management in SC is described. The proposal includes the definition of a SCEM system architecture conceived to provide system support for companies willing to engage in collaboration agreements for controlling the execution of their supply processes. The architecture allows supporting a collaborative execution of the SCEM business process by independent supply chain partners. Because of the complexity of the models required for feasibility check and schedule repair, and the models for monitoring orders and recourse, in the proposed SCEM system architecture, theses functionalities are performed by two centralized subsystems, the Feasibility Management and the Monitoring Subsystems, which are implemented as web services. The aim is to prevent members have to make these complex processes and decision analysis. That is: To evaluate the feasibility of a schedule and to collaboratively repair a disrupted schedule a Constrain Satisfaction Problem (CSP) has to be solved. This requires the use of appropriate CSPsolvers, for example, the IBM ILOG OPL Development Studio (IBM, 2010) has been used to solve the CSP for the scenario of the case study in Section 4.2. To predict if significant changes regards to the expected in the environmental variable may produce significant changes to the specification of an order or a resource, a cause-effect network has to be used. For example, in the case study (section 4.1) a representation of the Bayesian Network has been used, which has been processed using the inference engine of Hugin Expert A/S (Hugin, 2010).
A distributed Control Subsystem implemented by each member, is responsible for providing the functionality to control a schedule requesting monitoring function to the Monitoring Subsystem and feasibility verification and repairing to the Feasibility Management Subsystem when a disruptive even is detected, and engaging in collaborative repair.
The consistency of interoperation between the subsystems is granted in the semantic level with reference models that provide the basis for the definition of the business documents being exchanged among the subsystems. Reference models accomplish the description of the problem information in a very high level of abstraction and therefore being applicable to a wide range of SC processes, from procurement, manufacturing, distribution, and retailing domains. The reference models have the characteristic of providing self-contained descriptions of the information required for the decision making activities involved in the SCEM business process. This feature enables the possibility of automating the generation of decision models expressed in standard representations for decision making tools as mathematical programming solvers or inference engines.
The Feasibility Management Subsystem provides generic feasibility checking and repair mechanisms for local adjustments of the coordinated execution schedule within the space of

buffers already provided in the planned operations. This level of intervention is suitable for being delegated into automated procedures avoiding the need for triggering complex re-planning iterations.
The Monitoring Subsystem also exploit the generality of the reference models by framing the monitoring task into four well-identified activities that will capture the disruptive events that are rooted either on the orders dynamic or the resource availability.
A service-oriented solution applying standard SOMA techniques has been briefly described. The application of this technique allows the generation of the SOA specifications in full compliance with the SCEM business process and its requirements.
There are some issues that need to be addressed further for the proposal described in this chapter can be effectively deployed in real world scenarios. First, the generality of the reference models impose the burden of creating very rich and dense documents that collect information normally disperse in different business applications and databases. This is not a simple task in nowadays enterprise software. However as the service oriented approach gains momentum in the industry, and the concepts of cross-organizational information buses are becoming more and more popular, the gap for the requirements in this proposal will narrow in the short future.

7. References

Adhitya, A.; Srinivasan, R. & Karimi, I.A.(2007). A model-based rescheduling framework for managing abnormal supply chain events. *In Computers and Chemical Engineering 31* 496 – 518.

Arsanjani, A., Ghosh, S., Allam, A., Abdollah, T., Ganapathy, S., Holley, K. (2008). SOMA: A method for developing service-oriented solutions. *IBM Systems Journal* 47 (3), pp.377-396.

BedraxWeiss, T., McGann, C., and Ramakrishnan, S. (2003). Formalizing Resources for Planning. I*n International Conference on Automated Planning and Scheduling (13th)*. Italy, Trento.

Bui, T.; Hempsch, C.; Sebastian, H. & Bosse, T.(2009). A multi-agent simulation framework for automated negotiation in order promising. *In Proceedings of the Fifteenth Americas Conference on Information Systems*, San Francisco, California August 6th – 9th.

Cauvin, A.; Ferrarini, A. & Tranvouez, E. (2009). Disruption management in distributed enterprises: A multi-agent modelling and simulation of cooperative recovery behaviours. *In International Journal Production Economics 122* - 429 – 439.

Derrouiche, R. , Neubert, G. , Bouras, A. (2008). Supply chain management: A framework to characterize the collaborative strategies. *International Journal of Computer Integrated Manufacturing* 21 (4), pp 426-439.

Fernández, E., Salomone E., Chiotti, O. (2010). Model based on Bayesian Networks for Monitoring Events in the Supply Chain. *IFIP Advances in Information and Communication Technology* 338, pp.358-365.

Guarnaschelli, A., Chiotti, O. , Salomone, E. (2010). Service Oriented Approach for Autonomous Exception Management in Supply Chains. *I3E 2010*, pp. 292-303.

Hoffmann,O.; Deschner, D.; Reinheimer, S. & Bodendorf, F. (1999). Agent-Supported Information Retrieval in the Logistic Chain. *In proceeding of the 32nd Hawaii International Conference on System Sciences*, Maui.

Hugin Expert A/S, Hugin Researcher (2010). In: www.hugin.com.

IBM ILOG OPL Development Studio API.

Kärkkäinen, M., Främling, K. & Ala-RiMKU (2003). Integrating material and information flows using a distributed peer-to-peer information system. *In Collaborative System Production Management* (Jaddev H.S., Wortmann, J.C., Pets H.J. Eds), pp 305-319, Kuwer Academic Publishers, Boston.

Kleindorfer, P.R., and Saad G.H. (2005)., Managing Disruption Risks in Supply Chains, Production and Operations Management 14 (1), pp.53–68.

Knickle, K. & Kemmeler J. (2002). *Supply Chain Event Management in the Field Success with Visibility*, AMR Research, Boston.

Lee, H. L., Padmanabhan, V., and Whang, S. (1997). The Bullwhip Effect in Supply Chains, Sloan Management Review 38 (3), pp.93-102.

Liu, Q.& Min, H. (2008). A Collaborative Production Planning Model for Multi-Agent based Supply Chain. *In 2008 International Conference on Computer Science and Software Engineering*.

Masing, N. (2003). *Supply Chain Event Management as Strategic Perspective – Market Study: SCEM Software Performance in the European Market*. Master Thesis. Universitié du Québec en Outaouasis.

Mellor, S., Scott, K., Uhl, A., Weise, D. (2004). *MDA Distilled, Principles of Model Driven Architecture*. Addison-Wesley Professional, Addison-Wesley.

Object Management Group, Service Oriented Architecture Modeling Language (SoaML), version 1.0 - Beta 2, http://www.omg.org/spec/SoaML/, 2009.

Papazoglou, M. P. and Van Den Heuvel, W. (2007). Service oriented architectures: Approaches, technologies and research issues, *VLDB Journal* 16 (3), pp. 389-415.

Radjou, N., L.M. Orlov, and T. Nakashima (2002). Adapting To Supply Network Change, in The TechStrategy Report, F. Research, Editor.

Simchi-Levi, D., Kamanisky P. & Simchi-Levi E. (1999). *Designing and Managing the Supply Chain*, Mc Graw Hill.

Soosay, C., Hyland, P. and Ferrer, M. (2008). Supply chain collaboration: Capabilities for continuous innovation. *Supply Chain Management* 13 (2), pp. 160-169.

Speyerer, J.K. & Zeller, Andrew, J.(2004) Managing Supply Networks: Symptom Recognition and Diagnostic Analysis with Web Services. *Proceedings of the 37th Hawaii International Conference on System Sciencies*.

Szirbik, N.B., Wortmann, J.C., Hammer, D.K., Goosenaerts, J.B. M. & Aerts, A.T.M. (2000). Mediating Negotations in a Virtual Enterprise via Mobile Agents. *In Proceedings of the Academia/Industry Working Conference on Research Challenges* (IEEE Computer Society Eds.), pp. 237-242, Buffalo, NY.

Teuteberg F. & Schreber, D. (2005) Mobile Computing and Auto-ID Technologies in Supply Chain Event Management – An Agent-Based Approach. *In Proceedings of the Thirteenth European Conference on Information Systems* (Bartmann D, Rajola F, Kallinikos J, Avison D, Winter R, Ein-Dor P, Becker J, Bodendorf F, Weinhardt C eds.), Regensburg, Germany. (ISBN 3-937195-09-2)

Van Landeghem, H. & Vanmaele, H. (2002). Robust planning: a new paradigm for demand chain planning. *In Journal of Operations Management* 20, pp 769 – 783.

Wang, L.& Lin, S. (2009). A multi-agent based agile manufacturing planning and control system. *In Computers & Industrial Engineering* 57 620 – 640.

Zimmermann, R. (2006). *Agent-based Supply Network Event Management*. Whitestein Series in Software Agent Techonologies, Eds: Marius Walliser, Stefan Brantschen, Monique Calisti y Thomas Hempfling.

5

Power Optimization of Energy Service Companies (ESCOs) in Peak Demand Period Based on Supply Chain Network

Aurobi Das[1] and V. Balakrishnan[2]
[1]*Bureau of Energy Efficiency (BEE)-Ministry of Power, Govt. of India,*
[2]*Anna University of Technology,*
India

1. Introduction

A service value network may be defined as "the flexible, dynamic delivery of a service, and / or product, by a business and its networked, coordinated value chains (supply chains and demand chains working in harmony); such, that a value-adding and target-specific service and/or product solution is effectively, and efficiently, delivered to the individual customers in a timely, physical or virtual manner." This chapter has focused on the integration of renewable energy, specifically the solar energy resources into conventional electric grid and deployment of smart architecture of hybrid energy system in the context of Green House Effect to Climate Change with the deployment of energy conservation efforts by Energy Service Companies (ESCOs) under Energy Conservation Act 2001 under Bureau of Energy Efficiency (BEE) in Indian context for sustainable development of the rural and urban sector. A proposed research background for cost proposition for integrating distributed renewable –solar energy resources to the electricity grid is discussed.
ESCOs (Energy Service Companies), and ESCOs groups and ESCOs chains or e-energy service companies in the Smart-Grid network can optimize the national power shortage problem in peak demand period. It is a virtual service value network based on supply chain network of various energy trading companies. This proposition also helps to minimize the adverse challenges of climate change utilizing renewable energy resources at this service value network integrating into repository of conventional emery resources, thus reducing CO_2 emissions percentage and ultimately enhancing a green power scenario. The deployment of smart architecture of hybrid energy system for sustainable development of the rural and urban sector through the integrated renewable energy, specifically the solar energy resources into conventional electric grid with the concept of next generation mobile smart-grid city for efficient real-time collaborative use of renewable and non-renewable energy sources at smart user-centric device for sustainable green environment in the context of climate change proposition, which with the chain of ESCOs can reduce CO_2 emission ultimately with synchronization of all entities in the virtual network of Smart-Energy scenario. The cost proposition for integrating distributed renewable –solar energy resources to the electricity grid has been analyzed.

This chapter illustrates the deployment of Energy Portal (EP) for Renewable Energy Resources based on Service-Oriented-Architecture (SOA) technology. This EP based on Business Information Warehouse, will be utilized as Decision Support System for Energy Service Companies (ESCOs) and the Energy Information System Manager as well as the Enterprise Management System in the peak load time to utilize renewable energy resources to reduce power failure, to take decision about resource utilization of renewable energy resources in present global scenario of creating a pollution free environment based on Kyoto Protocol (The Kyoto Protocol is a protocol to the United Nations Framework Convention on Climate Change (UNFCCC or FCCC), an international environmental treaty with the goal of achieving "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”). Also utilization of SOA for renewable hybrid energy systems to be connected to the National Power Grid, and also Grid-Interactive Solar Energy System or Solar-Wind integrated System, which may be distributed but can be mapped for feeding into the National Electricity Grid through proper deployment of SOA has been analyzed through case studies.

2. Energy conservation act 2001 & its salient features in the context of India

The Act empowers the Central Government and, in some instances, State Governments to: (i) specify energy consumption standards for notified equipment and appliances; (ii) direct mandatory display of label on notified equipment and appliances; (iii) prohibit manufacture, sale, purchase and import of notified equipment and appliances not conforming to energy consumption standards; (iv) notify energy intensive industries, other establishments, and commercial buildings as designated consumers; (v) establish and prescribe energy consumption norms and standards for designated consumers; (vi) prescribe energy conservation building codes for efficient use of energy and its conservation in new commercial buildings having a connected load of 500 kW or a contract demand of 600 kVA and above; (vii) direct designated consumers to – (a) designate or appoint certified energy manager in charge of activities for efficient use of energy and its conservation; (b)get an energy audit conducted by an accredited energy auditor in the specified manner and interval of time; (c) furnish information with regard to energy consumed and action taken on the recommendation of the accredited energy auditor to the designed agency; (d) comply with energy consumption norms and standards; (e) prepare and implement schemes for efficient use of energy and its conservation if the prescribed energy consumption norms and standards are not fulfilled; (f) get energy audit of the building conducted by an accredited energy auditor in this specified manner and intervals of time. State government also is empowered by the act.

2.1 ESCOs in Indian context

ESCO (Energy Service Company) - A consultancy group engages in a performance based contract with a client firm to implement measures which reduce energy consumption and costs in a technically and financially viable manner.

The Government of India set up Bureau of Energy Efficiency (BEE) on 1st March 2002 [4] under the provisions of the Energy Conservation Act, 2001. The mission of the Bureau of Energy Efficiency is to assist in developing policies and strategies with a thrust on self-regulation and market principles, within the overall framework of the Energy Conservation

Act, 2001 with the primary objective of reducing energy intensity of the Indian economy. This will be achieved with active participation of all stakeholders, resulting in accelerated and sustained adoption of energy efficiency in all sectors. BEE is promoting energy efficiency measures in India under the Energy Conservation Act, 2001. BEE co-ordinates with designated consumers, designated agencies and other organizations and recognize, identify and utilize the existing resources and infrastructure, in performing the functions assigned to it under the Energy Conservation Act. The Energy Conservation Act provides for regulatory and promotional functions.

In addition to promoting energy audits among designated consumers by accredited energy auditors and facilitated by certified energy managers, BEE intends to promote implementation of energy conservation measures in existing buildings/facilities through the ESCOs route. With a view to tap the potential of bringing about energy efficiency improvement in existing buildings/ facilities BEE had undertaken shortlisting of ESCOs through an open invitation and evaluation process. 35 ESCOs have been qualified. This database of shortlisted ESCOs has been shared by BEE with the State Governments/ State Designated Agencies (SDA) which in turn would help in taking up energy efficiency improvement projects in their existing buildings/ facilities.

There are several estimates of energy efficiency and conservation potential in the Indian economy. Most of them have based their assessment at the macro level taking note of some demonstration projects that were implemented in various sectors. Prominent amongst them are the Integrated Energy Policy (2006) that provides an estimate of energy saving potential in the Indian economic activity of 15-20%, the ADB study (2004) of Demand Side Management potential in industry, buildings, municipalities and the very recent National Mission for Enhanced Energy Efficiency that seeks to unlock a market potential of Rs. 74,000 crores and an avoided capacity addition of 19,000 MW. In this background, it is necessary to assess detailed potential in each sector and in each state, given that the implementation of the Energy Conservation Act, 2001 is with the State Governments through their notified State Designated Agencies (SDAs).

BEE, with the approval of Ministry of Power, has initiated a scheme for capacity building of SDAs during the current plan period. A 19 point state level Energy Conservation Action Plan (ECAP) has been evolved for 32 states/ UTs and is under implementation. As a part of the program, it was considered necessary to carry out a detailed assessment state-wise in some key sectors of the economy. National Productivity Council (NPC), an autonomous organization under the Ministry of Commerce, Government of India, was tasked to undertake this work in all 35 states / UTs. The study focused only on estimation of the total electricity consumption and saving potential in the following sectors of each state / UT: (i) Agricultural pumping; (ii) Municipal water and sewage pumping, street lighting; (iii) Commercial buildings like Hotel/Resorts, Hospital, Shopping Mall/Multiplex, office building, public park/monument having connected load of more than 500 KW; (iv) Representative Small and Medium Enterprises (SMEs) which have high saving potential.

2.1.1 Policies to promote energy efficiency and renewable energy by BEE

(i) Increased industrial energy efficiency: In the major energy-consuming industrial sectors, such as cement, steel, aluminum, fertilizers, etc., average specific energy consumption has been declining because of energy conservation in existing units, and (much more) due to new capacity addition with state-of-the-art technology; **(ii) Electricity from renewables:** The Electricity Act, 2003, requires State Electricity Regulatory

Commissions to specify a percentage of electricity that the electricity distribution companies must procure from renewable sources. Several Commissions have already operationalized this mandate, and also notified preferential prices for electricity from renewables. This has contributed to an acceleration in renewable-electricity capacity addition, and over the past three years, about 2,000 MW of renewable-electricity capacity has been added in India every year, bringing the total installed renewable capacity to over 11,000 MW. Of this, a little over 7,000 MW is based on wind power. The National Hydro Energy Policy has resulted in the accelerated addition of hydropower in India, which is now over 35,000 MW; **(iii) Enhancing efficiency of power plants:** The Electricity Regulatory Commissions are also linking tariffs to efficiency enhancement, thus providing an incentive for renovation and modernization. New plants are being encouraged to adopt more efficient and clean coal technologies, and four new plants under construction have adopted the more-efficient supercritical technology for power generation[4]; **(iv) Introduction of labeling programme for appliances:** An energy labeling programme for appliances was launched in 2006, and comparative starbased labeling has been introduced for fluorescent tubelights, air conditioners, and distribution transformers, (See Fig. 1) providing information about the energy consumption of an appliance, and thus enable consumers to make informed decisions; **(v) Energy conservation building code:** An Energy Conservation Building Code (ECBC) was launched in May, 2007, which addresses the design of new, large commercial buildings to optimize the building's energy demand; **(vi) Energy audits of large industrial consumers:** In March 2007, the conduct of energy audits was made mandatory in large energy-consuming units in nine industrial sectors. These units, notified as "designated consumers" are also required to employ "certified energy managers", and report energy consumption and energy conservation data annually; **(vii) Accelerated introduction of clean energy technologies through the clean development mechanism (CDM):** Over 700 CDM projects have been approved by the CDM National Designated Authority, and about 300 of these have been registered by the CDM Executive Board, which have already resulted in over 27 million tones of certified CO2 emissions reductions, and directed investment in renewable energy and energy projects by reducing the perceived risks and uncertainties of these new technologies, thereby accelerating their adoption [4].

Fig. 1. Energy labels for refrigerators and fluorescent lamps

2.1.2 Literature review: The contribution of renewable energy to mitigate climate change-role of ESCOs in this issue

Changing smart energy scenario

Visions are: (i) "Use of advanced technologies to improve the performance of electric utility systems to address the needs of society." (ii) "A fully automated power delivery network, ensuring a two-way flow of electricity and information between the power plant and appliance, and all points in between. Its distributed intelligence, coupled with broadband communications and automated control systems, enables real-time transactions and seamless interface among people, buildings, industrial plants, generation facilities and the electric network." - U.S. Department of Energy Grid 2030. (iii) "Its foundation is new distributed data communication, computing, and control technologies – efficient transfer of data and control from/to/among many field units."

As stated in the Third assessment Report of the Intergovernmental Panel on Climate Change (IPCC), there is new and stranger evidence that most of the warming observed over the past 50 years is attributable to human activities, and that significant climate change would result if 21-st century energy needs were met without a major reduction in the carbon emissions of the global energy system during this century. Current CO_2 emission trends, if not controlled, will lead to more than a doubling of atmospheric concentrations before 2050, relative to pre-industrial levels[5]. Carbon dioxide, the most important anthropogenic greenhouse gas, increased markedly as a result of human activities, and its atmospheric concentration of 379 ppmv (parts per million, by volume) in 2005 by far exceeded the natural range of 180 to 300 ppmv over the last 650,000 years (CDIAC, 2005). This is being a serious challenge to sustainable development, the main strategies to prevent it are: (i) More efficient use of energy, especially at the point of end-use in buildings, transportation and production processes; (ii) increases reliance on renewable energy resources; (iii) accelerated development and deployment of new and advanced energy technologies, including next-generation fossil-fuel technologies that produce near zero harmful emissions. Due to lack of adequate investments on Transmission and distribution (T & D) works, the T & D losses have been consistently on the higher side, and are presently in the range of 22-23 %. Solar energy has immense potential as the amount of solar radiation intercepted by the earth is much higher than the annual global energy use. Large-scale availability of solar energy depends on a region's geographic position, typical weather conditions and land availability. Also the amount of final energy will depend on the efficiency of conversion device used (such as the photovoltaic cell applied). Implications of renewable energy resources are manifold towards climate change reducing CO_2 emissions, reducing T & D losses by substituting conventional resources, ultimately affecting overall economy of hybrid energy system. The appropriate break-up of T & D losses in the Indian Power System are as follows:

Transmission Loses (400 kV, 220 kV, 132 kV, 66 kV)	**4 %**
Distribution Losses (33 kV, 11k V and 400 volts)	**19 %**
	23 %

Out of the above loses 19% at distribution level, non-technical commercial losses account for about 5%, and thus the technical losses in distribution system may be taken as about 14%.

PV connected to the electrical system (domestic and small scale)

Mains connection means that the grid provides a reserve when output from the PV panels is not available. As well as acting as a source of electricity in the absence of PV output, the grid can also accept spill or surplus electricity generation when the connected load cannot accept any further power from the PV modules. This is particularly useful when the panels are producing electricity, with little or no available load.

The grid can absorb PV power that is surplus to requirements very much in the manner of a giant battery that is being charged. This excess (or spilled) electricity flows to the grid and will automatically replace fossil fuel-generated electricity from the power stations. The PV electricity generated carries the additional benefit that it is supplied locally to customers and saves the electrical losses that occur in the grid transmission and distribution system (as the electricity flows through transformers, wires and cables from the power station). Grid-connected systems such as solar PV are described as network or grid embedded generation.

In grid-connected PV systems, the DC output voltage from an array requires to be converted to a voltage and frequency that can be accepted by the grid, which is done using a grid-commutated inverter, which makes sure there is synchronization between the PV electrical output and the electricity mains. The excess electricity not used within the buildings can be exported to the network and credited, with the agreement of the local electricity distribution network operator (DNO) or energy supply company (ESCO). The rate paid for spilled electricity will very much depend on the spill payment offered by the ESCO. Suitable certified and approved meters are installed to measure the amount of electricity generated by the system (generation meter) and spill onto the grid (export meter).

Under some arrangements, payment is made for the spilled electricity as well as the environmental credit or greenness of the electricity generated by the PV system. The PV generation meter will register all the electricity generated by the panels. In some areas the ESCOs are considering the introduction of net metering systems. In this arrangement imported electricity is supplied and charged at the normal tariff rate for the installations, but exported electricity is deducted from the imported total and the installation is billed for the net balance between the import and exported electricity. It may be possible to have a net export of electricity with a payment for the exported balance from the ESCO, which is analogous to the energy company's main import meters running backwards during export.

2.1.3 Proposed research in renewable energy resources-solar energy to develop a smart energy scenario to cut CO_2 emissions

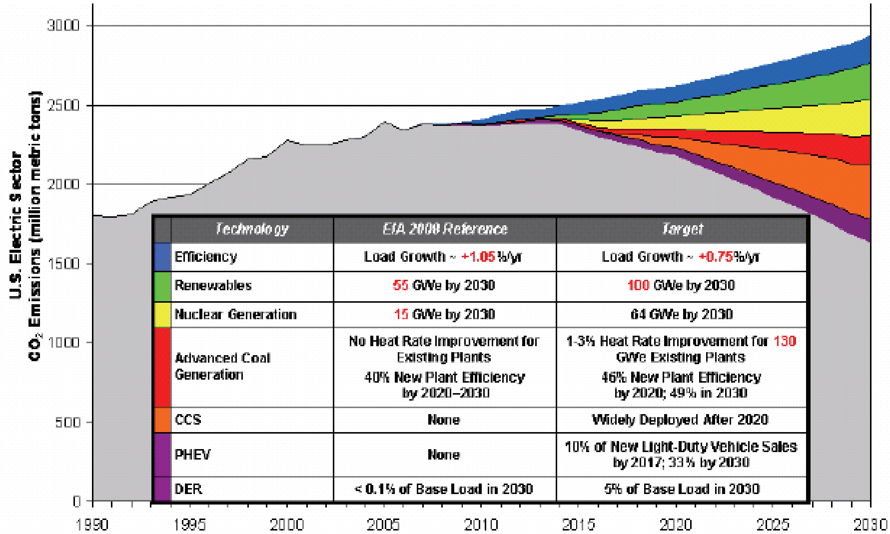
Energy produced from renewable energy resources such as solar specifically for example, is stored in battery before consumption, which is a solar module, which will be able to supply energy uninterupted. The main advantage of the system is that energy production's independence from electricity network. The proposed research is to investigate solar irradiance in a particular location and to build solar module at that location of maximum irradiance and to measure the solar energy produced and simultaneously send that estimated solar energy to a computer through wireless connection or cable. The system will be able to monitor specific types of investments that can be recommended for renewable energy resources are: (i) By expanded use of renewable energy resources for example PVs for small-scale applications in high-insolation areas can reduce the T & D losses of conventional energy resources; (ii) Use of PVs to provide supplementary power on grid-connected distribution systems, if the peak load matches solar insolation; (iii) To analysis the cost proposition for integrating distributed renewable –solar energy resources to the electricity grid; (iv) Deploy a Service Value Network for ESCOs in the Smart-Grid infrastructure of Hybrid Energy Systems of integrated renewable energy recourses to the electricity grid.

2.1.4 The “smart grid” applications

Grid-connected applications: There are two main options for feeding PV electricity into grid network: (i) Via large central power stations occupying many areas of lands; (ii) Via many small grid-connected systems distributed on the roofs of the buildings. **Centralized PV power stations:** Large-scale PV plants connected to the grid will have to compete with conventional sources of grid electricity, to become commercially viable to substitute the expensive peak-load power plants. This commercial grid-conned applications of PV is cost-effective in the peak-demand period. Specific Energy Systems Models is a linear programming type model that find the optimum combination of generators for a given electricity demand (characterized by a load-duration curve) and a given set of environmental restrictions. In case of a growth of demand in the electricity network, the capacity in the network should be increased. This increase of demand leads to an increase of peak load in the system, where this additional load will have to be supplied 100 % by additional plants. Assuming that renewable energy generators could take over some part of this capacity expansion, where some of the additional energy demanded can be supplied by the renewable energy resources. If the additional peak demand, for example, is solar driven, it may be possible that the demand will occur at times when the availability of this system is particularly high.

2.1.5 Prism analysis of EPRI in the context of CO_2 reduction in smart-grid scenario

As per analysis, a Smart Grid could potentially reduce annual energy consumption by 56 to 203 billion kWh in 2030, corresponding to a 1.2 to 4.3% reduction in projected retail electricity sales in 2030 [3]. In addition, a Smart Grid can facilitate greater integration of renewable generation resources and greater deployment of plug-in hybrid electric vehicles (PHEVs). Both of these mechanisms, while not associated with energy savings, will reduce greenhouse gas emissions, insofar as (a) renewables such as wind and solar displace fossil-burning energy sources and (b) PHEVs avoid emissions from conventional internal combustion engines in the transportation sector. **The combined environmental impact of these seven Smart Grid mechanisms is an estimated annual reduction in greenhouse gas emissions equivalent to 60 to 211 million metric tons of CO2 in 2030.** As per Prism analysis of Electric Power Research Institute (EPRI), the U.S. electricity sector will need to rely on a portfolio of technologies to meet future carbon reduction goals, including energy efficiency, renewables, nuclear, advanced coal, carbon capture and storage, plug-in hybrid electric vehicles, and distributed energy resources. The EPRI Prism chart, shown as Fig. 2, illustrates what most industry experts agree: energy efficiency – the top slice of the Prism shown in blue – is the most technically and economically viable near-term option for the electric power industry to reduce its carbon footprint [1]. As per view of EPRI, an integrated set of four building blocks constitutes an emerging infrastructure that can make energy efficiency more dynamic and robust over time, substantially expanding its potential [2], which are: (i) **Communications infrastructure** to allow bi-directional flow of information between electricity suppliers and consumers; (ii) **Innovative rates and regulation** to provide adequate incentives for energy efficiency; (iii) investments for electricity suppliers and consumers. This can encompass the promulgation of innovative retail rate design structures such as time-of-use or dynamic pricing, which provide electricity customers with rates that correspond to wholesale market conditions. It also includes regulatory structures that encourage utilities to pursue energy efficiency, such as shareholder incentive mechanisms; (iv) **Smart end-use devices** that are energy-efficient and able to receive and respond to real-time signals; (v) **Innovative markets** to ensure that energy efficiency measures instituted by regulation become self-sustaining in the marketplace. This can encompass the promulgation of progressive energy efficiency programs – implemented by utilities, state agencies, or other entities – and codes and standards that transform the market for energy efficient products and services.



Technology	EIA 2008 Reference	Target
Efficiency	Load Growth ~ +1.05%/yr	Load Growth ~ +0.75%/yr
Renewables	55 GWe by 2030	100 GWe by 2030
Nuclear Generation	15 GWe by 2030	64 GWe by 2030
Advanced Coal Generation	No Heat Rate Improvement for Existing Plants 40% New Plant Efficiency by 2020–2030	1-3% Heat Rate Improvement for 130 GWe Existing Plants 46% New Plant Efficiency by 2020; 49% in 2030
CCS	None	Widely Deployed After 2020
PHEV	None	10% of New Light-Duty Vehicle Sales by 2017; 33% by 2030
DER	< 0.1% of Base Load in 2030	5% of Base Load in 2030

Fig. 2. EPRI 2008 Prism – technical potential for CO_2 reductions in US electric sector

From a utility's perspective, a Smart Grid can be viewed as a means to further five primary Goals such as: (i) Enhance Customer Service; (ii) Improve Operational Efficiency; (iii) Enhance Demand Response and Load Control; (iv) Transform Customer Energy Use Behavior; and (v) Support More Utility Energy Efficiency Investment (See Fig. 3). As demonstrated in the Fig. 4, some of the energy savings and carbon reduction benefits overlap across the various goals. For example, indirect feedback to customers via improved billing is related to improvements in operational efficiency and to transforming customer energy use behavior. In addition, greater options for dynamic pricing and demand response are related to enhancing customer service as well as to enhancing demand response [2].

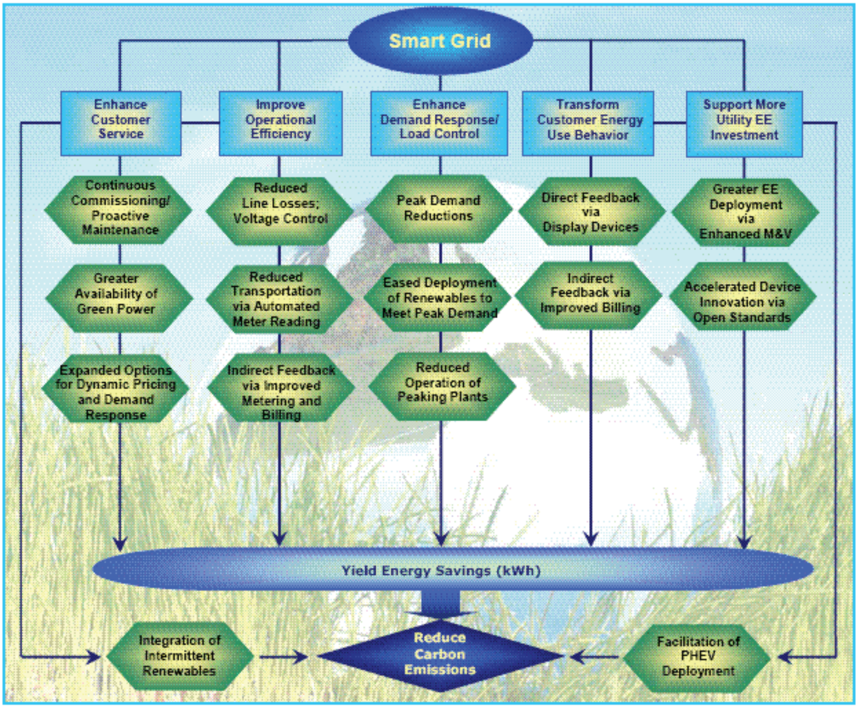


Fig. 3. Utility smart grid goals: All paths lead to carbon reductions

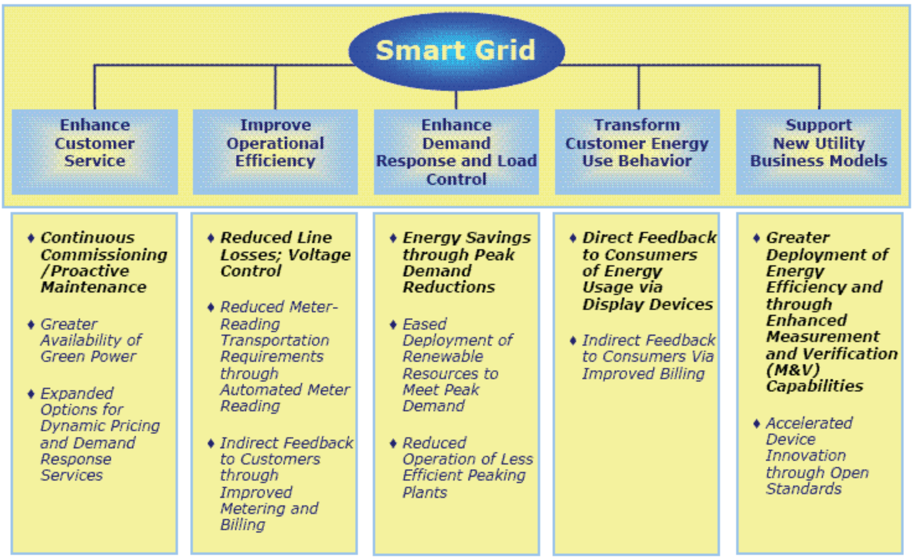


Fig. 4. Summary of energy-savings & carbon-reduction mechanisms enabled by a smart grid

2.1.6 Proposed methodology

(a) To identify the break-even point for integration; (b) Technology upgradation: (i) Creation of a Standardized Interface and testing of that interface regarding hybrid energy system integration; (ii) Usage of A high-voltage, direct current (HVDC) electric power transmission system: HVDC uses direct current for the bulk transmission of electrical power, in contrast with the more common alternating current systems. Also, for long-distance distribution, HVDC systems are less expensive and suffer lower electrical losses. Hence usage of HVDC in the context of renewable energy integration to electricity grid and vice-versa is proposed; **(iii) Super conductor research:** This is encouraged as transmission loss is reduced while transmission through super conductor and hence this research in the context of renewable energy integration to electricity grid and vice-versa is proposed; (c) Incorporating NASA Surface Meteorology and Solar Energy Data on Solar Energy Resources to estimate the solar energy potential at a particular latitude and longitude [7]; (d) Select Renewable Energy and Energy Efficient Systems (REEESs) whose market potential is to be mapped. Priority to be given to systems which are more promising for large scale application but present utilization is far below the potential; (e) Identification of all relevant factors affecting the market potential or acceptance level for any new REEESs under consideration; (f) Assess the significance level of each identified factor for the specific cases and assign the multiplication factor considering their availability, local, social and environmental conditions. Thus develop a scientific, elaborative, convenient and yet practically applicable method to calculate the Acceptance Index (AI)[7]; (g) Collection of relevant primary data from representative number of locations distributed over the geographic region, viz. the North Eastern Region of India. Test the kit with primary data so obtained for statistically representative locations. Make necessary modifications.

2.1.7 Cost proposition for integrating distributed renewables-solar energy resources to electricity grid

1. Cost of renewable energy at the point of demand

Cost of Renewable Energy at the point of Demand = Installation Cost + Transmission Cost
Where Installation Cost = Efficiency of the System + Area of the System

2. Cost of extension of grid to point of generation of solar energy

On the Map nearest Grid Point has to be located
System Cost + Extension of Grid to the Point of Generation
= Fixed Cost + Variable Cost + Energy Transmission Loss + Generation Efficiency + Installation Cost [Transmission line gap fill-up cost]

3. Social cost

Market price of conventional energy resources
Conventional Power Generation Cost + profit + social cost = Market Price (MP)
Market price of non conventional energy resources-renewable
Non Conventional Power Generation Cost + Profit – Social Benefits = Market Price (MP)
Environmental costs: Conventional power generation creates 'Social Costs' which are not included in the price of electricity. These social costs include damage done to the environment by acid rain and global warming, and effects on human health due to toxic emissions such as sulphurous and nitrous oxides.

Market price will then be set on equal plane if social cost of conventional energy resources can be given as subsidies to non conventional energy resources to replace conventional energy resources with non conventional –renewable energy resources. In this scenario, real completion of renewable is possible with conventional and renewable energy resources can compete farley with conventional energy resources.

2.1.8 Challenges faced by power companies and ESCOs

Environmental legislation in most industrialized countries calls for an increase in the production of renewable energy. The decentralized nature of facilities that produce green energy (solar energy), where **Green Energy or Sustainable Energy-**is the energy already passing through the environment as a current or flow, irrespective of there being a device to intercept and harness this power; compounded by natural fluctuations in power output, make it difficult for a power company to gather, validate, and deliver power-capacity data. Hence, estimation of reasonably accurate capacity forecasts is a greater challenge along with the changes in government policies that result in changes to subsidies and tax breaks granted to producers of green energy. Enterprise services into composite application of mainstream power business enable a power company to reliably gather green-energy data from disparate sources and to embrace change in the fast-moving green-energy part of its business. A power company needs timely information on its current and anticipated future capacities of green energy – a task that is extremely difficult to fulfill with error-prone manual and semiautomatic methods. Data sources typically include standard software solutions and a number of non-standard applications plus nonstandard databases run by the company's smaller suppliers of green energy. They may even include arrays of solar panels operated by individuals who merely have a separate electricity meter that relays data to the power company in real time. Collecting complex data from disparate sources such as these and then aggregating and validating all relevant data requires a tremendous amount of effort plus time-consuming communication. Also green energy is popular; a growing number of customers are prepared to pay a premium for "clean" power. To sharpen its competitive edge in a highly competitive and sometimes volatile market, a power company wants to deploy a solution designed to ensure the quality and currency of data; to automate the tasks of data gathering, aggregation, validation, and presentation; and to ensure sustained regulatory compliance [7]. Supply Chain Network of ESCOs should be integrated with the Network of energy trading Companies in Smart-Grid of hybrid energy system with the implications of treating energy trading companies as ESCOs.

2.1.9 SOA basic concepts

Service Oriented Architecture (SOA) is a business-centric IT architectural approach that supports integrating the business as linked, repeatable business tasks or services. SOA helps users build composite applications which draw upon functionality from multiple sources within and beyond the enterprise to support horizontal business processes. A composite application is a set of related and integrated services that support a business process built on SOA. As a gross generalization, a service is a repeatable task within a business process. Identification of business processes and then identification of set of tasks within that each process. Next tasks are defined as services and the business process is a composite of services. The Service Oriented Modeling and Analysis (SOMA) technique is an approach which has been devised to help to identify the appropriate granularity and construction of services derived from the business design. Service orientation is a way of integrating the business as a set of linked services. A Service Oriented Architecture, then, is an architectural style for creating an enterprise IT architecture that exploits the principles of service orientation to achieve a tighter relationship between the business and the information systems that support the business. Finally, SOA-based enterprise architecture will yield composite applications. A Service Oriented Architecture (SOA) is set of principles that define an architecture that is loosely coupled and comprised of service providers and service consumers that interact according to a negotiated contract or interface. These services provide the interfaces to Applications in the IT landscape. The primary goal of SOA is to expose application functions in a standardized way so that they can be leveraged across multiple projects. This approach greatly reduces the time, effort and cost it takes to maintain and expand solutions to meet business needs [12].

2.1.10 Role of enterprise service bus (ESB) in SOA configuration

ESB provides a comprehensive, scalable way to connect a large number of applications without the need for each pair of applications to make a direct connection. Such a direct connection between two applications is called a *point-to-point connection*. In Web Services, the connection between the service consumer application and the service provider application is "point to point". The point-to-point connection approach does not scale well because the number of applications involved in the integration increase; therefore, this integration approach is not suitable for a large enterprise where a large number of applications need to be integrated. The faturesof ESB are as: (i) An enterprise service bus (ESB) is the infrastructure of SOA; (ii) Its purpose is to provide interoperability (connectivity, data mapping, and routing) combined with some additional services such as security, monitoring, and so on; (iii) An ESB can be heterogeneous. Basic Services are services that each provide a basic business functionality, which provide the first fundamental business layer for one specific backend or problem domain. The role of these services is to wrap a backend or problem domain so that consumers (and high-level services) can access the backend by using the common SOA infrastructure. Hence, by introducing basic services, we get the fundamental SOA. With basic services introduced, service consumers can use an ESB to process the business functionality that one back end is responsible.

2.1.11 Business problems addressed by SOA

A large organization typically has many relationships with external business entities such as business partner and suppliers. Theses relationships are fluid in nature and frequently change for which a new approach is required to meet these fast-changing business conditions to provide flexible, agile IT systems that could meet theses fast-changing business needs of the time. SOA answer the problem with an emphasis on agile IT system through the use of reusable components. In this architecture, computer programs or components developed instead of solving a specific business problem, provide some generic functionality, where theses component can be threaded, linked, or integrated in a specific order or configuration to meet a specific business need. If the business requirement changes, there is no need to develop a new computer program and the system can be reconfigured to meet the new business requirement. Generally, the different kinds of technological heterogeneity exist in a large enterprise, which are as following: (i) Middleware heterogeneity: Generally in a large enterprise, more than one type of middleware is being used and two mot common types of them are application servers and message-oriented middleware (MOM);(ii) Protocol heterogeneity: This heterogeneity refers to the different transport protocols being used to access the services offered by various applications; (iii) Synchrony heterogeneity: There is always a need to support both synchronous and asynchronous interactions between applications, which leads to a situation where the types of interaction supported by the two applications that wish to interact do not match; (iv) Diversity of data formats: Most of the time the data is dependent on the middleware being used, also can cause a problem if two applications that wish to interact support different data formats; Diversity of interface declarations: There are large difference in the way the service interfaces are declared and used to invoke a service; No common place for service lookup: Sometime there are no common place to look up services to deal with the diversity of services in a large enterprise.

2.1.12 SOA-energy portal (EP)

Creating a SOA-EP onto a Smart Device for power generation, transmission and distribution companies and Energy Service Companies (ESCOs) will help to reference real-time data related to power generation, transmission and distribution and peak load scenario of different utility consumers from diverse sources; for which SOA-EP features a unification server. This unification server includes a collaboration component, supporting real-time collaboration among various ESCOs and power plants at different sites via virtual rooms and different collaboration tools. Also the supply chain capabilities of individual supply chain members of various renewable and nonrenewable energy sources are brought together through mapping of Supply Chain Configuration Framework for renewable and nonrenewable Energy sources to enable joint decision making and technological implementation of decisions. Cross-enterprise functionality of State Grid with the remote renewable energy sites and nonrenewable energy sites has to be efficiently shared information cross all the departments and power generation plants and transmission and distribution network and also to work seamlessly with ESCOs and suppliers and communicate easily with industrial and domestic energy customers. This state grid can interact with entities outside it i.e. can integrate with renewable and nonrenewable energy sources i.e. entities outside the boundaries of state grid and interaction has to be done to complete and succeed globally.

2.1.13 Solution through SOA

An intelligent electricity solution created on IBM's integrated, open-standards-based Service Oriented Architecture (SOA), connectgaia.com (Fig. 5) enables the Intelligent Grid work, to the advantage of all stakeholders – maintaining balance of electricity supply and demand in real time; allowing consumer participation in optimizing power and saving expenses through improved visibility; offering valuable demand response flexibility at relatively low cost. It will enable the creation of an intelligent power network that will pool dispersed and diverse resources and form a network that communicates and is in synergy with nature. The convergence of IT and Power Highway, the birth of an intelligent grid, that is alert, smart and communicates end to end.

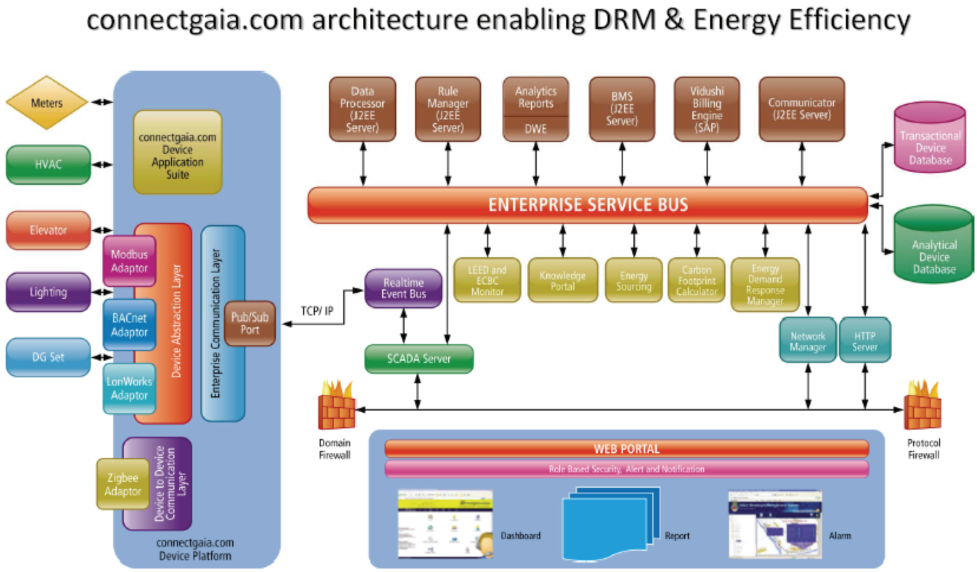


Fig. 5. Connectgaia.com architecture enabling Demand Response Module (DRM) & Energy

3. Conclusions

A smart-energy market where an integrated renewable energy system into the smart-grid –a service oriented architecture can be designed to assess market potential of conventional versus renewable via acceptance index which is accessible to a mobile device or any smart device into a single entry point to the utility customer for efficient reliable use of energy resources in the context of environmental pollution control scenarios reducing Grren House Gas(GHG) in the context of Kyoto Protocol for rural and urban sustainable development. In addition, 'Hybrid systems' also have enormous potential for remote areas. Wind turbines, possibly with additional solar resources, are used in conjunction with back-up diesel generators, which operate as required. The renewable sources typically supply 60-85 % of energy. Existing renewable energy systems and DG sets are not adequate to fulfill the actual demand of electricity at Sagar Island. Hence, more Solar Photovoltaic (SPV) and wind energy is required to be installed and which would be Grid-Conned via Eastern Regional Grid to form an unified Smart-Grid System, through which extra renewable energy after fulfilling the consumers demand of Sagar Island will be exported to the conventional National Grid and vice versa when there will be shortage of hybrid renewable energy sources to satisfy the needs of the customers of Sagar Island. Also intermittent supply of SPV and wind energy and other renewable sources should be fully utilized. Deployment of Service-Oriented-Architecture (SOA) will be based on the topology of this Hybrid Renewable Energy Systems and also Grid-Interactive Solar Energy System or Solar-Wind integrated System, which may be distributed but can be mapped for feeding into the National Electricity Grid through proper deployment of SOA.

A smart-energy market where an integrated hybrid energy system of renewables and conventional resources together, with the services of Energy Service Companies (EESCOs) can have impact to reduce CO_2 in the by replacing conventional with renewable. A Smart-

Grid scenario of integrated renewable energy system into the conventional electricity grid can be proposed and in this scenario, service value network of ESCOs in the Super Smart-Grid of Hybrid Energy System enabled with energy efficiency and energy conservation (ENCON) measures can optimize the demand for power in peak demand period to tackle the power failure synchronizing with the suitable location of insolation in case of electricity driven by solar energy resources as for example. A cost proposition of renewable energy resources can have impact to substitute conventional energy resources in the peak load scenario also thereby reducing T & D losses of conventional system ultimately. Supply Chain Network of ESCOs facing challenges which can be resolved bywith the design and testing of common Grid standardized Interface for integrated operations of tapping solar, bio, wind energy resources. Renewables can be coupled with energy efficiency measures along with strong environmental measures to go hand-in–hand with economic and social benefits.

4. Case studies

Case study 1: Objective of the proposed sample project

The Energy Study in Selected Char Villages of Malda to set up a solar power plant to integrate it to the conventional electricity grid with the projected findings of current and future energy demand synchronized with the current and future population along with their growth rate percentage in 2009, 2011 and 2021 respectively.

Sample specifications and features of solar power system

NASA Surface Metrology and Solar Energy Data for Solar Energy Resources is used to find out the exact solar radiation estimation at a particular latitude & longitude of the Malda District of West Bengal. A proposed research background is discussed with an Energy Optimization Model for accessing Market Potential Mappings (MPMs) of solar energy resources specifically through calculating Acceptance Index(AI) [7], [8], [9], [10], [11], considering socio-economic and environmental parameters of utility consumers utilizing NASA Solar Meteorology and Surface Energy Data in the context of East India as an experiment for application of pervasive computing technologies in energy & utility sector for sustainable rural and urban development in the era of future next generation smart-grid [7]. (See Appendix)

Case study 2: Objective of the proposed sample project

To set up reliable Hydro Power Supply System having dual sources of 3 kWe Aero Generator and 3 kWp PV Array for ensuring power supply operations.

Scope of work

The work involves: (a) timely procurement and transportation to site in properly packed condition of all equipment, materials and miscellaneous item required to complete the project; (b) design, manufacture, supply, installation, testing, commissioning and five years trouble free maintenance of two numbers Hybrid Power Supply System to be installed at two different schools under Sagar Block of South 24 Parganas District, West Bengal.

Sample specifications and features of wind-solar hybrid power system

The equipment and materials for Wind-Solar Hybrid Power Supply System shall include but not limited to the following: (a) Aero generator with blades, Gear driver train, shaft, Alternator and Yawing Mechanism; (b) Twisting cable, Tower Control Box with control switch; (c) Hinged type Tower with pin pole, if any; (d) Indoor JB and Control Switch; (e) Guy ropes and Guy anchors; (f) Aero Generator Isolating Switch' (g) PV Modules (Poly/mono crystalline or Thin film); (h) Module Mounting Structures and frames; (i) Module Interconnecting Junction Boxes; (j) PV Array Isolating Switch; (k) Wind-Solar Hybrid Charge controller; (l) Battery Bank; (m) Battery Isolating Switch; (n) Inverter' (o) Inverter Isolating Switch; (p) AC Power Distribution Board; (q) Data Logger with all transducers for measurement of wind, solar, voltage, current, temperature etc.; (r) Cable & Wires; (s) Earthling system including Lighting & Surge Protection arrangement; (t) Civil works for foundation of Tower; (u) Civil foundation for Guy Anchors' (v) Civil work for Foundation of PV Array; (w) Tool Kits; (x) Users Manual; (y) Spares. All civil works associated with the installation and commissioning of Aero Generator System and PV Array shall have to be done by the Contractor.

Case analysis of Moushuni solar PV power plant

West Bengal Renewabl Development Agency (WBREDA) has set up a 53.5 kWp Solar PV Power Plant with an integrated daytime water supply system at village Bagdanga of Moushuni Island. Total population of this island is about 20,000. Primarily 300 families will be benefited with this Power Plant (See Fig. 12). Moushuni Island is a small picturesque island situated near Sagar Island and between Muriganga and Chinai rivers but very close to Bay of Bengal. *(A 20 kW Biomass Gasifier System is recommended to give back-up to this Hybrid Renewables System for a reliable electric supply during shortage of intermittent renewable like solar, wind)*

WBREDA in Eastern part of India is trying to electrify remote isolated islands through hybrid renewable energies. The proposition is to optimize that hybrid renewable energy plants of remote islands so that it can be grid-connected to feed the extra renewable after optimized use at those islands and vice versa. The aim isto design, develop and successfully deploy a modular solution for an existing renewable power plant operated by WBREDA, located at Moshuni Island, in Sundarbans of West Bengal, India.

Objective of the Project: Objective of the Project is (i) To Install Grid Interactive Operation of Hybrid Solar Photovoltaic (SPV), wind, bio-mass System at Moushuni Island; (ii) To ensure the reliability and efficiency of the system to optimize the utilization of the hybrid renewable energy sources; (iii) To design, fabricate and deply reliable power electronic fron-end interface with modular hardware; (iv) This modular hardware is made indigenously for converting power output from multiple small-scale renewable energy sources and storage elements into usuable voltage and frequency levels.

Problems: (i) The existing components in the existing system in Moushuni Islands for tapping sources like solar, biomass, wind etc. are not uniformly designed for integrated operation; (ii) Issues of maintenance, service and spares tend to reduce availibility of theses power plants.

Solutions: All interfaces need to be on a common AC link, which also serves as the feeder to the loads. A universal interface for hybrid renewable energy sources with technology for integrated operation is required.

Technical Features are as follows (i) Maximum Power Point Tracking for wind electric generator (WEG) systems; (ii) MPPT for solar PV panels; (iii) Parallel operation of load side inverters; (iv) Parallel operation of battery chargers.

Input Side Features: The universal 10kW power electronic Basic Interface Module (BIM) with capability to interface with solar panels (variable current, DC), battery bank (fixed voltage, variable current, DC), wind generators (variable frequency, variable voltage AC), AC generator working from bio-mass(variable frequency, variable voltage AC) on the input side.

Output Side Features: The fixed frequency, fixed voltage AC link on the output side.
Control Algorithm: The control algorithm will ensure integrated operation of all the interface modules connected in parallel so as to feed a 20 kW load (Max.), to the feeder. Specific modules will be programmed with suitable control algorithms, which can be used to extract maximum power from a SPV source or WEG. A central controller is proposed to ensure the integrated operation of the power system and to realize user interface. (see Fig. 6).

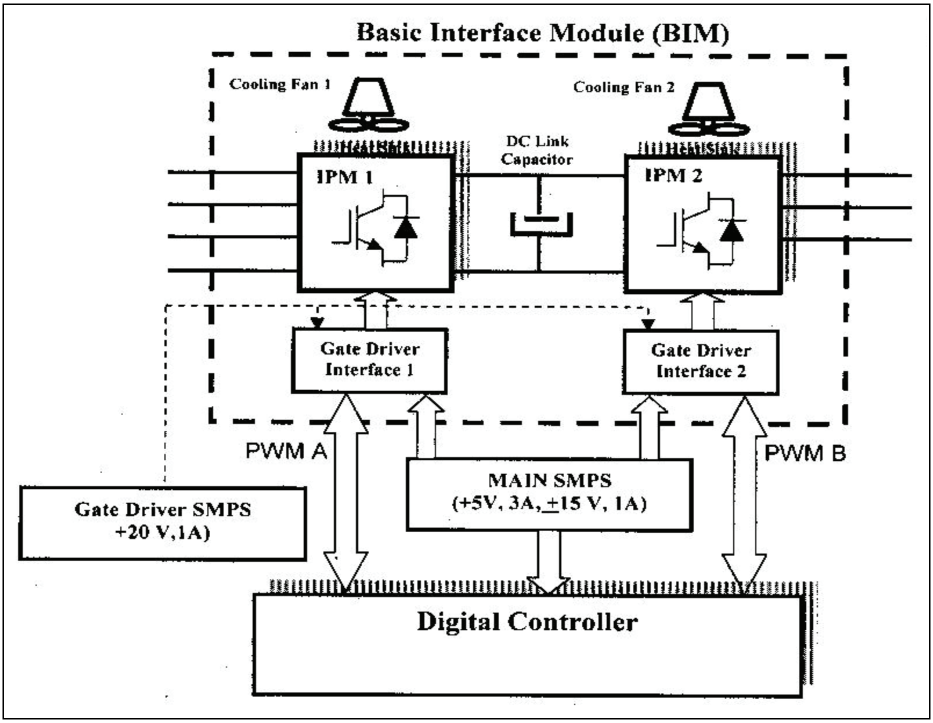


Fig. 6. Scheme of BIM and Digital Controller for Grid-Connected System at Moushuni Islands

Block diagram for BIM, digital controller proposed to be installed at Moushuni Island

Basic Interface Module (BIM): BIM is a back-to-back, three limb, two-level Voltage Source Inverter (VSI) topology sharing a common DC bus. This basic module can be customized through controls to fit the interfacing requirements of the known sources of renewable energy.
Topology for BIM: A four-wire topology needs to be used. As the BIM is proposed to have a three-limb topology, the four-wire AC output is to be realized through delta-star coupling transformers.
Fig. 7, 8 are the illustration for the Basic Interface Module (BIM) & Assembled and Tested units Proposed to be installed at Moushuni Island to control the solar-wind hybrid power plant for optimized use of renewable energy resources generated in the plant throughout the year to be grid-connected if required.

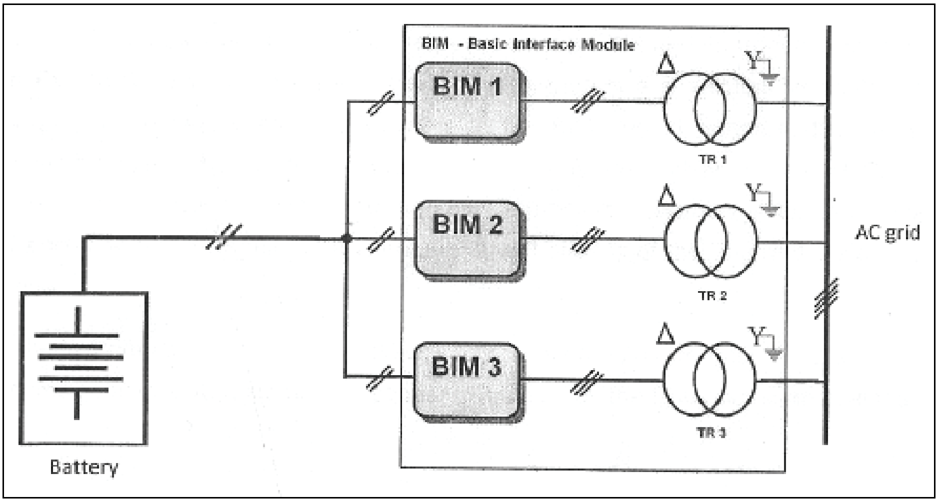


Fig. 7. BIM

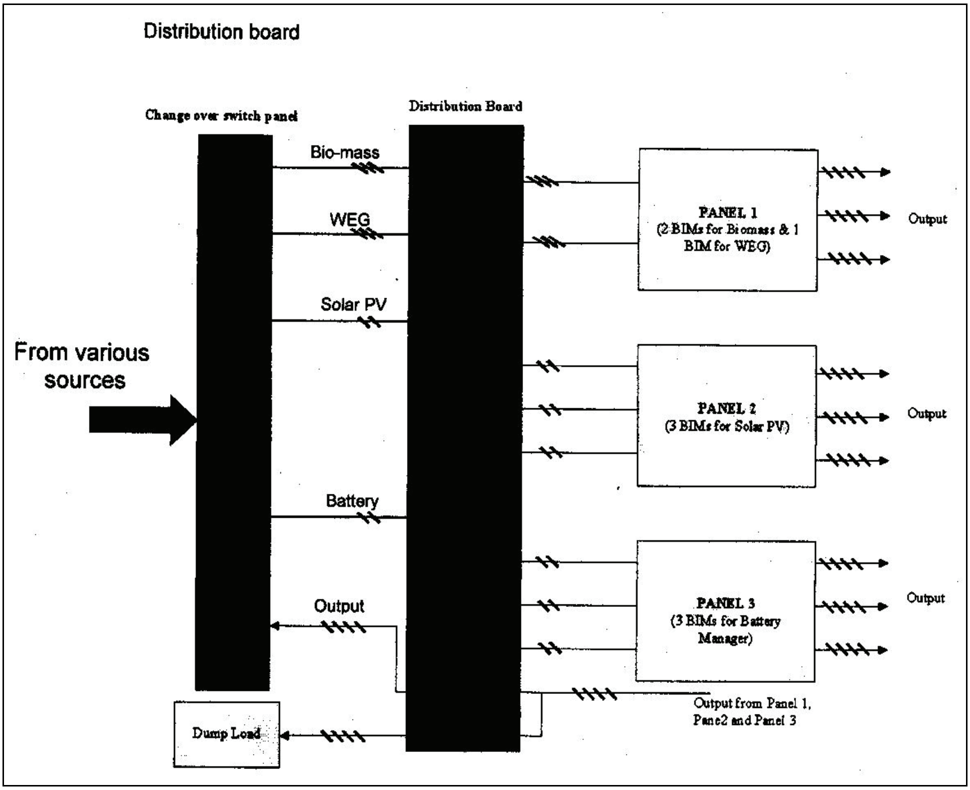


Fig. 8. Assembled and tested units at WBREDA- the illustration of the distribution board

Case analysis of energy scenario at Sagar Island

The island is separated from the mainland by Hooghly and Muriganga rivers and surface transportation is a major bottleneck for development of this area. The journey to Sagar Island from Calcutta involves 90 Km of road journey and 6 Km of boat journey (up to Kachuberia). The total length of black topped, semi metal and unpaved kutcha roads are 35 Km, 49 Km and 464 Km, respectively.
Problem Statements: (i) To reduce the generation cost by adding auxiliary sources of energy; (ii) To eradicate the barriers of non-reliability due to unpredictable availability of renewable energy sources, where wind is more unpredicted in nature than solar; (iii) Biomass is available during monsoon but contains lots of moisture which affects the system, but availability of wind is better in monsoon; (iv) There is no optimized operating zone.

Proposed main activities for the above two cases

(i) A Service-Oriented-Architecture (SOA) can be deployed for the proposed Hybrid Renewable Energy Systems integrating to the National Grid in Eastern Part of India, considering isolated Sundarban Islands, (here Sagar Island & Moushuni Island is considered) [7],[9],[10]; (ii) The similarity between the monthly availability of different renewable resources can be expressed in terms of correlation of hourly energy availability; (iii) Biomass supply chain should be maintained from energy security point of view; (iv) Diesel back-up must be maintained to cater demand in case of shortage of estimated renewable energy.

Decentralized solar energy for village electrification

The parameters for Green Grid in village electrification: The proposes methodology for the Green Grid in village electrification is considering following parameter such as: *(a)* Identification of parameters such as: *(i) Economic:* Cost of product, maintenance and operating cost, prevailing subsidy, tax benefits, benefit due to absence/lesser amount (than fossil-fuel-run equivalent system) of social/scarcity/opportunity cost, resale value, etc. – all in annualized quantities; *(ii) Social:* Energy habit of the customer, social custom, aesthetic value of the product, customers goodwill for reasons such as lowering of pollution by use of these “green systems”, political goodwill/propaganda, population density & accessibility of the location, grid connectivity, etc. and *(iii) Environmental:* Availability of solar radiation and other environmental conditions that would significantly affect the performance of the SPV system in consideration. *(b)* Quantification of each parameter should also take care of three levels of awareness of the target population, such as, **Willingness for Power- A: Very Willing; B: Somewhat Undecided; C: Unwilling. Also considering parameters** *(i) Totally un-aware; (ii) Aware but not yet totally realized;* and *(iii) Totally aware and realized. (c)* A reasonable time frame based on: *(i) Estimated product-life; (ii) The life of the technology;* and *(iii) Other factors* (viz. the dynamic nature of the above mentioned parameters, the replacement frequency that depends on general habit of the users etc.) **Also considering Supply Time-A: 24 Hour Supply; B: Fixed Time Supply; C: Any Time Supply** [see Appendix Table 6 & Table 7 for Sagar Islands for Commercial and domestic Consumers].

Case example of software utilization-SAP-APO for ESCOs

The SAP-Advance Planner & Optimizor (APO), the Supply Chain Management (SCM) initiative by SAP can be recommended in this Service Value Network of ESCOs to meet the challenges of managing the entire supply chain from end-to-end to meet the demand of utility consumers peak demand period as well as in power failure by ESCOs; because with

SAP-APO, SAP combined the ERP executing power of the SAP R/3 system with advanced data analysis [6].

5. Appendixes

Following is the surveyed and tested data for villages under Malda District of West Bengal, India for the project Specified in Case Study 1 with steps as: (i) Table 1 refers, to control the Market Price of Renewables in socio-economic [7] parameters using Algorithm of Acceptance Index(AI) [7], [8], [9], [10], [11]; (ii) Estimated Solar Radiation at a particular Latitude 25 and Longitude 87 provided as a sample at a particular point of the above mentioned Malda District along with, details of climate data at that location of earth throughout the year (See Table 2); (iii) Table 3: Socio-economic pattern of the same population of the above mentioned village; (iv)Table 4: Estimation of Latitude, Longitude, & Elevation in details for each block, gram panchayet under each village of the Malda – West Bengal-India; (v) Table 5: Projected population & energy demand by that population with growth rate percentage in details. Table 6 & Table 7: System Study for Modernization of Distributed Systems at Sagar islands –Load Demand Survey for Commercial & Domestic Consumers for respectively along with the parametes specified.

Acceptance Index (AI)

$$= \frac{\text{Life Cycle Cost of its Competing Conventional System}}{\text{Life Cycle Cost of Proposed System}}$$

Consider Solar Photo Voltaic (SPV) System as Proposed System & Coal Based Thermal Power Plant as Competing Conventional System

Hence, AI of SPV System

$$= \frac{\text{Life Cycle Cost of its Competing Conventional System}}{\text{Life Cycle Cost of Proposed SPV System}}$$

$$= \frac{\text{Life Cycle Cost of Coal Based Thermal Power Plant}}{\text{Life Cycle Cost of Proposed SPV System}}$$

$$\text{CRF} = \frac{d}{i - \left(\frac{i}{i+d}\right)^n}$$

Where CRF: Capital Recovery Factor
d: Discount Rate
n: Life in Number of Years
i: Capital Investment

Life Cycle Cost of Proposed SPV System=Fixed Cost X CRF + Maintenance Cost (Salary and Wages) + Fuel Cost (~0) – Cost of Power Sold – Subsidies

Life Cycle Cost of Conventional Coal Based Thermal Power Plant = Fixed Cost X CRF + Maintenance + Fuel Cost + Social Cost –Cost of Power Sold

Table 1. Algorithm for acceptance index [7], [8], [9], [10], [11]

Sample of NASA Surface Meteorology and Solar Energy Data for Northeast India-Malda District of West Bengal

	Unit	Climate data location	
Latitude	°N	25	
Longitude	°E	87	
Elevation	m	37	
Heating design temperature	°C	12.70	NASA Surface meteorology and Solar Energy: RETScreen Data
Cooling design temperature	°C	31.26	
Earth temperature amplitude	°C	15.95	
Frost days at site	day	0	

Month	Air temperature	Relative humidity	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days	Cooling degree-days
	°C	%	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January	17.6	47.9%	4.25	99.3	1.7	19.3	27	237
February	20.7	43.5%	5.30	99.1	2.1	23.5	2	302
March	25.1	40.4%	6.27	98.7	2.1	28.8	0	465
April	26.6	58.0%	6.70	98.4	2.6	29.8	0	499
May	26.6	76.8%	6.51	98.2	3.0	28.8	0	517
June	27.6	82.9%	5.39	97.8	2.9	28.9	0	527
July	27.4	85.7%	4.39	97.9	2.5	28.3	0	538
August	27.4	84.9%	4.44	98.0	2.1	28.1	0	539
September	26.3	84.3%	4.12	98.4	2.0	27.0	0	493
October	24.2	76.9%	4.86	98.8	1.6	24.9	0	450
November	21.6	57.5%	4.72	99.2	1.6	22.3	0	359
December	18.9	49.3%	4.17	99.4	1.6	20.1	7	284
Annual	24.2	65.7%	5.09	98.6	2.1	25.8	36	5210
Measured at (m)					10.0	0.0		

Table 2. Sample of climate data estimation of solar radiation [10], [11]

Village	name	Pancha-nandapur	Jamai Para	Peyari Pola	Mangadpur
Geographical Area	sq. km				
Gram Panchayet	name	Pancha-nandapur	Pancha-nandapur	Pancha-nandapur	Hamidpur
Population - Male	nos.				
Population - Female	nos.				
Population - Total	nos.	240	126	146	218
Population - School Going Children	nos.	80	36	46	35
Population - SC	nos.		126	101	95
Population - ST	nos.				
Population - Lit. Male	nos.	75	29	55	40
Population - Lit. Female	nos.	46	21	44	21
Population - Lit. Total	nos.	121	50	99	61
Population - Agri /lab	nos.	45	23	29	42
Population - Fishing	nos.	0	1	0	0
Population - Others	nos.	0	2	0	1
Population - Working Total	nos.	45	26	29	43
Total Income	rs.	59000	32700	38800	63700
No of Families	nos.	45	26	29	43
Avr. Income per Family	rs.	1311	1258	1377	1481
Average Monthly Fuel Requirement					
a) kerosene	litres	4.7	2.9	4.9	5.04
b) fuel wood	kg	115.5	85.3	93.1	172.5
No. of Points required					
a) Fan	nos.	55	47	30	71
b) Light	nos.	113	60	59	103
c) TV	nos.	18	19	3	34
Electrical Load					
a) Fan (@ 60 W each)	kw	3.3	1.9	1.2	2.84
b) Light	kw	11.3	6	5.9	10.3
c) TV	kw	4.3	4.5	0.72	8.16
d) Total	kw	18.9	12.4	7.82	21.3
e) Summer (3 Hrs/day for 6 months)	kwh/month	9612	6696	4222.8	11502
f) Winter (3 Hrs/day for 6 months)	kwh/month	9612	6696	4222.8	11502
h) Total (S:1602 ; W:1602)	kwh/year	19224	13392	8445.6	23004

Table 3. Estimation of socio-economic parameters [11]

Block	Gram Panchayet	Char Village	NASA Surface Meteorology and Solar Energy Data		Elevation (ft)
			Latitude	Longitude	
Kaliachak-ii	hamidpur	harutola	24°55'01.45"N	88°01'20.86"E	93
Kaliachak-ii	hamidpur	khatiakana	24°55'17.99"N	88°02'45.23"E	69
Kaliachak-ii	hamidpur	mangadpur	24°57'08.45"N	87°57'15.32"E	97
Kaliachak-ii	hamidpur	janki sorkar	24°54'06.43"N	87°57'19.39"E	75
Kaliachak-ii	hamidpur	sripur	24°53'46.48"N	87°57'19.39"E	78
Kaliachak-ii	hamidpur	hallas tola	24°52'16.43"N	87°57'19.39"E	88
Kaliachak-ii	hamidpur	katlamary	24°51'26.53"N	87°57'19.39"E	85
Kaliachak-ii	hamidpur	jugal tola	24°55'01.40"N	87°52'15.37"E	92
Kaliachak-ii	panchanandapur	sibu tola	24°56'04.00"N	87°59'33.94"E	76
Kaliachak-ii	panchanandapur	jamai para	24°57'05.08"N	87°57'39.98"E	84
Kaliachak-ii	raj nagar	naya gram	24°55'08.27"N	87°51'11.45"E	75
Kaliachak-ii	raj nagar	charbabu pur	24°55'08.27"N	87°51'11.45"E	69
Kaliachak-ii	raj nagar	napitpara	24°55'01.41"N	87°52'12.47"E	97
Manikchak	dakshin chandipur	jitentola	24°03'47.50"N	87°53'12.36"E	95
Manikchak	dakshin chandipur	gudurtola	24°13'01.55"N	87°57'20.36"E	85
Manikchak	dakshin chandipur	raghunathtola	24°15'06.48"N	87°57'25.26"E	79
Manikchak	dakshin chandipur	aaikattola	24°55'01.45"N	87°57'12.36"E	81
Manikchak	dakshin chandipur	master tola	24°55'04.40"N	87°57'39.90"E	88
Manikchak	dakshin chandipur	jagabandhu	25°50'53.61"N	85°57'37.36"E	79
Manikchak	dakshin chandipur	jadutola	25°55'43.55"N	86°55'42.46"E	75
Manikchak	dakshin chandipur	raghu tola	25°51'41.50"N	87°56'47.26"E	81
Manikchak	dakshin chandipur	bhabani tola	24°00'42.74"N	87°57'88.06"E	84
Manikchak	dakshin chandipur	sadhucharantola	24°05'41.75"N	87°57'12.36"E	97
Manikchak	dakshin chandipur	samastipur	25°04'43.61"N	87°47'09.37"E	85
Manikchak	dakshin chandipur	paschimnarayanpur	25°12'58.50"N	87°48'40.51"E	82
Manikchak	dakshin chandipur	kartik tola	25°12'58.50"N	87°48'40.51"E	83
Manikchak	dakshin chandipur	chabilaltola	24°55'25.57"N	87°57'06.73"E	75
Manikchak	hiranandapur	sonar tola	24°49'26.38"N	87°58'13.61"E	90
Manikchak	hiranandapur	nathuram tola	24°55'01.45"N	87°57'12.36"E	76
Manikchak	hiranandapur	rekha tola	24°55'31.35"N	87°51'11.26"E	77
Manikchak	hiranandapur	lalmohan tola	24°55'21.55"N	87°58'42.66"E	78
Manikchak	hiranandapur	ramananda tola	24°55'31.35"N	87°52'32.46"E	94
Manikchak	hiranandapur	natun tola	24°°52'22.45"N	87°50'13.66"E	85
Manikchak	hiranandapur	raghubirtola	24°51'07.45"N	87°51'17.76"E	87
Manikchak	hiranandapur	fulchand tola	25°11'56.40"N	87°55'16.39"E	79
Manikchak	hiranandapur	someswar tola	25°04'40.70"N	87°51'12.52"E	78
Manikchak	hiranandapur	sankar tola	24°55'01.35"N	87°57'12.36"E	87
Manikchak	hiranandapur	fuluktola	24°55'23.45"N	87°57'12.36"E	86
Manikchak	hiranandapur	amirchandtola	24°51'01.45"N	87°57'12.36"E	85
Manikchak	hiranandapur	bipin tola	24°45'01.34"N	87°51'08.26"E	83

Table 4. Estimation of latitude, longitude & elevations [10], [11]

MALDA DISTRICT OF W.B.-INDIA			POPULATION				ENERGY DEMAND (kW)			
BLOCK	GRAM PANCHAYET	CHAR VILLAGE	GROWTH RATE	2009	2011	2021	GROWTH RATE	2009	2011	2021
KALIACHAK-II	HAMIDPUR	HARUTOLA	2.58%	220	231.4984408	298.6585949	3.55%	17.58	18.8503352	26.71899443
KALIACHAK-II	HAMIDPUR	KHATIAKANA		316	332.5159422	428.9823454		20.02	21.46665021	30.4274328
KALIACHAK-II	HAMIDPUR	MANGADPUR		227	238.8643003	308.1613684		21.37	22.91420154	32.47923271
KALIACHAK-II	HAMIDPUR	JANKI SORKAR		222	233.6029721	301.3736731		13.13	14.07877708	19.95565398
KALIACHAK-II	HAMIDPUR	SRIPUR		211	222.02805	286.4407433		12.11	12.98507163	18.40540515
KALIACHAK-II	HAMIDPUR	HALLAS TOLA		174	183.0942214	236.2117978		10.11	10.84055113	15.36570158
KALIACHAK-II	HAMIDPUR	KATLAMARY		183	192.5646121	248.4296494		10.16	10.89416414	15.44169417
KALIACHAK-II	HAMIDPUR	JUGAL TOLA		284	298.8434418	385.5410953		19.01	20.38366735	28.89238249
KALIACHAK-II	PANCHANANDAPUR	SIBU TOLA		204	214.6621906	276.9379698		10.53	11.29090043	16.00403933
KALIACHAK-II	PANCHANANDAPUR	JAMAI PARA		122	128.3764081	165.6197663		10.75	11.52679769	16.33840672
KALIACHAK-II	RAJ NAGAR	NAYA GRAM		273	287.2685197	370.6081655		16.5	17.69229413	25.0775545
KALIACHAK-II	RAJ NAGAR	CHARBABU PUR		169	177.8328932	229.4241025		10.76	11.53752029	16.35360524
KALIACHAK-II	RAJ NAGAR	NAPITPARA		277	291.4775823	376.0383218		16.73	17.93891398	25.42712041
MANIKCHAK	DAKSHIN CHANDIPUR	JITENTOLA	2.05%	178	185.3728045	227.0785492	3.58%	14.71	15.78208892	22.43486977
MANIKCHAK	DAKSHIN CHANDIPUR	RAGHUNATHTOLA		309	321.7988573	394.1981557		24.29	26.06029504	37.04575029
MANIKCHAK	DAKSHIN CHANDIPUR	AAIKATTOLA		207	215.5739918	264.0744927		11.18	11.99481674	17.05111108
MANIKCHAK	DAKSHIN CHANDIPUR	MASTER TOLA		145	151.0059363	184.9797171		11.99	12.86385086	18.28647781
MANIKCHAK	DAKSHIN CHANDIPUR	JAGABANDHU		391	407.1953178	498.807375		27.17	29.15019416	41.43816531
MANIKCHAK	DAKSHIN CHANDIPUR	JADUTOLA		421	438.4379253	537.0790406		32.95	35.35145004	50.25349823
MANIKCHAK	DAKSHIN CHANDIPUR	RAGHU TOLA		157	163.5029793	200.2883833		8.93	9.580833045	13.61953685
MANIKCHAK	DAKSHIN CHANDIPUR	BHABANI TOLA		130	135.3846325	165.8438843		12.19	13.07842719	18.59150663
MANIKCHAK	DAKSHIN CHANDIPUR	SADHUCHARANTOLA		217	225.9881943	276.8317145		16.5	17.70254706	25.16487772
MANIKCHAK	DAKSHIN CHANDIPUR	SAMASTIPUR		339	353.0414648	432.4698213		23.03	24.70846417	35.12406872
MANIKCHAK	DAKSHIN CHANDIPUR	PASCHIMNARAYANPUR		344	358.248566	438.8484322		22.91	24.57971837	34.94105143
MANIKCHAK	DAKSHIN CHANDIPUR	KARTIK TOLA		232	241.609498	295.9675473		14.16	15.19200402	21.59604051
MANIKCHAK	DAKSHIN CHANDIPUR	CHABILALTOLA		283	294.7219308	361.0293788		20.97	22.49832799	31.98227186
MANIKCHAK	HIRANANDAPUR	SONAR TOLA		188	195.787007	239.8357711		9.84	10.55715534	15.00741798
MANIKCHAK	HIRANANDAPUR	NATHURAM TOLA		236	245.775179	301.0704361		13.35	14.32296989	20.36067379
MANIKCHAK	HIRANANDAPUR	REKHA TOLA		255	265.5621638	325.3091576		14.18	15.21346166	21.6265434
MANIKCHAK	HIRANANDAPUR	LALMOHAN TOLA		243	253.0651208	310.0004914		12.98	13.92600369	19.79637047
MANIKCHAK	HIRANANDAPUR	RAMANANDA TOLA		140	145.798835	178.6011061		6.75	7.24195107	10.2947227
MANIKCHAK	HIRANANDAPUR	NATUN TOLA		142	147.8816755	181.1525505		8.38	8.990748143	12.78070759
MANIKCHAK	HIRANANDAPUR	RAGHUBIRTOLA		157	163.5029793	200.2883833		8.93	9.580833045	13.61953685
MANIKCHAK	HIRANANDAPUR	FULCHAND TOLA		176	183.289964	224.5271049		9.23	9.902697537	14.07708008
MANIKCHAK	HIRANANDAPUR	SOMESWAR TOLA		192	199.952688	244.9386599		10.11	10.84683338	15.41920689
MANIKCHAK	HIRANANDAPUR	SANKAR TOLA		126	131.2189515	160.7409955		7.26	7.789120706	11.0725462
MANIKCHAK	HIRANANDAPUR	FULUKTOLA		211	219.7396728	269.1773814		11.23	12.04846082	17.12736829
MANIKCHAK	HIRANANDAPUR	AMIRCHANDTOLA		254	264.5207435	324.0334354		16.54	17.74546233	25.22588348
MANIKCHAK	HIRANANDAPUR	BIPIN TOLA		231	240.5680778	294.6918251		12.32	13.2179018	18.78977536

Table 5. Projected population with growth rate & energy demand [10], [11]

Ref. Location	Rudra nagar Bazar	Rudra nagar Bazar	Rudra nagar Bazar	Rudra nagar Bazar	Rudra nagar Bazar	Rudra nagar Bazar
Name of Establishment	Com.	Com.	Com.	Com.	Com.	Com.
Owner's Name	Pasu pati Das	Bhusan Ch. Maity	Bhava Sankar Pradhan	Barendra Nath Jana	Kali Pada Jana	Barendra Nath Mondal
Business Type	Shop	Shop	Shop	Shop	Shop	Shop
Source of Supply	W.B.S.E.B. (1X25 kVA Tr)	W.B.S.E.B. (1X25 kVA Tr)	W.B.S.E.B. (1X25 kVA Tr)	W.B.S.E.B. (1X25 kVA Tr)	W.B.S.E.B. (1X25 kVA Tr)	W.B.S.E.B. (1X25 kVA Tr)
Connected Load						
Light		2T+3B	2T+2B	5B	10T+2B	8T+3B
Fan		2	1	-	2	2
TV		-	-	-	-	-
Freezes		-	-	-	-	-
Others		1X5A Plug	2X5A	1X5A	1X5A 1X1.5Kw Motor	1X5A
Total Load in kW	0.6	0.58	0.54	0.48	2.86	0.88
Demand Load in kW	0.3	0.39	0.29	0.31	0.89	0.63
Willingness for Power A: Very Willing B: Somewhat Undecided C: Unwilling		A	A	A	A	A
Preferred Supply Time A: 24 Hour Supply B: Fixed Time Supply C: Any Time Supply		A	A	A	A	A
Possible of Expansion of Business with Increased Availability of Power		Yes	Yes	Yes	Yes	Yes

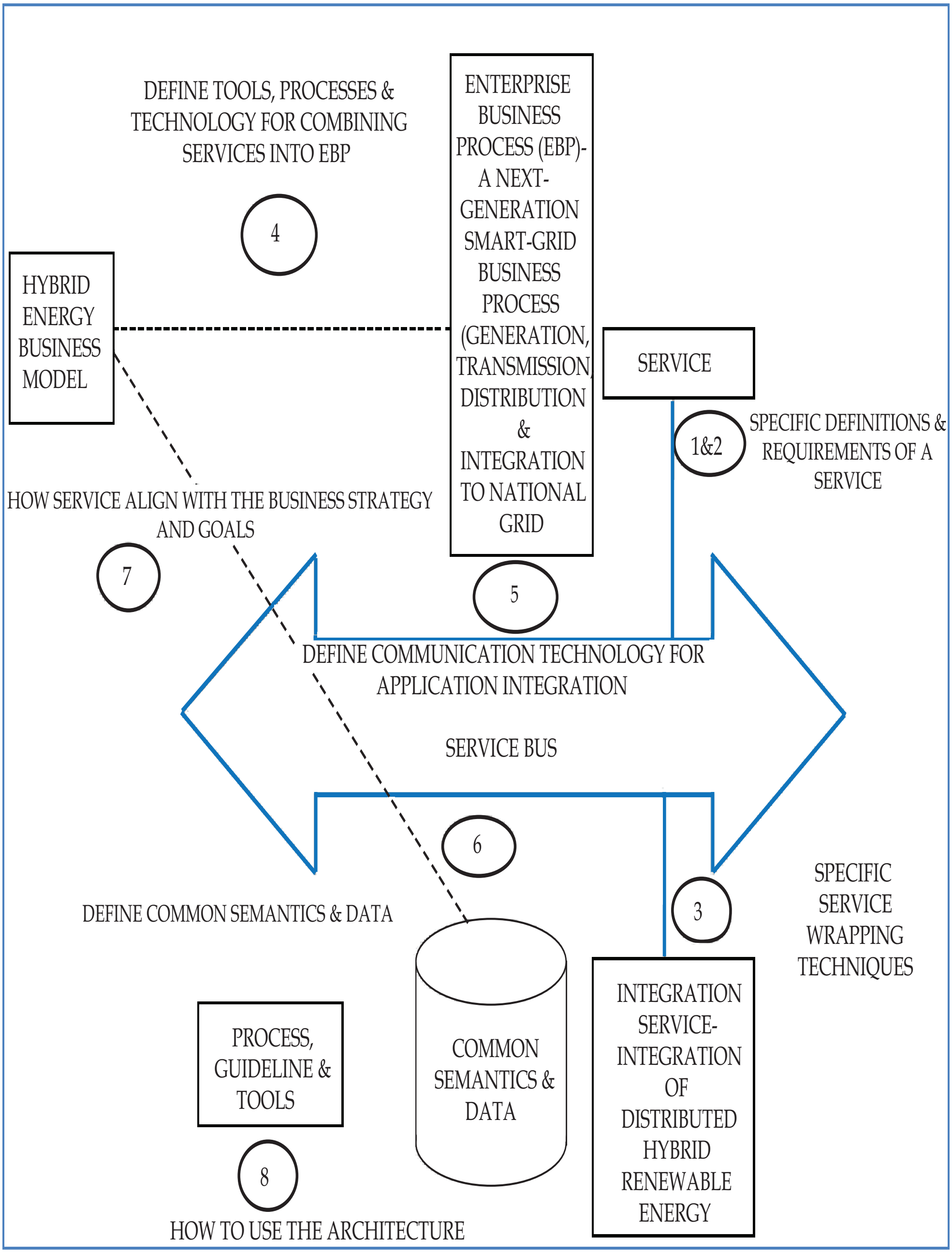
Table 6. System Study for Modernization of Distributed Systems at Sagar Islands –Load Demand Survey for Commercial Consumers [13]

Features of Systems Study as per Table 6 are as below:
Type of the Load: Commercial
Reference Location: Rudranagar Bazar
Source of Supply: (1X25kVA Tr) by West Bengal State Electricity Board (WBSEB)
Parameters Considered: Willingness for Power
A: Very Willing ; B: Somewhat Undecided; C: Unwilling
Preferred Supply Time
A: 24 Hour Supply; B: Fixed Time Supply; C: Any Time Supply

Ref. Location	Rudra nagar Bazar	Rudra nagar Bazar	Rudra nagar Bazar	Rudra nagar Bazar	Rudra nagar Bazar	Rudra nagar Bazar
Name of Consumer	Bhuban Ch. Maity	Mahadev Maity	Nibedar Bera	Sasankya Sekhar Panda	Bala Lal Giri	Dibash Ch Bera
Address	Rudra nagar Chowringhee	Rudra nagar Chowringhee	Rudra nagar Chowringhee	Rudra nagar Chowringhee	Rudra nagar Chowringhee	Rudra nagar Chowringhee
Source of Supply	W.B .S.E.B. (1X25 kVA Tr)	W.B .S.E.B. (1X25 kVA Tr)	W.B .S.E.B. (1X25 kVA Tr)	W.B. S.E.B. (1X25 kVA Tr)	W.B .S.E.B. (1X25 kVA Tr)	W.B .S.E.B. (1X25 kVA Tr)
Connected Load						
Light	3T+2B	1T+2B	5B	3T+5B	4T+4B	5T+7B
Fan	-	-	-	2F	2F	3F
Pumps	-	-	-	-	-	-
TV	-	-	-	-	-	1
Others	2X5A Plug	2X5A	2X5A	3X5A	3X5A	4X5A
Total Load in kW	0.51	0.41	0.58	0.99	.98	1.53
Demand Load in kW	0.23	0.17	0.27	0.47	0.47	0.72
Willingness for Power A: Very Willing B: Somewhat Undecided C: Unwilling	A	A	A	A	A	A
Preferred Supply Time A: 24 Hour Supply B: Variable Time Supply C: Fixed Time Supply (When)	A	A	A	A	A	A

Table 7. System Study for Modernization of Distributed Systems at Sagar Islands –Load Demand Survey for domestic consumers [13]

Features of Systems Study as per Table 6 are as below:
Type of the Load: Domestic; Reference Location: Rudranagar Chowringhee
Source of Supply: (1X25kVA Tr) by West Bengal State Electricity Board (WBSEB)
Parameters Considered: Willingness for Power
A: Very Willing; B: Somewhat Undecided; C: Unwilling
Preferred Supply Time
A: 24 Hour Supply; B: Variable; Time Supply; C: Fixed Time Supply (When)



Source: Adopted from Applied SOA: Service-Oriented Architecture and Design Strategies by Michael Rosen, Boris Lublinsky , Kevin T. Smith , Marc J. Balcer

Fig. 9. A Next-Generation Smart-Grid Perspective of SOA[7], [10]

Fig. 9 depicts a Next-Generation-Smart-Grid perspective of SOA and the numbered circles in this figure correspond to the numbered list as: (1) A definition of services, the granularity, and types of services; (2) How services are constructed and used; (3) How existing packaged and legacy systems are integrated into the service environment; (4) How services are combined into processes; (5) How services communicate at a technical level (i.e., how they connect to each other and pass information); (6) How services interoperate at a semantic level (i.e., how they share common meanings for that information); (7)How services align with the business strategy and goals; (8) How to use the architecture.

6. Acknowledgment

Our sincere thanks to the National Renewable Energy Laboratory (NREL) for incorporating NASA Surface Meteorology and Solar Energy Data. Also our sincere thanks to West Bengal Renewable Development Agency(WBREDA) for their cooperation with useful resources during research.

7. References

[1] The Power to Reduce CO2 Emissions: The Full Portfolio. EPRI, Palo Alto, CA: 2008.

[2] EPRI "Turning on Energy Efficiency," *The EPRI Journal*, EPRI, Palo Alto, CA: Summer 2006.

[3] U.S. Energy Information Administration. "Annual Energy Outlook 2008". Reference Case electricity forecast for Residential, Commercial, and Industrial Sectors.

[4] Website: http://www.bee-india.nic.in-Adderessing Energy Security and Climate Change.

[5] Intergovernmental Panel on Climate Change (IPCC), 2007: Climate Change 2007.

[6] Website: help.sap.com/saphelp_apo

[7] Aurobi Das, V. Balakrishnan, A Next Generation Smart-Energy Technology, Proceedings of the 2nd International Conference on Computer Sciences and Convergence Information Technology (ICCIT 09), ACM International Conference Proceeding Series; Vol. 403

[8] Aurobi Das, V. Balakrishnan, Analysis of Critical Problems In ERP Implementation to Enhance Service Oriented Architecture (SOA) for Energy & Utilities-A Case Study, Proceedings of the Enterprise Information Systems International Conference on Research and Practical Issues of EIS (CONFENIS 2009) at Gyor, Hungary.

[9] Aurobi Das, V. Balakrishnan, Analysis of Critical Problems In ERP Implementation to Enhance Service Oriented Architecture (SOA) for Energy & Utilities-A Case Study; SEFBIS Journal No. 3. (2009): Professional Journal of the Scientific and Educational Forum on Business Information Systems; Editor: SEFBIS (GIKOF) Community of the John von Neumann Computer Society (NJSZT), ISSN 1788-2265

[10] Aurobi Das, V. Balakrishnan, A Next Generation Smart-Energy Technology, International Journal on Research and Innovation: Advances in Information Sciences and Service Sciences(AISS), Vol 2, June 2010

[11] Aurobi Das, V. Balakrishnan, Energy Service Companies (ESCOs) to Optimize Power in Peak Demand Period in Hybrid Energy System- An Impact on Climate Change, Proceedings of the 2nd IEEE Green Technology Coferernce, 2010 at Dallas, Texas

[12] Enterprise SOA Development Handbook, Enterprise Services Enhancement Guide

[13] West Bengal Renewable Development Agency (www.wbreda.org) & West Bengal State Electricity Distribution Company Limited (www.wbsedcl.in)

6

The Value of Supply Chain Finance

Xiangfeng Chen and Chenxi Hu
School of Management, Fudan University
China

1. Introduction

In traditional study of supply chain management, people mainly consider the decisions from perspective of the operations management, such as, capacity, inventory, ordering level, pricing, etc., and often ignore to consider the impact of financial flow within the supply chain. However, the key function of supply chain management is concerned with the coordination of material flows, information flows, and funds flow (Figure 1). Therefore, the operation decisions of a firm is affected by its own initial capital status. For instance, with the globalization and international competition intensified, many companies have experienced a shortage of capital. The constrained capital of a company could affect the funds flow in the supply chain, and the performance of the entire supply chain as well.

In global supply chain, and especially in the post-financial-crisis era, capital constraints are strengthened by common cash-management practices that promote collecting account receivable as quickly as possible while postponing payments to providers and suppliers. This "war for cash" (Milne, 2009) is squeezing small companies harder—these cash-strapped companies find themselves faced with increasing chances of going out of business. Also, the fact that large buyers are forcing suppliers from less developed countries to move to open account has further contributed to the problem of cash flow (UPS Capital, 2007). Consequently, a company with capital constraints who cannot raise funds from bank credit channel or other's channel could hurt its own profit as well as that of the entire supply chain.

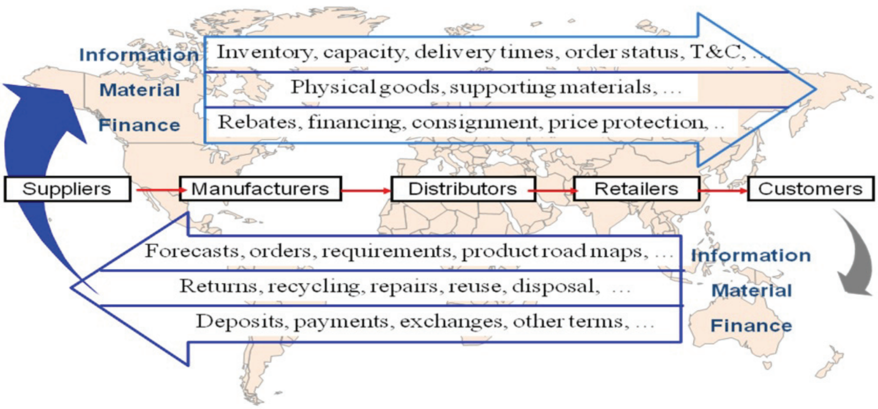


Fig. 1. Three types of flows in the supply chain

How to solve this grave problem of capital constraints in the supply chain in developing or developed economics? To answer this question, this chapter sheds some light on how Supply Chain Finance (SCF) impacts agents' operational and financial decisions under the symmetric/asymmetric information and how SCF can create value for supply chain with capital constraints. In this chapter, we define SCF as the jointly operations/logistics and financing service, offered by a 3PL firm (Control Role), or an alliance of 3PL firm (Delegation Role) and financial institution (i.e., bank), etc. On one hand, SCF is a financing service which can relax the capital constraints in the supply chain; on the other hand, SCF is combined with a logistics service or trade transaction service.

Different from traditional commercial loans which rely on fixed assets as the securities, SCF commonly depends on the liquid asset, such as inventories, accounting receivables or others, as the collateral. Since the bank does not have the resources to track or monitor the status of liquid assets, the bank could refuse to offer financing service with liquid assets as the collateral. Instead, the bank prefers to offer the fixed asset based financing. Unfortunately, the small-medium size firms are often of limited fixed asset, and could not raise funds from the bank by fixed-asset-based-financing. Even the development of Globalization and Outsourcing has resulted in fewer assets for the firms in the supply chain, making it more difficult for firms to borrow funds secured by fixed-based-financing. Then, SCF, as an innovative financing solution, bridges the bank and capital-constrained firms in the supply chain, reduces the mismatch risk of supply and demand in the financial flow, and creates value for supply chain with capital constraints.

Based on the definition of SCF, the 3PL firm plays an important role in SCF, since it is able to have access to various information generating from supply chain's activities, and then marry this information with the material flow. Consequently, the coupling of information and material flows enable lenders (i.e., banks) to mitigate financial risk within the supply chain, and then reduce the credit risks of financing service. The mitigation of financing risk allows the capital-constrained firm in the supply chain more capital to be raised, capital to be accessed sooner or capital to be raised at lower rates[1].

Before characterizing the value of SCF in the supply chain with capital constraints, we further illustrate the meanings of SCF by the following three examples in real business operations (Caldentey and Chen 2010, Chen and Wan 2011, Chen and Cai 2011).

Chinese Material Shortage Transportation Group (CMST) is one of the largest logistics enterprises in China. Many small and medium size paper manufacturers in mainland China purchase materials from international suppliers. It is not uncommon that the financial system is unable to provide adequate services to support these manufacturers though they are short of capital. As a result, most of these small manufacturers find themselves making suboptimal procurement decisions. CMST viewed this gap as a business opportunity and, since 2002, started financing these small paper manufacturers to buy paper materials from international suppliers while simultaneously providing the logistics services required in these transactions. Under this credit contract, the paper manufacturer pays a fraction of the wholesale price charged by the supplier as a deposit and CMST covers the difference. After the sale season, the manufacturer repays CMST the remaining fraction of the wholesale price. With this supply chain financing service, CMST has become one of the leading

[1] We refer the reader to read UPS Captal Global Supply Chain Finance in 2007.

logistics-financing service providers in China. In 2006, CMST financing supply chain business was about 1.1 billion dollars, up from 750 million dollars in 2005. Currently, this operation is one of most popular modes of financing for small-and-medium companies in China. As the CMST example unveils, bringing financing services into supply chain management has the potential to improve the operational efficiency and the profits of the entire supply chain.

In an example of a mobile-phone supply chain in China, a manufacturer sells mobile-phones to end-users via retailers. Although demand for the mobile phones is high, many retailers can order only a limited number of mobile phones from the manufacturer because of limited cash. Hence, the capital constraints of retailers strongly influence both the retailers' and manufacturer's revenue, as well as the performance of the entire supply chain. With the above situation taken into consideration, the manufacturer built an alliance with a local bank to motivate the bank to offer commercial loans to those capital-constrained retailers. This practice achieved great success and the manufacturer attained its largest market share in 2002. Since then, many mobile-phone manufacturers in China have started to cooperate with banks to help capital-constrained retailers make loans from banks to increase their revenue. As discussed above, capital constraints may influence the operational decisions in a supply chain while financing may relax the constraints with additional costs (usually in form of interest). Therefore, it is important to know how financing influences the operational decisions and performance of individual firms in a capital-constrained supply chain, and how a retailer jointly makes operational and financial decisions under capital constraints.

Financing support from banks could facilitate capital-constrained companies greatly. A professional aluminum ingots trading company grew from less than 5 million Yuan to over 600 million Yuan in one year, with the aid of a goods-ownership mortgage loan (50 million Yuan) from Shenzhen Development Bank. However, not all companies could get as lucky as the one in this case. Banks might not be willing to provide financing service for it's difficult for them to monitor the transactions of the products. Thus, without accurate real-time information about the transactions, banks would have to figure out some way to keep the capital-constrained companies from diverting the loan to other riskier projects. Here comes the *integrating logistics and financing service (ILFS)*, through third party logistics (3PL) firms that ally with financial institutions and provide cooperative logistics and financial solutions to capital-constrained retailers. The benefits of ILFS are absolutely worth discussing.

These examples show that SCF plays an important role in the real business. However, the research on SCF is very limited in the literature. The motivation of this chapter is to make a first step on the research about this field.

The rest of this chapter is organized as follows. We review the literature in Section 2. Under the symmetric information, we inspect the value of financing service to the supply chain with capital constraints, and examine the jointly operations and financing decisions for the agents, in Section 3. We then model to highlight the value of 3PL firm in SCF under asymmetric information, and analyze how SCF could create more value for supply chain in Section 4 and 5. We conclude in Section 6.

2. Literature review

Our work is relative to the interface research of operations and financial management. In this section, we firstly review the related work in the economic and financial area;

secondly, we further review the current research of operations/finance track; finally, we analyse the related work in which 3PL firm plays a role in supply chain's financing service.

Economics research has shown that a buyer's budget constraints may influence the optimal mechanism of supply/procurement contract. In this vein, Levaggi (1999) develops a principal-agent model in which the principal (a buyer) faces a binding budget constraint, and argues the budget constraint does not guarantee that the principal is always better off if an incentive compatible contract is used. Hence the likely outcome is either a pooling or a bargaining solution. Che and Gale (2000) argues that a buyer's budget constraint may make it optimal for the seller to use non-linear pricing, to commit to a declining price sequence, to require the buyer to disclose her budget, or to offer financing. Simchi-Levi and Thomas (2002) study the non-linear pricing problem when a budget constraint limits the magnitude of monetary transfer. The literature examines only the operational decisions, and does not consider the interaction between operational decisions and financial decisions. In this chapter, we study the supply chain management problem in which the retailer is capital-constrained, thus involving both financial decisions and operational decisions simultaneously.

In finance literature, researchers mostly study a firm's integrated investment decision which influences its capacity sizes and debt decisions, and implicitly study a firm's integrated operational and financial decisions. For example, Dotan and Ravid (1985) show that the investment and optimal financial decisions have to be made simultaneously and that a negative relationship exists between capacity expansion and the financial leverage. Dammon and Senbet (1998) analyse how the corporate and personal taxes influence a firm's optimal investment and financial decisions under uncertainty. They show that, when investment (equity investment) is allowed to adjust optimally, the existing prediction about the relationship between investment-related and debt-related tax shields must be modified. Mello and Parsons (1992) compare the operational decisions of a mine under all-equity financing policy with those mines of partial financing to maximise leveraged equity value. Mauer and Triantis (1994) analyse the case where the firm has the flexibility to shut down or reopen its production facility in response to price fluctuations. In contrast to the literature in economics and finance, this chapter incorporates the financial decisions into operational decisions more directly and analyses the interactions between financial and operational decisions.

In the literature on supply chain management, researchers are mostly concerned with the material flow and often ignore the impact of the financial flow. For instance, in Graves and Ton (2003) and Simchi-Levi et al. (2004), the mostly studied problems include production planning/inventory control, capacity expansion and performance of supply chains. However, financial flows are important in real-world supply chain management. Caldentey and Haugh (2005) argue that budget constraints are quite common in practice due to many reasons.

Recently, more and more studies in operations management have started to look at the interface between operations and financial management. Chen and Wan (2011) reveal how supply chain could benefit from financing services, compared to the situation without financing services. However, most literature is concerned with the integrated operational and financial decisions based on retailer's behaviour/strategy in a supply chain under symmetric information. For instance, most literature focuses on discussion of the budget-constrained firm's production/inventory or capacity decisions and debt decisions, and seeks to demonstrate that it is important to incorporate financial decisions into operational decisions. Buzacott and Zhang show the importance of joint production and financial decisions in a start-up setting, where the firm's growth capability is mainly constrained by its limited capital and depends on bank loans. They use a single period newsvendor model to explain the motivation for asset-based financing by analysing the decision-making at a bank and a set of retailers with different budgets. Hu and Sobel (2005) use a dynamic newsvendor model with a criterion of maximising the expected present value of dividends to analyse the interdependence of a firm's capital structure and its short-term operational decisions involving inventory, dividends and liquidity. Chao et al. (2008) use multi-period inventory models to provide insights into the interaction between financial and operational decisions, and shows that it is essential for the retailers to take financial considerations into their operational decisions, especially for the retailers who are short of capitals. Boyabatli and Toktay (2006) analyse the impact of capital market imperfection on a firm's operational and financial decisions in a capacity investment setting, where the firm's limited budget, depending partly on a tradable asset, can be increased by borrowing from external market (commercial loan collateralised by physical asset), and its distribution can be altered with financial risk management (using forward contract to reduce the financial risk of tradable asset). However, all literature except for Buzacott and Zhang (2004) assume the interest rate of a loan is exogenous, ignoring the impact of competition of financial market or borrowing level on the interest rate of loan. Buzacott and Zhang (2004) consider the bank's decision on the interest rate but their optimal interest rate is independent of the competition in a financial market.

Although currently an increasing number of literature considers the jointly operations and financial decisions in the supply chain management area, limited literature characterises the value of SCF or the role of 3PL firm in the supply chain with capital constraints. Hofman (2005) introduces some conceptual insights of supply chain finance, and help the executives to look behind the SCF approach. To the best of our knowledge, among the first to examine the value of 3PL firm's integrated logistics and financing service is the paper by Chen and Xie (2009). They use the model to show that if 3PL firm offers the conventional logistics service, the budget-constrained retailer may not apply for loans successfully because of the asymmetric information, and also show that a monopolistic or competitive financing market can create value for budget-constrained supply chain. Lu et al. (2009) inspect the incentive of logistics service provider (LSP) for a 3PL firm to provide financial support to the retailer/supplier and to establish the backup inventory. Chen and Cai (2010) investigates an extended supply chain model with a supplier, a budget-constrained retailer, a bank, and a 3PL firm, in which the retailer has insufficient initial budget and may borrow or obtain trade credit from either a bank (traditional role) or a 3PL firm (control role). Their analysis indicates that the control role model yields higher profits not only for the 3PL firm but also for the supplier, the retailer, and the entire supply chain.

In order to inspect the value of supply chain finance, in this current chapter we would mostly summarize some of the results and highlights from Chen and Wan (2011), Chen and Xie (2009), and Chen and Cai (2011). This chapter emphasizes on understanding of SCF and 3PL firm's value in the capital-constrained supply chain.

3. Model description and assumptions

We consider a simple supply chain with a supplier and a retailer. The supplier produces a single product which retailer sells to customers. Demand D is a nonnegative random variable with a cumulative distribution function $F(D)$. We define the Hazard Function $h(D) = f(D)/\bar{F}(D)$ and the Generalized Failure Rate (GFR) $H(D) = Dh(D)$, where $\bar{F}(D) = 1 - F(D)$ is the tail distribution of $F(D)$. We also impose the following assumption to guarantee the existence and uniqueness of the equilibrium of our model.

Assumption A1: The demand distribution function $F(D)$ has the following properties:

i. It is absolutely continuous with density $f(D) > 0$ in (a, b), for $0 \le a \le b \le \infty$.

ii. It has a finite mean $\bar{D}$.

iii. The generalized failure rate $H(D)$ is increasing in $D \ge 0$ (IGFR).

We discuss the situation with symmetric information (i.e., all information is common knowledge to both the supplier and the retailer) first (and asymmetric information will be mentioned later). In particular, we assume the supplier and the bank know the retailer's initial capital B, the demand probability distribution $F(D)$, and the retail price p. We use superscripts, B, R and S to denote the bank, the retailer, and the supplier, respectively, and use subscripts F or NF to denote the case the retailer does or does not have the chance to raise funds from a competitive financial market, respectively.

A feature of our model is the introduction of an initial capital constraint on the retailer, which may limit her order levels. We assume the retailer has an initial capital B for ordering products from the supplier while the supplier has no capital constraints (i.e., he has sufficient working capital to pay for the manufacturing costs). Furthermore, we assume that all parties (the supplier, the retailer, and banks) are risk-neutral. Based on the financial "pecking order" theory, we also assume the retailer uses up all her capital before considering making a loan from a bank. Let the risk-free interest rate of the financial market be r_f . The banks are always willing to finance the retailer for purchasing products with an interest rate r_F (B), and act competitively such that the expected return on a loan is equal to the expected return with the risk-free interest r_f . Here, r_f can be regarded as the average return on investment in the competitive financial market. Therefore, r_f can be used to measure competition of services in the financial market. The lower the risk-free interest rate r_f, the stronger the competition in the financial market. For example, the financial market has the strongest competition when $r_f = 0$. Intuitively, many banks competing sufficiently in the financial market could lead to the result that the average return on investment for the financial market be reduced to (normalized) zero.

Due to the popularity of the wholesale price contract in both academics and practice, we consider a capital-constrained supply chain with financing service under such a contract. In our model, we assume the following sequence: At the beginning of the period $(t = 0)$, the supplier offers a wholesale price contract (w), an exogenous variable, to the retailer, then the retailer decides to accept or reject the contract; If the retailer accepts the contract and chooses ordering quantity $Q_F(w)$, she may also make a commercial loan from the bank; Learning $Q_F(w)$, the bank announces the interest rate $r_F(B)$ for the loan that amounts to $(wQ_F(w) - B)^+$, where $(x)^+ = \max\{x, 0\}$; The retailer borrows loan $(wQ_F(w) - B)^+$ from the bank and pays the amount $wQ_F(w)$ to the supplier for her order; The supplier produces and deliveries to the retailer before the selling season. At the end of the period $(t = T)$, demand is realized. The revenue is equal to $p \min\{D, Q_F(w)\}$, where p is a fixed retailer price, and finally a payment $((wQ_F(w) - B)^+(1 + r_F(B)))$ is made by the retailer to the bank. Certainly, if the retailer rejects the contract, the game ends and each firm earns a default payoff. Neither a salvage value nor a return policy for unsold units is assumed in our model.

Before we inspect the 3PL firm's role, we model the game between the bank and the retailer in this current section.

3.1 The bank

Assume banks in the financial market have enough cash for loans. At time $t = 0$ (i.e., beginning of selling season), the retailer makes an order quantity $Q_F(w)$ in response to the wholesale price contract w chosen by the supplier, and a bank may announce a loan contract ($r_F(B)$) to the retailer, whose initial capital is B, for loan size $(wQ_F(w) - B)^+$. With the support of a loan from the bank, the retailer is able to make the full payment to the supplier. At time $t = T$ (i.e., the end of the selling season), the loan generates a random payoff $\mathcal{L} = p\min\{D, Q_F(w)\}$ for the retailer, and revenue for the bank is equal to $\min\{\mathcal{L}, L(B)(1 + r_F(B))\}$, where $L(B) = (wQ_F(w) - B)^+$. If revenue $\mathcal{L}$ falls below the sum of the principle and the interest of a loan (i. e., $L(B)(1 + r_F(B))$), then the retailer may declare a bankruptcy, and the bank suffers a loss from the loan. Otherwise, the bank makes an expected profit $L(B)r_F(B)$ as a return on the loan.

From previous assumption, the bank is risk-neutral and operates in a competitive financial market, it will set an interest rate $r_F(B)$ that yields the expected profit. The profit is equal to the one generated by a risk-free interest rate r_f in the competitive financial market. Intuitively, under the risk-neutral assumption, banks are indifferent to risks, and the payoff of risk- free capital and the return of financing service are identical. Hence, the interest rate on a loan is determined by the following equation:

$$L(B)(1 + r_f) = E\left[\min\{\mathcal{L}, L(B)(1 + r_F(B))\}\right] \quad (1)$$

Here, the bank evaluates the credit risk of loans based on the retailer's initial capital. The assumption of competitive financing is also found in the previous literature in economics, finance, and operations field, such as, Brenna et al. (1988), Dotan and Ravid (1985), Xu and Birge (2004), etc..

3.2 The retailer

The impact of the retailer's limited initial capital on the execution of the wholesale price contract is twofold. First, the order quantity placed at $t = 0$ could satisfy the capital constraint $B \le wQ_F(w)$. Second, if demand D is too low, then the retailer is unable to pay the bank the full amount $(wQ_F(w) - B)^+(1 + r_F(B))$ that is due at time T. In this case (occurring if $p\min\{D, Q_F(w)\} < (wQ_F(w) - B)^+(1 + r_F(B))$), the retailer declares bankruptcy and the bank collects only $p\min\{D, Q_F(w)\}$ instead of $(wQ_F(w) - B)^+(1 + r_F(B))$. In this case we say the retailer has limited liability.

For a given wholesale price contract (w), the capital-constrained retailer with an initial capital B chooses order quantity $Q_F(w)$, and may raise funds $(wQ_F(w) - B)^+$ from the bank under the interest rate $r_F(B)$. Then, the retailer's net expected payoff is a function of $Q_F(w)$ and defined as:

$$\pi_F^R(Q_F(w)) = E\left[\left(p\min\{D, Q_F(w)\} - (wQ_F(w) - B)^+(1 + r_F(B))\right)^+ - B\right],$$

where $E[\cdot]$ denotes the expectation with respect to F(D). Note that in the definition of $\pi_F^R(Q_F(w))$ the initial capital B is subtracted from the retailer's profits. Hence, $\pi_F^R(Q_F(w))$

measures the net profit the retailer obtains by operating in this supply chain. For example, if the retailer chooses Q_F (w) = 0 then her net payoff is zero, reflecting the fact that she gains nothing from her business. The retailer's optimal net expected payoff is obtained by solving the following program:

$$\begin{aligned}\Pi_F^{R*}(B) &= \max_{Q_F(w)\geq 0} \pi_F^R\big(Q_F(w)\big) \\ &= \max_{Q_F(w)\geq 0} E\left[\big(p\,min\{D, Q_F(w)\} + B - wQ_F(w) - L(B)r_F(B)\big)^+ \right. \\ &\left. - B\right] \end{aligned} \tag{2}$$

subject to:

$$L(B) = (wQ_F(w) - B)^+ \tag{3}$$

It is worth noting that the positive part in the definition of Π_F^{R*}(B) captures the retailer's limited liability in the case of bankruptcy. Here we implicitly assume the retailer has no other investment opportunity except her retailing business. This is to clearly show the financing service (represented here by banking loans) is a value generating activity.
Notice that when the retailer cannot have the access to the financial market, the optimization problem for her is then given by:

$$\Pi_{NF}^{R*}(B) = \max_{Q_{NF}(w)\geq 0} E\left[p\,min\{D, Q_F(w)\} - wQ_{NF}(w)\right] \tag{4}$$

subject to:

$$0 \leq wQ_{NF}(w) \leq B \tag{5}$$

If the retailer does not have capital constraints, the capital constraint (5) is redundant and has no impact on the retailer's order decisions. Hence, (4) becomes a standard newsvendor problem and the optimal order level is given by $Q^N(w) = \bar{F}^{-1}\left(\frac{w}{p}\right)$. However, if the initial capital is not sufficient to support optimal ordering (i.e., $\frac{B}{w} < Q^N(w)$), the capital constraint (5) is active and the retailer cannot achieve her optimal order level. (4)-(5) indicate the retailer's capital constraints may influence her order level. Depending on the tightness of the constraints, the effects can be significant. Therefore, when the retailer has no access to the financial market, the optimal order policy for the retailer with capital constraints is $Q_{NF}^*(w) = \min\{\frac{B}{w}, Q^N(w)\}$.
In the following section, we should analyse how the financing service has the impacts on the performance of supply chain with capital constraints under symmetric information.

4. Financing service and supply chain's performance

Based on the assumptions in Section 3, under the case where the retailer has access to a financial market, and then chooses order quantity $Q_F(w_F)$ for an exogenous wholesale price w_F from the supplier. Noting that when the retailer orders $Q_F(w_F)$, the bank immediately announces an interest rate r_F (B).
We proceed backwards to derive the equilibrium in the competitive finance market and the supply chain. Firstly, we determine the interest rate r_F^* (B) by solving Eq. (1); Secondly, we

compute the retailer's best response as a function of a strategy chosen by the supplier by solving the retailer's optimization problem in (2)-(3) to find $Q_F^*(w_F, r_F^*(B))$ for a fixed wholesale price (w_F) and a given $r_F^*(B)(B)$.

4.1 Supply chain performance without financing service

In the following discussion we assume the retailer has no access to financial markets as a benchmark for comparison, to address the motivation of financing services from a competitive financial market.

Recall that the optimal order problem without the financing service for a retailer who has capital constraints in (4)-(5) is:

$$Q_{NF}^*(w_{NF}) = min\left\{\frac{B}{w_{NF}}, \bar{F}^{-1}\left(\frac{w_{NF}}{p}\right)\right\}$$

In the setting in which retailers cannot have access to the financial market, the optimal ordering level for the retailers Q_{NF} is $Q_{NF}^*(w) = min\left\{\frac{B}{w}, \bar{F}^{-1}\left(\frac{w}{p}\right)\right\}$. When $B \le w\bar{F}^{-1}\left(\frac{w}{p}\right)$, $Q_{NF}^*(w) = \frac{B}{w}$; When $B > w\bar{F}^{-1}\left(\frac{w}{p}\right)$, $Q_{NF}^*(w)$ is the constant value of $\bar{F}^{-1}\left(\frac{w}{p}\right)$. Obviously, without the support of financing service from financing market, the capital-constrained retailer is not able to make an optimal ordering level in the traditional newsvendor model, $Q^N(w) = \bar{F}^{-1}\left(\frac{w}{p}\right)$, and leads to the loss to the supply chain performance.

4.2 Supply chain performance with financing service

Different to the previous subsection, we consider that the capital-constrained retailer has access to a competitive financing market during the operations of supply chain. We should show how the financing service affects the supply chain performance.

The decisions of bank

Recall the assumption of financing market in Section 3, by (1), the bank may determine the optimal interest rate $r_F^*(B)$ as follows:

$$(w_F Q_F(w_F) - B)^+(1 + r_f) = E\left[min\left\{\mathcal{L}, (w_F Q_F(w_F) - B)^+\left(1 + r_F^*(B)\right)\right\}\right] \qquad (6)$$

We can show the existence and uniqueness of $r_F^*(B)$ by the following reason, for any $r_f \ge 0$, any scalar $y \ge 0$, and any random variable $\mathcal{L} \ge 0$, there exists a unique $r \ge r_f$ such that $y(1 + r_f) = E[min\{\mathcal{L}, y(1 + r)\}]$ if and only if $E[\mathcal{L}] \ge y(1 + r_f)$. (Refer to Chen and Wan 2011).

Consequently, , let y be the loan size $L(B) = (w_F Q_F(w_F) - B)^+$, $r = r_F^*(B)$, and let L be the retailer's random revenue $p\min\{D, Q_F(w_F)\}$, then if the condition $E[\mathcal{L}] \ge (w_F Q_F(w_F) - B)^+(1 + r_f)$ holds, we can obtain a unique interest rate $r_F^*(B) > r_f$ by solving the equation $(w_F Q_F(w_F) - B)^+(1 + r_f) = E\left[\min\left\{\mathcal{L}, (w_F Q_F(w_F) - B)^+\left(1 + r_F^*(B)\right)\right\}\right]$. Furthermore, we can derive the optimal interest rate for a bank as follows.

For a given order level $Q_F(w_F) \ge 0$ and $c \le w_F \le p$, the retailer with an initial capital B may make a loan $(w_F Q_F(w_F) - B)^+$ from a bank in the competitive financial market, with a risk-free interest rate $r_f \ge 0$. If the capital-constrained retailer has limited liability, then:

i. there exists a unique interest rate $r_F^*(B)$ charged by the bank satisfying the following equation: $(w_F Q_F(w_F) - B)^+(1 + r_f) = E\left[\min\left\{\mathcal{L}, (w_F Q_F(w_F) - B)^+\left(1 + r_F^*(B)\right)\right\}\right]$;

ii. $r_F^*(B)$ is monotonically increasing when retailer's initial capital B decreases;
iii. for a fixed initial capital B, $r_F^*(B)$ increases with the risk-free interest rate r_f .
The above characteristics of $r_F^*(B)$ can be illustrated by Figure 2.

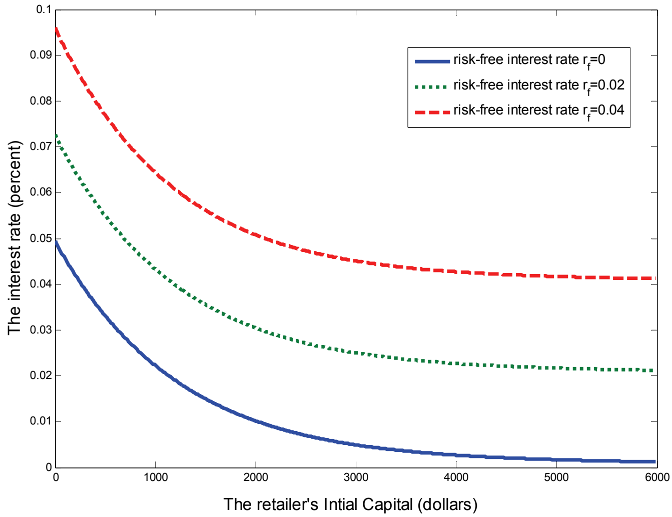


Fig. 2. The relationship between interest rate $r_F^*(B)$ and B, r_f

The decisions of retailer

If the wholesale price contract is w_F, then the retailer may make a loan of $L(B) = (w_F Q_F(w_F) - B)^+$ with an interest rate $r_F^*(B)$ from a bank in the financial market. By the decisions of the bank, we can show that the sufficient and necessary condition for the existence of a loan is $pE[\min\{D, Q_F(w_F)\}] \geq (w_F Q_F(w_F) - B)^+(1 + r_f)$. Therefore, the retailer's optimization problem with financing service (2)-(3) can be formulated as:

$$\Pi_F^{R*}(B) = \max_{Q_F(w_F)\geq 0} E\left[\left(p\min\{D, Q_F(w_F)\} + B - w_F Q_F(w_F) - L(B) r_F^*(B)\right)^+ - B\right]$$

subject to :

$$L(B) = (w_F Q_F(w_F) - B)^+$$

$$pE[\min\{D, Q_F(w_F)\}] \geq (w_F Q_F(w_F) - B)^+(1 + r_f) \qquad (7)$$

$$L(B)(1 + r_f) = E\min\left[p\min\{D, Q_F(w_F)\}, L(B)\left(1 + r_F^*(B)\right)\right]$$

We can rewrite the constraint in Eq. (7) as follows

$$E[\min\{p\min\{D, Q_F(w_F)\} - L(B)(1 + r_f), L(B)(r_F^*(B) - r_f)\}] = 0$$

Then, by virtue of the constraint in (7), the retailer's optimization reduces to the following equation.

$$\Pi_F^R(B) = \max_{Q_F(w_F)\geq 0} E[p\min\{D, Q_F(w_F)\} - L(B)(1 + r_f)] - B$$

subject to:

$$E[\min\{p\min\{D, Q_F(w_F)\} - L(B)(1 + r_f), L(B)(r_F^*(B) - r_f)\}] = 0$$

Solving problem (7) we get: $Q_F^*(w_F) = \bar{F}^{-1}\left(\frac{w_F(1+r_F)}{p} \wedge 1\right)$, where $x \wedge y = \min[x, y]$. To ensure the operability of the supply chain, the market price must exceed the purchasing cost, that is, $w_F(1 + r_f) \leq p$. And we can rewrite $Q_F^*(B) = \bar{F}^{-1}\left(\frac{w_F(1+r_f)}{p}\right)$.

Recall that, in the traditional newsvendor model with no capital constraint (Hadley and Whitin (1963)), for a given w_F, the retailer's optimal solution $Q^N(w_F)$ solves the equation $p\bar{F}(Q^N(w_F)) = w_F$. This is the first-order optimality condition where the marginal revenue of an extra unit, $p\bar{F}(Q^N(w_F))$, is equal to the cost of the extra unit, w_F. Here, the first-order optimality condition is $p\bar{F}(Q_F^*(w_F)) = w_F(1 + r_f)$. Since $w_F(1 + r_f) \geq w_F$, it follows that a retailer with financing service and limited liability has higher marginal costs and $Q_F^*(w_F) \leq Q^N(w_F)$.

In the case where retailers can have access to a competitive financial market, the optimal ordering level for the retailers can be described by the following. When the retailer has a capital small to medium in size (i.e., $B \leq w\,\bar{F}^{-1}\left(\frac{w(1+r)}{p}\right)$), the optimal order level for the retailer with limited liability is a constant $\bar{F}^{-1}\left(\frac{w(1+r_f)}{p}\right)$, and $Q_F^*(w) \geq Q_{NF}^*(w)$; When the retailer has a medium capital (i.e., $w\bar{F}^{-1}\left(\frac{w(1+r)}{p}\right) < B \leq w\bar{F}^{-1}\left(\frac{w}{p}\right)$), the retailer does not make any loan but simply uses up her initial capital to order $Q_F^*(w) = \frac{B}{w}$, and $Q_F^*(w) = Q_{NF}^*(w)$. In fact, the marginal revenue from a loan is not enough to offset the financial cost; hence, the retailer does not make any loan from banks; When the retailer has a large capital (i.e., $B > w\bar{F}^{-1}\left(\frac{w}{p}\right)$), the optimal order level is $Q_F^*(w) = Q_{NF}^*(w) = Q^N(w)$, and it is actually the optimal order level in a traditional newsvendor problem. Therefore, we can characterize the optimal operational and financial decisions of the retailer as functions of her initial capital as follows.

These conclusions are shown in Table 1. We show that the risk-free interest rate r_f of the competitive financial market may influence the retailer's optimal order level and loan size.

In Figure 3, we plot the optimal order level as a function of the retailer's initial capital. Note that the initial capital is B, demand follows a normal distribution N(500, 200), the risk-free interest rate is set to 0, 0.02, and 0.04, respectively, and p = 10, w = 8. As seen in Figure 2, all observations are consistent with what we discussed in this section.

Fascinatingly, results in our model are related to the Modigliani-Miller Theory. If the capital markets are perfect, Modigliani and Miller (1958) prove that managers may consider financial decisions independently from the firm's other decisions (e.g., capacity investment). In Section 4.2, a retailer with a small to medium capital and limited liability can raise funds from banks in a competitive financial market. Thus, we can instead hold that the retailer has access to an unlimited capital account with interest rate r_f, which is similar to the perfect capital market in Modigliani-Miller Theory. Interestingly, the results show the retailer's financial decisions on loan size can be separated from the order decisions. Therefore, we can conclude that a competitive financial market decouples the financial decisions and operational decisions.

Initial capital	Loan	$Q_F^*(w)$
$B \le w\bar{F}^{-1}\left(\frac{w(1+r_f)}{p}\right)$	Yes	$\bar{F}^{-1}\left(\frac{w(1+r_f)}{p}\right)$
$w\bar{F}^{-1}\left(\frac{w(1+r_f)}{p}\right) < B \le w\bar{F}^{-1}\left(\frac{w}{p}\right)$	None	$\frac{B}{w}$
$B > w\bar{F}^{-1}\left(\frac{w}{p}\right)$	None	$\bar{F}^{-1}\left(\frac{w}{p}\right)$

Table 1. The optimal operational and financial strategy of the retailer. (Refer to Chen and Cai, 2011)

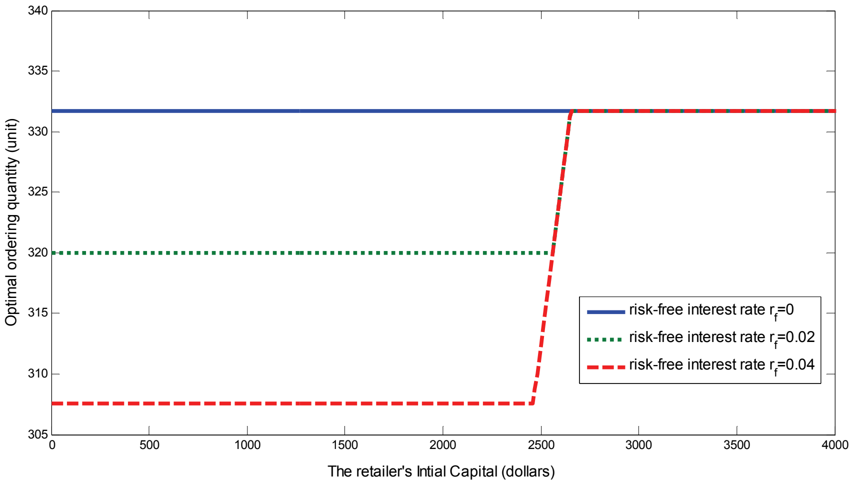


Fig. 3. The optimal order level Q_F^* as a function of the initial capital B. (Refer to Chen and Cai, 2011)

5. The role of 3PL firm in supply chain financing

Following the above discussion about simple supply chain with a supplier and a retailer, we then introduce how the third party logistics (3PL) firm plays an important role in adding value to all parties and supply chain as a whole.

In this section, we investigate three different roles of a 3PL firm in an extended supply chain with a supplier, a retailer, a 3PL firm, and a bank. The retailer is capital-constrained and may borrow capital from either the bank or the 3PL firm. The first role is called the Traditional Role (TR), where the 3PL firm provides only the traditional logistics services in the supply chain when the retailer borrows capital from the bank. The second role is regarded as the Delegation Role (DL), in which the 3PL firm aligning with the bank provides capital-constrained retailer with the integrated logistics and financing service. The third role is referred to as the Control Role (CR), where the 3PL firm provides both logistics services and trade credit financing to the capital-constrained retailer. Note that in supply chain finance, 3PL plays as either DR or CR.

The retailer is of limited liability and procures a single product from the supplier with a wholesale price w_p, and then sells to a random market by a fixed retail price p normalised to be one. More specially, the 3PL firm offering TR or DR to the capital-constrained retailer is also involved in the supply chain. Without loss of generality, this paper assumes that the 3PL firm would charge the retailer w_l for per unit product under TR or DR with cost c_l per unit in its business operations.

To make the operations of supply chain feasible, we offer the following assumption.

Assumption A2: $w_l > c_l$, $w_p > c_p$ *and* $(1 + r)(w_p + w_l) = (1 + r)w < 1$

5.1 3PL firm with TR in SCF

With TR, we consider 3PL firms offering traditional logistics service to the supply chain, and then analyse the capital availability to the capital-constrained retailer. The roles of suppliers and 3PL firms are passive, and their payoffs depend on retailer's ordering quantity only. Suppose that the retailer borrows funds from a bank in a monopolistic financial market and pays the supplier in full payment for the stock of goods purchased, we may then focus on studying the interplay between the retailer and the bank.

We first discuss the game between the bank and the retailer under symmetric information and show that the retailer cannot separate operations and financial decisions in a monopolistic financial market. Then, we show that under asymmetric information on retailer's initial capital, the bank may refuse to provide commercial loans for capital-constrained retailers.

Decisions of retailer and bank under symmetric information

Before characterizing the bank's decisions of interest rate, we start with examining capital-constrained retailer's optimal strategies.

The retailer's optimal strategies

Based on Eq (2), for a given $r_M(B)$ (the interest rate on a loan in the monopolistic finance market), we rewrite the retailer problem as follows:

$$\Pi_M^R = \max_{Q_M(B)} E\left\{\left(\min\{D, Q_M(B)\} - (wQ_M(B) - B)\left(1 + r_M(B)\right)\right)^+ - B\right\} \tag{8}$$

The characteristics for the retailer's optimal ordering strategy and its basic properties can be written by the following: Suppose Assumptions A1 and A2. Under symmetric information, regardless the 3PL firm playing TR or CR, at a given interest rate on a loan $r_M(B)$ in a monopolistic financial market (1) the optimal ordering quantity of the retailer, Q^*, is given by $\bar{F}(Q_M) = w\left(1 + r_M(B)\right)\bar{F}\left[(wQ_M(B) - B)\left(1 + r_M(B)\right)\right]$; (2) the capital-constrained retailer should get a loan with size $(wQ^* - B)$. (Refer to Chen and Cai, 2011).

As the retail price is normalised to 1, $\bar{F}(Q_M^*)$ represents the retailer's expected marginal revenue from ordering an additional unit, while the expected marginal cost of ordering an additional unit is $w(1 + r_M)\bar{F}\left[(wQ_M(B) - B)\left(1 + r_M(B)\right)\right]$. The volume of marginal cost depends on the interest rate $r_M(B)$, and might be greater or less than the marginal cost in traditional newsvendor model.

Here, we show that in the capital-constrained supply chain, the retailer's operational decision (e.g. ordering quantity) and financial decisions (e.g. loan size) cannot be separated. Consequently, under perfect information, the Modigliani-Miller Theory cannot hold water in this setting. If the capital markets are perfect, Modigliani and Miller (1958) hold that the managers may consider financial decisions independent of the firm's operational decisions.

In contrast, we show that the capital-constrained retailer has to integrate the operations and financial decisions to optimize her payoff.

The interest rate of the bank

There is Stacklberg-Nash game between the retailer and the bank. The optimal problem for the bank in a monopolistic financial market would be addressed by the following:

$$\Pi_M^B = \max_{r(B)} E\{min\{min\{D,Q\},(wQ-B)(1+r(B))\}-(wQ-B)\} \quad (9)$$

Combing Eqs. (2) and (9), we can describe the bank's decision problem in the following.

$$\Pi_M^B = \max_{r_M} E\{min\{min\{D,Q_M^*\},(wQ_M^*-B)(1+r_M)\}-(wQ_M^*-B)^+\} \quad (10)$$

Let $\mathrm{L(r)} = (\mathrm{wQ}_M^* - B)^+(1+\mathrm{r_M(B)})$. We denote that $\mathrm{r(B)} = r_M^*(\mathrm{B})$ is the optimal solution for Eq. (10). We then present the characteristics of the interest rate in the monopolistic financial market by the following,

Suppose Assumption A1 and Assumption A2. Under symmetric information, the optimal interest rate $r_M^*(\mathrm{B})$ in a monopolistic bank is given by: $\bar{\mathrm{F}}(Q_M^*) = w\frac{1-L(\mathrm{r_M(B)})h[L(\mathrm{r_M(B)})]}{1-\frac{\mathrm{wQ}_M^*-B}{w}h(Q_M^*)}$; Q_M^* is always less than the optimal ordering level $\mathrm{Q^N}$. (refer to Chen and Cai, 2011).

We then show that $Q_M^*(\mathrm{B}) < \mathrm{Q^N}$. So the optimal ordering of retailer in monopolistic financial market $Q_M^*(\mathrm{B})$ is always less than traditional newsvendor optimal ordering quantity $\mathrm{Q^N}$.

Compared to 'deep pocket' assumption in the traditional newsvendor model, the capital-constrained retailers intuitively have to pay interest to the bank, and increase the marginal cost of operations.

The behaviour of the retailer and the bank under asymmetric information

Suppose the bank provides a loan contract (r(B)) with the borrower (the capital- constrained retailer) and evaluates the retailer's credit risk based on her initial capital. If there is no device to screen the information on the retailer's initial capital, the retailer can falsify her initial capital information and get a corresponding contract to increase her profit.

We then conclude that under the asymmetric information, given a commercial loan menu r(B) from a bank operating in a monopolistic finance market, the capital-constrained retailer with $\mathrm{B} < w\mathrm{Q^N}$ may overstate her initial capital to get a lower interest rate of loans (refer to Chen and Cai, 2011 in detail).

Accordingly, Chen and Cai (2011) show under asymmetric information of retailer's initial capital, the bank may incur a loss in lending funds to the capital-constrained retailer. And under asymmetric information of retailer's initial capital, the capital-constrained retailer has the incentive to falsify her real initial capital to get higher payoff. In turn, the bank would suffer a loss from loans due to asymmetric information. Naturally, the bank might refuse to extend loans to capital-constrained retailers. These insights can explain why the small-medium size companies are not able to borrow loans from the financial institutions during the operations in supply chain.

5.2 3PL with DR in SCF

The asymmetric information of initial capital may break the equilibrium under full information and move part of revenue from the bank to the retailer. Hence the bank cannot get its expected return from a loan. As a consequence, some banks might leave the financial market because of credit risk, hurting individual firms in the capital-constrained supply chain.

However, the DR of 3PL firm can help the bank to track the liquid collateral of loan (inventory, etc.) and share the retailer's real information. In this case, the retailer would have no chance to overstate her initial capital to the bank. Also, if the bank offers loan contract menu (L(B),r(B)), the retailer would have no chance to lie about her initial capital either. But the retailer may divert funds in loans to a higher risk project without 3PL firms' monitoring, leaving the bank with a higher risk. It follows that the bank would be unwilling to offer loans to the capital-constrained retailer if the bank has no effective approach to monitor the retailer's real procurement behaviour.

Then we can conclude the motivation of 3PL firm's DR under asymmetric information with the following: Under asymmetric information of retailer's initial capital, 3PL firm's DR might force the retailer to declare her real information and help individual firms to achieve the equilibrium under symmetric information (Refer to Chen and Cai, 2011).

As is shown above, under asymmetric information, the bank may have no incentive to offer commercial loans to the capital-constrained retailer with TR, because the retailer may falsify her initial capital or divert capital loans. Without DR, the retailer's ordering level would be $Q_{NF} = \min\left\{\frac{B}{w}, Q^N\right\}$. But with DR, the bank would be encouraged to provide loans for the capital-constrained retailer. And the ordering level for the capital-constrained retailer $Q_F^* = \min\{Q_M^*, Q^N\}$ is always no less than Q_{NF}.

Since the payoffs of supplier, 3PL firm, and the supply chain involving the bank and 3PL firm are respectively, $\Pi^S = (w_p - c_p)Q$, $\Pi^L = (w_l - c_l)Q$, $\Pi^{SC} = E[min[D, Q] - CQ]$, we can obtain the following results directly: The payoffs of individual firms in the capital-constrained supply chain with DR are greater than those with TR. (Refer to Chen and Cai, 2011).

As DR brings all entities to the table – 3PL firm, bank, buyer and supplier, it helps to bridge the information gap and understand the needs of each party. As we explained earlier in the introduction the role of 3PL firm's DR for capital optimization within a capital-constrained supply chain, the coupling of information and physical control benefits lenders in the supply chain as well. For instance, the mitigation of risk allows more capital to be raised, or more capital to be assessed sooner. So the supply chain would be more efficient with the innovation service, DR of 3PL firm.

We move on to show that DR would impact the performance of individual firms as well as the entire supply chain, create value in the capital-constrained supply chain, and that asymmetric information might account for the motivation of DR.

5.3 Competitive financial market and SCF

DR of 3PL firm might decrease the financial risk when financial institutions offer loans to capital- constrained retailers in the supply chain. And more and more financial institutions have got the incentive to join hands with third party firms in order to enhance their profits and competitive advantages, which raises competition in the finance market. For instance, the 3PL firm could ally with many banks to provide integrated logistics and financing service to its clients in the supply chain, and banks have to confront a more competitive market in offering loans to capital-constrained retailers. We next examine how competition in the finance market influences decisions of agents in the supply chain.

The interest rate of a loan

Since the bank is risk-neutral and operates in a competitive financial market, it will set an interest rate r(B) that yields the expected profit. The profit is equal to the one generated by risk-free interest rate r_f. In this chapter, we assume $r_f = 0$.
In Eq (4), the bank may determine the optimal interest rate $r_B^*(B)$ as follows:

$$(wQ_{CF} - B)^+ = E\left[min\{(wQ_{CF} - B)^+(1 + r(B)), \mathcal{L}\}\right] \tag{11}$$

We can derive the optimal interest rate for a bank in the following: For a given ordering level $Q_{CF} \geq 0$ and $C \leq w \leq 1$, where C denotes the production cost, the retailer with an initial capital B may borrow a loan $(wQ_{CF} - B)^+$ from a bank in the competitive finance market. If the capital-constrained retailer is of limited liability, there exists a unique interest rate r_B^* charged by the bank through solving (11), while r_B^* is monotonically decreasing in retailer's initial capital B.
As the finance market is highly competitive, the bank's equilibrium interest rate r_B^* equates the expected discounted return from the loan $(wQ_{CF} - B)^+$ subtracting its costs. We note that r_B^* depends on the retailer's initial capital B. As B increases over the internal $[0, wQ^N]$, the loan size decreases and so does the bank's risk associated with the retailer's limited liability. Therefore, the prevailing interest rate decreases.

The retailer's optimal strategy

Fascinatingly, the above problem corresponds to the standard newsvendor problem. By combining Eqs (2) and (6), we can immediately get the following results：Suppose Assumptions A1 and A2. In the competitive financial market with DR, the optimal ordering level for a capital-constrained retailer is $Q_{CF}^*(B) = Q^N$ (the standard newsvendor quantity) and is independent of her initial capital B. In addition, the capital-constrained retailer would borrow $(wQ^N - B)$ from the bank.
The above results are related to Modigliani-Miller Theory. In this chapter, we show that the retailer's financial decisions on loan size can be separated from ordering decisions, and the ordering decision is the constant value and corresponds to the optimal ordering level in traditional newsvendor model. We then conclude that the competitive financial market can decouple financial and operational decisions of the capital-constrained retailer. (Refer to Chen and Cai, 2011)
The competitive financial market motivates the capital-constrained retailer to order a quantity up to Q^N, which increases the value of all players in the supply chain. As a result, the competitive financial market creates value in the capital-constrained supply chain.

5.4 The value of 3PL firm with CR in SCF

In the traditional role model, the 3PL firm provides the transportation service only and does not provide any screening effect as suggested in adverse selection. Lu et al. (2009) mention the incentive of logistics service provider (LSP) to provide financial support to the retailer/supplier and to establish the backup inventory. We will inspect more deeply on 3Pl financing. If the 3PL firm forms an alliance with the bank, then the 3PL firm could monitor the transaction of products from the supplier to the retailer for the bank. Consequently, the retailer's false revelation of the initial capital would be discovered and prohibited.
In the control role model, the 3PL firm provides not only logistics services but also trade credit to the retailer. While the retailer has insufficient capital to order directly from the supplier, the 3PL firm procures the products from the supplier for the retailer through trade

credit financing and then transports them to the retailer. In addition, the 3PL firm can effectively track and monitor the transaction of products in addition to providing trade credit to the capital-constrained retailer.

In the first stage of the Stackelberg game, the 3PL firm offers a trade credit contract $(\mathrm{w}, \mathrm{r}_{cl}(B))$ and in the second stage, the retailer orders $\mathrm{Q}^*_{cl}(B)$ from the supplier through the 3PL firm. The retailer's decision process is the same as in the traditional role model. The 3PL firm's profit is given as follows.

$$\Pi^{3PL}_{cl}(B) = \max_{0 \le r_{cl}(B) \le \tilde{r}(B)} E\Big\{(w - C_{cl})Q^*_{cl}(B) + (wQ^*_{cl}(B) - B)^+ r_{cl}(B) - \Big(min[D, Q^*_{cl}(B)] - (wQ^*_{cl}(B) - B)\big(1 + r_{cl}(B)\big)\Big)^-\Big\} \tag{12}$$

where $C_{cl} = \mathrm{w_p} + \mathrm{c_l}$ represents procurement and logistics operational costs incurred to the 3PL firm and $\mathrm{x}^- = \min\{\mathrm{x}, 0\}$. The above payoff consists of two components: the operational revenue $(\mathrm{w} - C_{cl})Q^*_{cl}(\mathrm{B})$ and the financial revenue $(\mathrm{w}Q^*_{cl}(\mathrm{B}) - B) - \Big(min[D, Q^*_{cl}(\mathrm{B})] - (wQ^*_{cl}(\mathrm{B}) - B)\big(1 + \mathrm{r_{cl}}(\mathrm{B})\big)\Big)^-$. It is straightforward that the operational profit is positive as long as $\mathrm{w} > C_{cl}$; however, the financial profit could end up with a negative value if demand uncertainty is too high; as a result the retailer could not repay the trade credit plus interest. Thus, a trade-off occurs: on the one hand, the 3PL would like to choose a small $\mathrm{r_{cl}}(\mathrm{B})$ to improve operational performance; on the other hand, the 3PL would like to choose a large $\mathrm{r_{cl}}(\mathrm{B})$ to satisfy his financial motive. The 3PL firm optimizes its trade credit contract while taking both motives into consideration.

We characterize the optimal interest rate in the following: In the control role model, the optimal interest rate $\mathrm{r}^*_{cl}(\mathrm{B})$ for the 3PL firm financing is

$$\mathrm{r}^*_{cl}(\mathrm{B}) = \begin{cases} \tilde{\mathrm{r}}(\mathrm{B}) & \text{if } \epsilon_{\mathrm{cl}}\big(\tilde{\mathrm{r}}(\mathrm{B})\big) \le 1, \\ 0 & \text{if } \epsilon_{\mathrm{cl}}(0) \ge 1, \\ \tilde{\mathrm{r}}_{\mathrm{cl}}(\mathrm{B}) & \text{if } \epsilon_{\mathrm{cl}}(0) < 1 \text{ } and \text{ } \epsilon_{\mathrm{cl}}\big(\tilde{\mathrm{r}}(\mathrm{B})\big) > 1 \end{cases}$$

The unique $\tilde{r}_{cl}(B)$ satisfies $\epsilon_{cl}\big(r_{cl}(B)\big) = 1$, and $\epsilon_{cl}\big(r_{cl}(B)\big) = \frac{\bar{F}\left(Q^*_{cl}(\mathrm{B})\right)\left[1 - H\left(Q^*_{cl}(\mathrm{B})\right) + \frac{B}{w}h\left(Q^*_{cl}(\mathrm{B})\right)\right]}{C_{cl}\left[1 - H\left[(wQ^*_{cl}(\mathrm{B}) - B)(1 + \mathrm{r_{cl}}(\mathrm{B}))\right]\right]}$ and even $\epsilon_{cl}\big(r_{cl}(B)\big)$ increases in $r_{cl}(B) \in [0, \tilde{r}(B)]$ (Refer to Chen and Cai, 2011).

If the order quantity is inelastic to the interest rate change, where $\epsilon_{cl}\big(r_{cl}(B)\big) \le \epsilon_{cl}\big(\tilde{r}(B)\big) \le 1$ and hence $\frac{\mathrm{d}\Pi^{3PL}_{\mathrm{cl}}(B)}{\mathrm{d}r_{cl}(B)} \ge 0$, the 3PL firm charges the interest rate at the highest level, $\tilde{r}(B)$, to optimize his profit. If the order quantity is very elastic to the interest rate, where $\epsilon_{cl}\big(r_{cl}(B)\big) \ge \epsilon_{cl}(0) \ge 1$ ad hence $\frac{\mathrm{d}\Pi^{3PL}_{\mathrm{cl}}(B)}{\mathrm{d}r_{cl}(B)} \le 0$, the 3PL firm achieves its optimum by completely waiving the interest for the retailer. When interest-demand elasticity is in the medium range, the 3PL firm can find a unique optimal interest rate that balances the tradeoff between the financial and operational benefits. In reality, the benefit of a control role model can be even more significant because the 3PL firm can reduce logistics costs ($\mathrm{c_l}$) by taking advantage of the economy of scale by grouping many retailers together.

Comparison of the 3PL's Roles

Based on the analysis in Section 5.2, we find that the decisions of retailer and bank are the same in both TR and DR settings. In order to simplify the analysis, in this subsection, we let discussion of TR include that of DR.

It is not difficult to show that the optimal interest rate in the control role is no higher than that in the traditional/delegation role. The optimal order quantity in the control role is no less than that in the traditional /delegation role. The inequality holds when interest-demand elasticity is in the medium range. This result occurs because the 3PL firm shares a higher risk of demand uncertainty through the financing service and would like to reduce the interest rate to stimulate a higher order from the retailer. If interest-demand elasticity (ϵ) is either too large or too small for both traditional and control roles, the optimal interest rates are reached at the boundary; thus, the optimal interest rates and order quantities are the same in both cases.

$\epsilon_{cl}(r_{cl}(B))$	$\epsilon_t(r_t(B))$	Elasticity (ϵ)	$r_{cl}^*(B)$	$r_t^*(B)$	$Q_{cl}^*(r_{cl}(B))\&Q_t^*(r_t(B))$
$\epsilon_{cl}(\tilde{r}) \le 1$	$\epsilon_t(\tilde{r}) \le \epsilon_{cl}(\tilde{r}) \le 1$	Low	$\tilde{r}$	$\tilde{r}$	Indifference
$\epsilon_{cl}(0) \ge 1$	$\epsilon_{cl}(0) \ge \epsilon_t(0) \ge 1$	High	0	0	
$\epsilon_{cl}(0) \ge 1$	$\epsilon_t(\tilde{r}) \le 1$	Medium	0	$\tilde{r}$	$Q_{cl}^*(0) > Q_t^*(\tilde{r})$
	$\epsilon_t(0) < 1, \epsilon_t(\tilde{r}) > 1$		0	$\tilde{r}_t$	$Q_{cl}^*(0) > Q_t^*(\tilde{r}_t)$
$\epsilon_{cl}(0) < 1,$ $\epsilon_{cl}(\tilde{r}) > 1$	$\epsilon_t(\tilde{r}) \le 1$		$\tilde{r}_{cl}$	$\tilde{r}$	$Q_{cl}^*(\tilde{r}_{cl}) > Q_t^*(\tilde{r})$
	$\epsilon_t(0) < 1, \epsilon_t(\tilde{r}) > 1$		$\tilde{r}_{cl}$	$\tilde{r}_t$	$Q_{cl}^*(\tilde{r}_{cl}) > Q_t^*(\tilde{r}_t)$

Table 2. Optimal interest rates and ordering quantities in traditional and control roles

We can obtain additional technical details, as illustrated in Table 2 (Refer to Chen and Cai, 2011). The itemized results in Table 2 are determined by the interplay of interest-demand elasticity rates in both the control and traditional roles. For any given interest rate, interest-demand elasticity in the control role is no less than that in the traditional role. If both interest-demand elasticity rates are low, a low interest rate does not stimulate much demand; thus, the 3PL/bank will charge the interest rate at its highest level in both the control and traditional models. In contrast, if both interest-demand elasticity rates are high, the benefit from a higher demand will overweigh the benefit of a higher interest rate; in this case, the 3PL/bank will charge a zero interest rate in both the control and traditional role models. If interest-demand elasticity is in the medium range, the interest rates in both models will differ in the four sub-cases, as shown in Table 2. Nevertheless, the optimal interest rate in the control role is no more than that in the traditional role; while the optimal order quantity in the control role weakly dominates that in the traditional role.

Owing to a higher order quantity in the control role, we may expect that the entire supply chain will be more efficient in the control role. In the control role model, compared with the traditional role model, the 3PL firm more significantly shares the risk of demand uncertainty with the retailer when offering the trade credit and logistics services together. Thus, the retailer benefits from a lower interest rate, the supplier benefits from a larger order quantity, and the 3PL firm benefits from the integration of the financing and its traditional logistics services. This result provides theoretical support to the practice of 3PL firms integrating their logistics services with financing services, such as UPS and others.

Because of the capital constraint, one might expect that neither of our above models can outperform the classic newsvendor model (without capital constraint) in terms of overall supply chain profit. Note that supply chain profit includes the profits of the supplier, retailer, 3PL, and/or the bank and, hence, can be written as follows.

$$\Pi_i^*(B) = E\{\min[D, Q_i^*(B)] - (c_p + c_l)Q_i^*(B)\}, \text{ where the subscript } i = t, c_l, N.$$

The following result delivers a somewhat counterintuitive message: Compare overall supply chain profits in the traditional role, control role, and classic newsvendor models, (1). The classic newsvendor model outperforms the traditional role model (i.e., $\Pi_{\mathrm{t}}^{*}(\mathrm{B}) \leq \Pi_{\mathrm{N}}^{*}(\mathrm{B})$; (2) The control role model outperforms the classic newsvendor model (i.e., $\Pi_{\mathrm{cl}}^{*}(\mathrm{B}) \geq \Pi_{\mathrm{N}}^{*}(\mathrm{B})$), as long as C_{cl} is sufficiently low (i.e., $\mathrm{C}_{cl} \leq \frac{w-(w\mathrm{Q}_{\mathrm{cl}}^{*}(\mathrm{B})-B)h(\mathrm{Q}_{\mathrm{t}}^{*}(\mathrm{B}))}{1-H\left[(w\mathrm{Q}_{\mathrm{cl}}^{*}(\mathrm{B})-B)(1+\mathrm{r}_{\mathrm{cl}}^{*}(\mathrm{B}))\right]}$), where $\mathrm{C}_{cl} = w_p + c_l$. (Refer to Chen and Cai, 2011).

The first statement above suggests the traditional role model cannot outperform the classic newsvendor in terms of entire supply chain efficiency, which is intuitive because the retailer bears additional financial risk plus the same demand uncertainty as in the classic newsvendor model. As for the control role model, the second statement indicates that overall supply chain profit in the control role model outweighs the classic newsvendor model. The rationale behind is that the 3PL firm shares the risk of demand uncertainty with the retailer by lowering the interest rate, such that the retailer orders a larger quantity that consequently yields a higher profit for the entire supply chain. Compared with the traditional role model, the 3PL in the control role model coordinates the supply chain by integrating the financial and logistics services. A lower combined value of product wholesale price and logistics operational cost (C_{cl}) enables the 3PL firm to charge a lower interest rate than in the traditional role model. This result conveys the message that an integrated service of financing and logistics can coordinate the capital constrained supply chain, and thus is a win-win-win solution to the retailer, the 3PL firm, and the supplier. However, if C_{cl} is too high, the burden of the capital constraint would outpace the benefit of 3PL coordination, such that the classic newsvender model would outperform the control role model in terms of overall supply chain efficiency.

6. Conclusion

We have studied the operational and financial decisions for a capital-constrained supply chain and the impact of financing on individual firms and the entire supply chain under wholesale price contract.

Our analysis indicates that financing can create value for a supply chain with small-medium capital retailer, and greater competition in a financial market leads to better performance improvement for the individual firms as well as the entire supply chain. Specifically, when the retailer has small-medium capital, she can make loans from a bank and place an order at a given level, depending on the market's risk-free interest rate, and the supplier should reduce his wholesale price to encourage the retailer to order more, thus increasing the transfer payment to the supplier. When the retailer has a medium capital, the retailer does not make loans and places an order at a level increasing with the size of her initial capital, and the supplier offers a suitable wholesale price, which is decreasing with the size of the retailer's initial capital to draw out all of the retailer's funds. When the retailer's capital is large, she never makes a loan from banks and sets an order level equal to the optimal order level in the traditional newsvendor model. We also show that interest rate on loans would decrease in the retailer's initial capital. We emphasize that when the retailer has small-medium capital, decisions on wholesale price and order level are independent of the initial capital.

Another important point is that with 3PL firm playing the traditional role in the monopolistic financial market, the retailers have to consider the integrated operations and financial decisions to optimise her payoff, and the optimal ordering quantity is less than that of the traditional newsvendor model. However, under asymmetric information and without effective screening devices, the bank might refuse to offer financing service to the capital-constrained retailer. The main reasons lie in two factors: (1) the retailer has the incentive to overstate her initial capital; (2) the retailer could divert the loan to projects with higher risks. And interestingly, this chapter shows asymmetric information view might account for the motivation of 3PL firm's delegation role and control role, and both DR and CR could create value for the capital-constrained supply chain. As for 3PL firm's DR and CR, the retailer has to declare her private information of initial capital truly and might even have no chance to divert the capital loans.

We then further investigate the influence of the different roles of a 3PL firm in a supply chain with a capital-constrained retailer. The retailer can borrow capital from a bank or trade credit from a 3PL firm with financing services. We compare the traditional and control roles where the 3PL firm provides only logistics or logistics plus trade credit, respectively. Our analysis indicates the control role model yields higher profits not only for the 3PL firm, but also for the supplier and the retailer.

This chapter reveals the relation between financing services and supply chain management, and introduces how logistics firms could add value to all parties in supply chain. Supply Chain Finance is bringing not only more value, but also new trends of innovative financing services for supply chain management, which absolutely deserves further study.

7. Acknowledgement

The authors gratefully acknowledge financial support from NSF of China (70972046, 70832002, NCET-10-0340), Shanghai Pujiang Program and the Scientific Research Foundation for the Returned Overseas Chinese Scholars, State Education Ministry of China, in 2009, and Xiyuan Research Program in 2011.

8. References

Barnett, W. (1997) 'What's in a name? A brief overview of asset-based lending', *Secured Lender*, Vol. 53, pp.80–81.

Boyabatli, O., L. B. Toktay. (2006), "Capacity investment in imperfect capital markets: the interaction of operational and financial decision", *Working Paper*, TM, INSEAD, Fontainebleau, France.

Brennan, M., V. Maksimovic, and J. Zechner (1988). Vendor financing. Journal of Finance 43(5), 1127-1141.

Burkart, M. and T. Ellingsen (2004). In-kind finance: A theory of trade credit. *The American Economic Review* 94 (3), 569–590.

Buzacott, J. A.and R. Q. Zhang. (2004), "Inventory management with asset-based financing", *Management Science*, Vol.50 No.9, pp. 1274-1292.

Caldentey, R. and M. B. Haugh. (2009), "Supply Contracts with Financial Hedging", *Operations Research*, Vol.57 No.1, pp.47-65.

Caldentey, R. and X. F. Chen. (2011), "The Role of financing service in procurement contracts", In Handbook of Integrated Risk Management in Global Supply Chains, co- edited by Panos Kouvelis, Onur Boyabatli, Lingxiu Dong, and Rong Li, John Wiley & Sons, Inc..

Chao, X., J. Chen and S. Wang. (2008), "Dynamic inventory management with financial constraints", *Naval Research Logistics*, Vol.55 No.8, pp.758-768.

Che, Y. K. and I. Gale. (2000), "The optimal mechanism for selling to a budget- constrained buyer", *Journal of Economic Theory*, Vol.92, pp.198-233.

Chen, J. and P. C. Bell (2009). The impact of customer returns on pricing and order decisions. *European Journal of Operational Research* 195(1), 280–295.

Chen, X. F. and G. Cai. (2011). Joint logistics and financial services by a 3PL firm, *European Journal of Operational Research,* doi:10.1016/i.ejor, 2011.05.010.

Chen, X. F. and G. Wan. (2011). The effect of financing on a budget-constrained supply chain under wholesale price contract, *Asia-Pacific Journal of Operational research*. Vol.28, No.4, pp.1-29

Chung, C.-S., J. Flynn, and J. Zhu (2009). The newsvendor problem with an in-season price adjustment. *European Journal of Operational Research* 198(1), 148–156.

Dada, M. and Q. Hu (2008). Financing newsvendor inventory. *Operations Research Letters* 36, 569–573.

Dammon, R. M. and L. W. Senbet. (1988), "The effect of taxes and depreciation on corporate investment and financial leverage", *Journal of Finance*, Vol.43, pp.357-374.

Dotan, A. and S. A. Ravid. (1985), "On the interaction of real and financial decisions of the firm under uncertainty", *Journal of Finance*, Vol.40, pp.501-517.

Gerchak, Y. and Y. Wang (2004). Revenue-sharing vs. wholesale-price contracts in assembly systems with random demand. *Production and Operations Management* 13(1), 23–33.

Graves, S. and Ton de Kok. (2003), *Handbooks in Operations Research and Management Science: Supply Chain Management*. North-Holland: Elsevier.

Groenevelt (2007). Impacts of financial collaboration in a three-party supply chain. The Simon School, University of Rochester, Working Paper.

Hadley, G. and T. Whitin. (1963), *Analysis of Inventory System*. NJ: Prentice-Hill. Hu, Q. and M. J. Sobel. (2005), "Capital Structure and inventory management", Working paper. Weather head School of Management, Case Western Reserve University, USA.

Haris, M. and Raviv, A. (1985) 'The theory of capital structure', *Journal of Finance*, Vol. 46, pp.297–355.

Hofmann Erik. (2005). "Supply Chain Finance- some conceptual insights", Logistik Management – Innovative Logistickonzepte, by Lasch, R./Janker, C.G.(Hrsg.), Wiesbaden 2005, S. 203-214.

Hu, Q. and Sobel, M.J. (2005) 'Capital structure and inventory management', *Working paper*, Weather head School of Management, Case Western Reserve University, USA.

Hu, Q., Y. Wei, and Y. Xia (2010). Revenue management for a supply chain with two streams of customers. *European Journal of Operational Research* 200(2), 582–598.

Jing, B., X. Chen, and G. Cai (2010). Equilibrium financing in a distribution channel with capital constraint. Working paper, Kansas State University.

Kouvelis, P. and W. Zhao (2008). Financing the newsvendor: Supplier vs. bank, optimal rates, and alterative schemes. Working paper, Olin Business School of Management, Washington University, St. Louis.

Lariviere, M. A. and E. L. Porteus. (2001), "Selling to the newsvendor: An analysis of price-only contracts", *Manufacturing and Service Operations Management*, Vol.3 No. 4, pp.293-305.

Lau, H.-S. and A. H.-L. Lau (1999). Manufacturer's pricing strategy and return policy for a single- period commodity. *European Journal of Operational Research* 116(2), 291–304.

Levaggi, R. (1999), "Optimal procurement contracts under a binding budget constraint", *Public Choice*, Vol.101, pp.23-37.

Lu, M., T. Wu, and H. Yan (2009). Inventory management in decentralized supply chains with logistics service provider. Working paper, The Chinese University of Hongkong.

Mauer, D. and A. J. Triantis. (1994), "Interactions of corporate financing and investment decisions: a dynamic framework", *Journal of Finance*, Vol.49, pp.1253-1277.

Mello, A. S. and J. E. Parsons. (1992), "Measuring the agency cost of debt", *Journal of Finance*, Vol.47, pp.1887-1904.

Modigliani, F. and M. H. Miller. (1958), "The cost of capital, corporation finance, and the theory of investment", *American Economic Review*, Vol.48 No.3, pp.261-297.

Parlar, M. and Z. K. Weng (2003). Balancing desirable but conflicting objectives in the newsvendor problem. *IIE Transactions* 35(2), 131–142.

Rajan, R. and L. Zingales (1995). What do we know about capital structure? Some evidence from international data. *The Journal of Finance* 53, 80–81.

Simchi-Levi, D, S. D. and Wu, Z. Shen. (2004), *Handbook of Quantitative Supply Chain Analysis: Modeling in the eBusiness Era*. NY: Kluwer Academic Publisher.

Spengler, J. (1950), "Vertical integration and antitrust policy", *Journal of Political Economy*, Vol.58, pp.347-352.

Thomas L. (2002), "Non-linear pricing with budget constraint", *Economic Letters*, Vol.75, pp. 257-263.

Xu, X. D. and J. R. Birge. (2004), "Join production and financing decisions: modeling and analysis", *Working Paper*, Graduate School of Business, University of Chicago, USA.

Xu, X. D. and J. R. Birge.(2006), "Equity valuation, production, and financial planning: A stochastic programming approach", *Naval Research Logistics*, Vol.53No.7, pp.641-655 .

Xu, X. D. and J. R. Birge. (2008), "Operational Decisions, Capital Structure, and Man- agerial Compensation: A News Vendor perspective", *Engineering Economist*, Vol.53 No. 3, pp.173-196.

Zhou, Y.-W. and S.-D. Wang (2009). Manufacturer-buyer coordination for newsvendor-type-products with two ordering opportunities and partial backorders. *European Journal of Operational Research* 198(3), 958–974.

Part 3

Project and Technology Issues in Supply Chain

7

Impact of RFID and EPCglobal on Critical Processes of the Pharmaceutical Supply Chain

Alberto Bucciero, Anna Lisa Guido, Luca Mainetti and Luigi Patrono
University of Salento
Italy

1. Introduction

The need to implement and guarantee effective item-level tracing systems is becoming more and more important for a wide range of business applications, such as manufacturing, logistics, healthcare, and anti-counterfeiting. Among these, the pharmaceutical supply chain, with millions of medicines moving around the world and needing to be traced at item level, represents a very interesting reference scenario. Furthermore, the growing counterfeiting problem raises a significant threat within the supply chain system. Recently, several international institutions (e.g. Food and Drug Administration, European Medicines Agency, European Federation of Pharmaceutical Industries and Associations, GS1) are encouraging the use of innovative solutions in healthcare and in the pharmaceutical supply chain, to improve patient safety and enhance the efficiency of the pharmaceutical supply chain, with better worldwide drug traceability (FDA, 2004).

Currently, the most popular auto-identification technology is optical one. Although the bar code (one- or bi-dimensional) is a very low cost solution, there are many valid reasons for not considering it as the primary auto-identification technique (Schroeter, 2008) in the near future. In fact, every kind of bar code technology requires line-of-sight (LoS), it cannot be written or read in bulk, it can be easily counterfeited, it can limit the speed of packaging line operations, etc.

On the contrary, RFID (Finkenzeller, 2003) technology promises to optimize the critical processes in the Supply Chain Management (SCM) systems and to improve the patient safety, resolving problems of traditional optical auto-identification solutions.

Passive RFID tags can be classified according to the frequency band used and the type of coupling between tag and reader antennas. The use of RFID solutions, in particular those working in Ultra High Frequency (UHF) band, could easily exceed the previous performance problems justifying the initial investment required by a process re-engineering of the pharmaceutical supply chain. Recent works (Uysal, 2008; De Blasi, 2010; Catarinucci, 2010) have highlighted that passive UHF RFID tags represent the more suitable solution for item-level tracing systems in a supply chain.

Another fundamental element that is increasing exponentially the diffusion of the RFID in the automate logistics processes is the asserting of some international standards related to goods traceability, such as EPCglobal (Barchetti, 2009; Thiesse, 2009), GS1 (Global Standard 1) (Barchetti, 2010) and ebXML (Electronic Business using extensible Markup Language) (Barchetti, 2010), which are just a few interesting examples. The EPCglobal consortium, mainly represented by the GS1 organization, defines the standards for developing a universal identification system and an open architecture able to guarantee interoperability and data sharing in a complex multi-vendors scenario. In particular, it proposes the EPCglobal network architecture, whose main feature is represented by the use of the Electronic Product Code (EPC), a code able to uniquely identify each item. This architecture is composed of a set of standards for hardware devices (e.g. reader), software systems, network services, and data interfaces that allow EPCglobal network to play a very important role in traceability systems. EPCglobal is an open architecture, based on a distributed database, able to guarantee effectiveness, flexibility, and scalability.

Although, the use of these technologies promises many benefits, today's RFID and EPC adoption is still limited its deployment in the healthcare and pharmaceutical sectors due to barriers such as: (i) hardware technology current weaknesses (Catarinucci, 2010; Niktin & Rao, 2006) (e.g. data reliability, read rate in critical conditions, lack of unified standard for interoperability), (ii) software weakness (e.g. scalability, single-point of failure, integration with informative systems), (iii) relatively high costs related to tags, software customization and systems integration, (iv) security issues (Mirowski, 2009), (v) lack of scientific literature on the evaluation of potential effects of RFID exposure on molecular structure and potency of drugs (Acierno, 2010; Acierno, 2011; Cox, 2006; Uysal, 2010).

These open issues amplify some scepticism remains in the community of potential adopters of these technologies since there is no clear indication of the model to follow when assessing the impacts and benefits of RFID-based tracing systems in the supply chain. In particular, return on investment is uncertain if one attempts to assess both cost reductions and value added at each stakeholder of the supply chain.

Several studies have been performed on different supply chains (e.g. fashion, agro-food, cargo, etc.) by using different approaches. Most works attempt to evaluate, through particular methodologies such as Key Performance Indicators (KPIs) or Critical Successful Factors (CSFs), the potential benefits due to applying innovative technologies such as RFID in re-engineered processes of the supply chain. Unfortunately, this kind of analysis is strongly dependent on a particular application scenario. Currently, it is not easy to find exhaustive analysis of these performance indicators on the pharmaceutical supply chain.

The main goal of this chapter aims to analyze main processes of the pharmaceutical supply chain and to evaluate the impact of the combined use of RFID and EPCglobal in some critical processes. Particular attention is focused in the wholesaler because it represents a middle point of the supply chain very stressed in terms of constraints and products flow. Taking into account the main inefficiencies highlighted in the defined AS IS model, a re-engineered TO BE model has been proposed. Furthermore, some KPIs have been defined for the wholesaler in order to make easier a quantitative analysis of the benefits due to the re-engineering.

The rest of the chapter is organised as follows. Section 2 summarizes a brief state of the art of related works on the evaluation of potential benefits provided by the use of innovative technologies in supply chain management systems. A description of the reference scenario, the pharmaceutical supply chain, is reported in Section 3. Section 4 provides a brief overview on the three main standards (i.e. RFID, EPCglobal, and ebXML) and summarizes a recent pilot project focused on the traceability at item level in the pharmaceutical supply chain. A detailed analysis of the main processes of the wholesaler, representing the AS IS model, is reported in Section 5. Instead, in Section 6 is reported the TO BE model that shows the main re-engineered processes of the wholesaler by a combined use of RFID and EPCglobal. A discussion on the main methods to evaluate potential benefits related to the combined use of RFID and EPC in the pharmaceutical wholesaler is reported in Section 7. Finally, Section 8 reports conclusions and future works.

2. Related works

Some attempts have been recently carried out by using different approaches to different scenarios in order to give qualitative and quantitative indications on the usefulness to perform process re-engineering procedures exploiting RFID and EPCglobal.

Previous works on the evaluation of impacts of RFID and EPCglobal on main business processes in a supply chain can be classified, taking into account the adopted approach, in two different groups: theoretical, and test bed.

The first includes conceptual papers that describe some critical trends and implications of applying RFID to supply chain management systems or suggest interesting strategies and technology solutions to optimize traceability and business messages interchange (Barchetti, 2010; Srivastava, 2004; Gunasekaran & Ngai, 2005; Pramataris, 2005). In this category, many mathematical and simulation approaches are also included. For instance, (Lee, 2004) demonstrates the potential benefits of RFID in inventory reduction and service level improvement in manufacturer-retailer supply chains. (Gaukler, 2005) reports a model of benefits of an item level RFID system to two members of a supply chain. (Hou & Huang, 2006) proposes six models of cost-benefit analysis for RFID applications in different logistics activities in the printing industry. (Ustundag & Cevikcan, 2007) presents a methodology for the adaptation of RFID technology to the service processes of a cargo firm. (Bottani, 2009) introduces a detailed mathematical model to assess the economic impact of RFID technology and EPC network adoption for traceability management within a supply chain. (Bottani, 2008) reports a discrete event simulation model reproducing the adoption of RFID technology for the optimal management of common logistics processes of a Fast Moving Consumer Goods (FMCG) warehouse. (Vue, 2008) analyzes the pharmaceutical supply chain, in particular, some processes of the manufacturer, and attempts to summarize the main CSFs (Critical Success Factor) when RFID is applied in pharmaceutical enterprises.

The second approach aims to focus the attention on studies that have allowed to estimate performance indicators and costs by using test bed carried out in laboratories or in field. Among papers with empirical results, (Loebbecke, 2005) analyses some Metro group pilots in Germany, highlighting that the use of RFID in combination with particular kind of marketing is able to increase significantly the sales. (Hardgrave, 2008, 2009) present some studies where the influence of RFID on potential improvements is analysed. (Bottani et al. , 2009) analyses the potential impact of these innovative technologies in the fashion supply chain exploiting an empirical approach based on questionnaires, interviews and measurements in field. In particular, Bottani et al., 2009) is one of the few works that attempts to evaluate the benefits due to a combined use of RFID and EPC. (Gandino, 2007) reports interesting experiences carried out in the agro-food chain. It describes and validates a new tracing system by using tests in a laboratory and in a working fruit warehouse.

All works analysed highlight the need to evaluate potential benefits due to re-engineering procedures performed on most critical processes of a supply chain and hypothesizing the use of innovative technologies such RFID. Furthermore, an empirical test case, carried out directly in the field, is able to obtain very interesting results taken from potential adopters of these new technologies. This increases the complexity of this kind of studies because it requires performing customized analyses for each scenario.

3. Description of the pharmaceutical scenario

The pharmaceutical supply chain, shown in Fig. 1, is a complex scenario with millions of pharmaceutical products moving around the world each year. The actors of the pharmaceutical supply chain that have a significative impact on the traceability of products are three: (i) the *manufacturer,* who produces the packaging of pharmaceuticals, (ii) the *wholesaler,* who buys and resells large quantities of medicinal products, and (iii) the *pharmacy retailer*, who in general is a pharmacy or hospital. Let us observe that the pharmaceutical scenario follows the traditional manufacturer-retailer model used for the most supply chains except that medicinal products are not returned but destroyed once they exceed their sell-by date. In fact, every product that can no longer be sold is sent to the *disposal company,* another minor actor in this supply chain. It is very useful to consider some data able to characterize the reference supply chain. Each year, about 30 billion packages of pharmaceutical products are produced by European industries (Fuhring, 2009). The European supply chain incorporates about 2,200 manufacturers, 50,400 wholesalers, and 142,000 retailers.

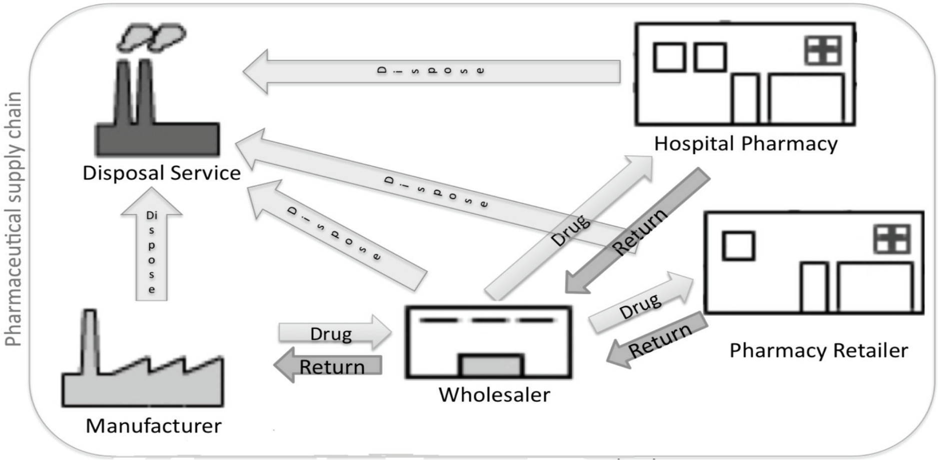


Fig. 1. Pharmaceutical supply chain

A small-scale, but very interesting, vision of the pharmaceutical scenario is offered by the Italian market that is composed of about 320 manufacturers, 140 wholesalers, and 18,000 pharmacy retailers. The average number of pharmaceutical items managed by one wholesaler per year is greater than 50,000. Furthermore, there are strict requirements, in terms of delivery time and dispatching order time, imposed by national laws. This vision introduces the need to understand how an efficient tracing and tracking procedure is strongly desired by all members of the pharmaceutical supply chain.

The item-level traceability of drugs starts just after the packages are filled during the manufacturing process. In this step, each tagged product is individually scanned on the conveyor belt and then cased to be sent to the wholesalers. The wholesalers separate the products according to their identifiers and place them onto the shelves. Wholesalers receive orders from retailers. These orders often consist of small quantities of different products; they may contain a large number of items. The products in the orders of the retailers are picked and put into some large envelope bags that are scanned and confirmed before their distribution. Upon receipt, the pharmacy retailer scans the contents of each bag without opening it.

4. Overview on the main innovative solutions for the Supply Chain Management

4.1 International standards

The three main keywords able to improve significantly a SCM system are RFID, EPCglobal, and B2B. Recent works (Barchetti, 2009, 2010) have demonstrated that the combined and coordinated use of these technologies delivers enormous advantages for every actor in the pharmaceutical supply chain. Some basic concepts related to the roles of these technologies in traceability management in the whole supply chain are briefly reported below.

RFID is a very interesting auto-identification wireless technology that promises to replace the traditional barcode. It guarantees the ability to trace and track individual objects in the whole supply chain. Typically, an RFID system consists of three main components: RFID tags, RFID readers, and data processing systems. RFID transponders, often called "tags", can be passive, semi-passive, or active. In a passive RFID system, the reader transmits a modulated RF signal, which is received by the tag antenna. The RF voltage generated on the antenna is converted into DC (direct current). This voltage powers up the chip, which sends back the contained information. Passive RFID tags can be classified according to the frequency band used (LF, HF, UHF, etc.) and the type of coupling (magnetic or electromagnetic) between tag and reader antennas. An RFID tag is attached to the items or conveyance, e.g., pallet, packaging material, or the product itself. One key benefit is that RFID does not require LoS with a reader, whereas barcodes require a scanner to pass over each item. Recent works (De Blasi, 2010; Catarinucci, 2010) have highlighted that passive UHF is most promising technology for item-level tracing systems on the whole supply chain. The success of UHF can be mainly attributed to the asserting of EPCglobal international standard (Thiesse, 2009).

The EPCglobal standard is an open architecture for tracking and tracing objects over the Internet. EPCglobal aims to develop an efficient distribute database that can be queried to obtain quickly every data fragment associated to the history of a given object. In fact, it defines a full protocol stack to enable item-level data sharing about products that move in the whole supply chain. The EPCglobal architecture, shown in Fig. 2, is mainly based on the Electronic Product Code (EPC), Application Level Events (ALE), EPC Information Service (EPCIS), Object Naming Service (ONS), and Discovery Service. The EPCglobal architecture is able to guarantee effectiveness, flexibility, and scalability. Furthermore, it is important to observe that this architecture was designed to exploit all advantages of RFID technology, but continues to also be valid in the presence of other automatic identification solutions.

The third component, fundamental for successful SCM solutions, is related to the ability to support the interoperability among different firms to overcome problems about the e-business messages interchange on a whole supply chain. There are consolidated standards, such as ebXML, that have improved SCM from an e-business perspective. An interesting approach aims both to provide a high degree of freedom in the business process design and formalisation of the specific business message and to suggest to the companies the use of a single technology of interchange that is flexible and easy to integrate with the company's information system. The recent challenge is to have a supply chain characterised only of automatic data flows to increase the effectiveness and to reduce human errors. Some works

(Barchetti, 2009, 2010) have suggested the combined use of ebXML, as the data interchange standard, and UBL (universal business language), as the standard for defining e-business messages.

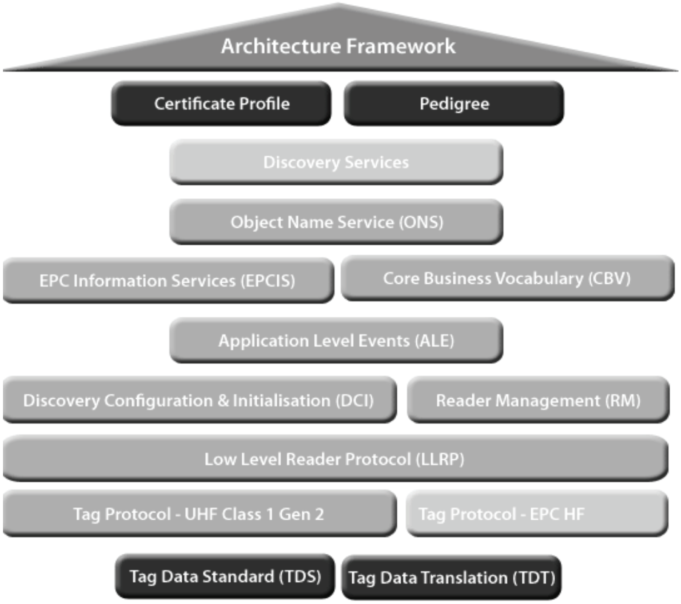


Fig. 2. EPCglobal network architecture (EPCglobal, 2005)

4.2 Description of a pilot project in the pharmaceutical scenario

In (Barchetti, 2009, 2011) is described an pilot research project that aims to apply, in combined mode, the previous technologies in a prototypal system able to guarantee item-level traceability in the pharmaceutical supply chain. The main research activities of this pilot faced the following two challenges: (i) development of an innovative software framework compliant with EPCglobal standard for traceability in the pharmaceutical supply chain, and (ii) performance evaluation of passive UHF RFID tags in critical operating conditions (e.g. presence of liquids and metals, misalignment between reader and tag antennas, etc.). Two important features of this innovative framework are: ebXML as the proper standard to guarantee the interoperability among different firms, and EPCglobal as the proper standard to guarantee the identification and traceability of products and goods. The data interchange system is based on ebXML and uses an application layer to guarantee an e-business messages exchanging service according to the UBL standard. The defined software architecture has been designed by merging the two main previous components: EPCglobal protocol stack and the ebXML for messaging services. In this way, the overall system is able to answer the requests from factory users by sending reports and information about a specific product, marked by an EPC code, or providing the possibility to perform messaging operations such as, for example, sending an order. In order to guarantee high flexibility and reliability, the overall framework is based on two open-source implementations provided by the scientific community: (i) the e-business message exchange

sub-system is modelled by the freebXML project, which provides an open-source implementation of the ebXML standard, and (ii) the traceability sub-system is modelled by the Fosstrak framework, which provides an open-source RFID software platform that respects exactly the current standards provided by EPCglobal.
The performance evaluation, carried out in a particular test environment (see Fig. 3) configured to simulate the main steps and characteristics of the pharmaceutical supply chain, allowed to obtain very interesting experimental results related to the use of passive UHF RFID tags in item-level tracing systems. Some results, reported in (De Blasi, 2010), demonstrated that RFID UHF tags could suffer of performance degradation when used in presence of electromagnetically hostile materials, such as metals and liquids, as well as under very stressful conditions such as high scanning speed, possible misalignment between tag and reader antennas, and multiple reading of tags. In order to face these performance problems, some enhancements, proposed in (Catarinucci, 2010), show very impressive findings and clearly demonstrate that well designed ad hoc Far Field UHF tags effectively improve the performance of any item-level tracing system.

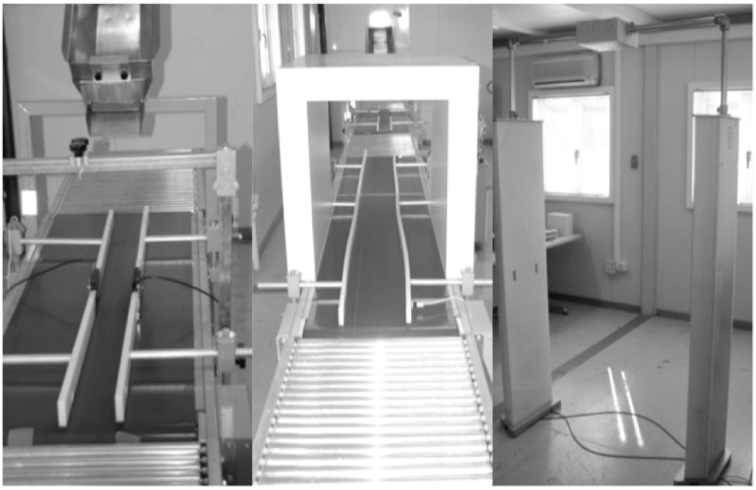


Fig. 3. Test environment to simulate the supply chain

Furthermore, this pilot project, characterized by encouraging results in software and communication engineering fields, has recently stimulated further scientific collaborations with some biologist groups in order to define a multidisciplinary approach able to investigate potential exposure risks of RFID devices in UHF band on the molecular structure and potency of a biological drug. Some recent works (Acierno, 2011), carried out on human insulin preparation and Gonal-F, have demonstrated that the drug molecular structure was unaffected by UHF exposure.

5. AS IS model analysis

The enormous complexity of the reference scenario has suggested starting this analysis focusing particular attention to one of stakeholders of the pharmaceutical supply chain: the wholesaler. The choice is motivated by the fact that it represents the most stressed condition in terms of products flows. Furthermore, a wholesaler interacts with manufactures, other wholesalers, and pharmacy retailers. For these reasons, it is a very critical member of the supply chain

The defined AS IS model summarizes the main features of the most critical processes of the wholesaler such as: products receiving, storage, picking, products outgoing, return flows management (from pharmacy retailer or to manufacturer), and products deadline management. An overall vision of these critical processes are shown in Fig. 4 and is described in this section in order to highlight main points where the use of innovative technologies, such as RFID and EPCglobal, could improve the logistics aspects of the wholesaler.

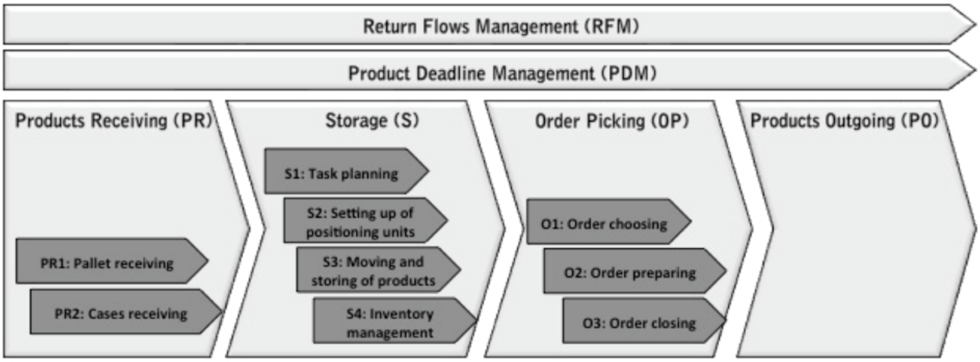


Fig. 4. Abstract vision of the AS IS model of the wholesaler

Fig. 5 reports an overview of the main business processes of the wholesaler by using the Business Process Modeling Notation (BPMN) (BPMN, 2006). This standard, defined for business process modeling, is able to provide a graphical notation for specifying business processes through a flowcharting technique. The main objective of BPMN is to support business process management for both technical users and business users by providing a notation that is intuitive to business users yet able to represent complex process semantics. It represents an effective choice able to satisfy the main requirements of this kind of analysis based on KPIs.

The BPMN design of the business processes is reported in the next section in order to better appreciate the performance comparison between AS IS model and re-engineered model (TO BE).

Main features of the AS IS model are below reported starting with the analysis of the pallet receiving process.

The Pallet Receiving (PR) process, carried out by the receiving clerk, is composed of the following sub-processes:

- Pallet receiving (PR1): One or more pallets, associated with the same manufacturer, are received from the wholesaler. A worker, through a manual procedure, performs a first check of the received products. This check consists to choose and open, in random way, one case from one of the received pallets. Just one item (single medicine package) is taken and analysed. In particular, the worker reads manually (i.e., without the use of an electronic device) number of lot and deadline date. This data is compared and verified with the information reported on the delivery note. Furthermore, the same worker counts manually the number of cases contained on this pallet. The value is thus verified with the delivery note. If these two manual and rough tests are validated then all products received are accepted to wholesaler. The BPMN design of the current Pallet receiving subprocess is shown in Fig. 6(a).

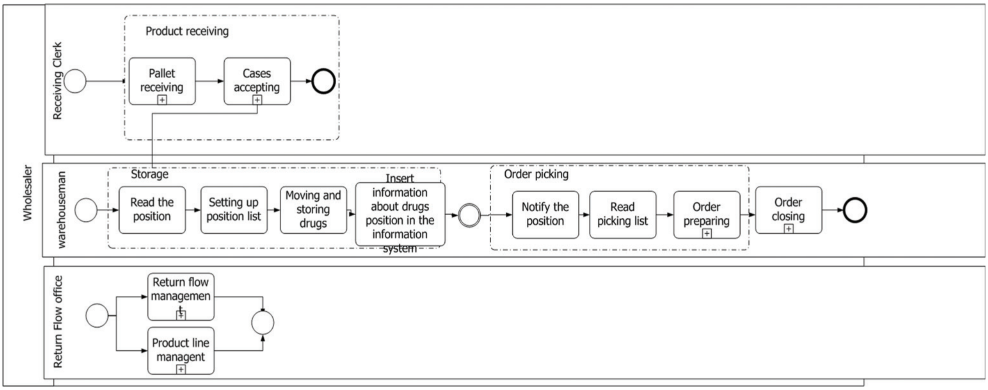


Fig. 5. Overview of the main business processes of the wholesaler by using BPMN

- Cases accepting (PR2): Each pallet accepted is divided in cases. The received cases can be classified into two categories: standard case and mixed case. Each standard case contains medicine packages of the same type, whereas, a mixed case contains different types of drugs within the same case. In the case of standard cases, the worker opens just one case per kind of drug and takes just one single item. This item is identified by using a portable optical device that reads the bar code printed on the secondary package of the drug. This code is transformed into the corresponding lot number and expiration date, which are verified by comparing with the delivery note. Let us observe that this procedure hypotheses that the rest of the case is composed of the same type of medicine product. This might not be true. Instead, for mixed cases, where one case is composed of heterogeneous pharmaceutical products, the worker has to open all these cases and for each he/she has to take one item per kind of drug and verify it by using the previous manual procedure. This kind of verification is not able to guarantee an effective tracing at item level of all received products. This check on all received cases and the validation taking into account the data reported on the delivery note complete the products accepting procedure carried out currently to wholesaler. After this step, all received products are memorized in the Information System (IS) of the wholesaler. The BPMN design of the Case accepting process is shown in Fig. 7(a).

  The *Storage* (S) process, carried out by the warehouseman, is composed of the following activities:

- Tasks planning (S1): this activity is performed by the Information System that prepares the positioning list, where for each type of drug that has to be stored there is a specific quantity and location (i.e., shelf and shelves). The system optimizes the positioning list, taking into consideration different factors: priority of the restoration of the products out of stock (for example the robot line must be always loaded with all high rotation medicines, because the 50% of the orders are dispatched by itself alone), order dispatch priority (often incoming orders are accepted before the medicines are correctly positioned in the warehouse, even if they are physically already in the goods entrance area). The IS notifies the optimized positioning list to the operator through his/her Personal Digital Assistant (PDA) device where he/she can read all positioning details.

- Setting up of positioning units (S2): the operator takes medicines from the cases in the goods entrance area, that have been previously checked (Cases accepting phase) and set them on one or more carts.
- Moving and storing of products (S3): carts are moved in the area of the warehouse identified by the PDA and the operator place each item in its final position one by one with a FIFO (First In First Out) policy (positioning newer packages at the end of the stack in order to leave at the front those with the most recent sell-by date).
- Inventory management (S4): the operator notifies to IS the number, type and position of the medicines just stored through his/her PDA.

Due to the simplicity of the Storage process, it has been identified in the Fig. 5 using the *group* primitive of BPMN labelled with the name “Storage”.

The *Order Picking* (OP) process, carried out by the warehouseman, is composed of the following activities:

- Order choosing (OP1): taking into account several factors (i.e. priority, type of received orders, current status of the storage area, etc.), the IS generates and assigns one picking list for any worker available in that moment. This list is sent to worker that uses a PDA device equipped with a Wi-Fi adapter. The worker takes one case, scans its bar code by using his/her PDA and starts the next activity. The BPMN representation of this sub-process is shown in Fig. 5 inside a group named “Order Picking”.
- Order preparing (OP2): this activity can be carried out in three different modes. These are: Automatic (OP2.1), Manual (OP2.2), and Hybrid (OP2.3). The worker receives instructions about the preparing mode directly from the IS. In Automatic mode, the case related to a given order is composed exclusively by using the robot line. In this case, the picking procedure does not use any employee. All medicine packages included in the picking list automatically fall into a plastic box. On the contrary, the second mode (i.e. Manual) does not use the robot line. The worker, following the indications received by the PDA, reaches the suggested location (i.e. shelf and floor), takes the packages indicated in the picking list and scans them by using the optical reader (i.e. PDA). In the Hybrid mode, the plastic box is filled by using both the previous modes. The BPMN design of the order preparing process is reported in the Fig. 8(a).
- Order closing (OP3): when all products specified in a picking list have been deposited in the plastic box, one copy of the delivery note is printed and included in. The box is closed and labelled with destination references (e.g. name and mail address of the pharmacy retailer). The worker again scans the bar code associated with the box in order to close the order. Furthermore, the IS gives instructions on where the closed box is to be moved towards a particular out gate. Let us observe that in the goods outgoing area there are several out gates that take into account the presence of different couriers that cover different geographic zones. The BPMN design of the Order closing sub-process is shown in Fig. 9(a).

  The *Products Outgoing* (PO) process, not represented in the design reported in Fig. 5, is composed mainly to one activity related to last step that characterizes the products flow within of the wholesaler. A courier takes all closed boxes deposited temporarily at the specific out gate.

The *Return Flows Management* (RFM) process, carried out by the Return Flow office, can be classified into two sub-processes. The first impacts on all products returned from pharmacy retailers. In this case, some employers have to carry out several checks on the returned products. This activity aims to verify, for instance, the product integrity, return reason (e.g., errors in the order delivery, deadline date, etc.), and wholesaler origin. Unfortunately, a wholesaler has problems to verify the wholesaler origin of a specific item because currently there is not an effective item-level tracing system on the whole supply chain. The second sub-process manages, instead, pharmaceutical packages with some irregularities such as deadline date, damaged package, etc. The wholesaler has to organize the return to manufacturer or the transport to disposal company. Currently, all these procedures are manual.

The *Products Deadline Management* (PDM) process is carried out periodically (e.g. 2 times per month) in the wholesaler. Currently, this check is split and assigned among several employees. Each of them receives the specifics related to particular portion of the storage area. He/she reads the deadline date reported on the pharmaceutical package and selects all packages expired or near to expiration that will be managed in the RFM process.

Unfortunately, several processes or activities in the wholesaler are performed in manual mode and so they can be a critical issue, especially, in terms of timeliness (spent time for activity) and correctness. To give a smoother reading, the BPMN design of the last two sub processes (Return Flow Management and Product Deadline Management) has been omitted.

6. Processes re-engineering: TO BE model

Starting from the previous analysis summarized in the AS IS model, the TO BE re-engineering consisted of developing new scenarios, where RFID technology, EPCglobal standard, and B2B are exploited to optimize the critical processes of the wholesaler. The re-engineering of the wholesaler processes is only part of a re-engineering procedure that could be applied on the whole pharmaceutical supply chain. Specifically, the TO BE model of the wholesaler has been developed in order to ensure: traceability at item level, efficient management of logistics activities, and improvement of business messages interchange. The TO BE model is defined hypothesising the use of RFID tags, RFID readers, reader antennas, and software infrastructure as follow reported in detail.

The *Products Receiving* (PR) process is re-engineered as follow:

- Pallet receiving (PR1): The use of passive RFID tags is hypothesised to trace both items and cases. In particular, RFID tags for UHF band are considered because they are able to guarantee high performance in item-level tracing systems (Catarinucci, 2010). One pallet will be composed of tagged cases and each case will be composed of tagged pharmaceutical packages (i.e. items). The goods entries of the wholesaler will be equipped with RFID gates. Each RFID gate could be characterized by two RFID readers (e.g. Impinj Speedway) and eight far field reader antennas in UHF band. This gate configuration is able to guarantee high performance in terms of successful read rate of cases. In the TO BE model, a worker only has to move the incoming pallets through the RFID gate. All cases will be identified and automatic validated with data of an electronic version of the delivery note. In this case, the use of an innovative Business-to-Business (B2B) solution, based on an international standard such as ebXML, is also hypothesised. This solution aims to remove the previous problems (i.e. timeliness and correctness) highlighted in the AS IS model.

In order to understand the difference of the complexity between AS IS and TO BE models, Fig. 6(a) and Fig. 6(b) show respectively the current vision and the re-engineered vision of the "Product Receiving" subprocess.

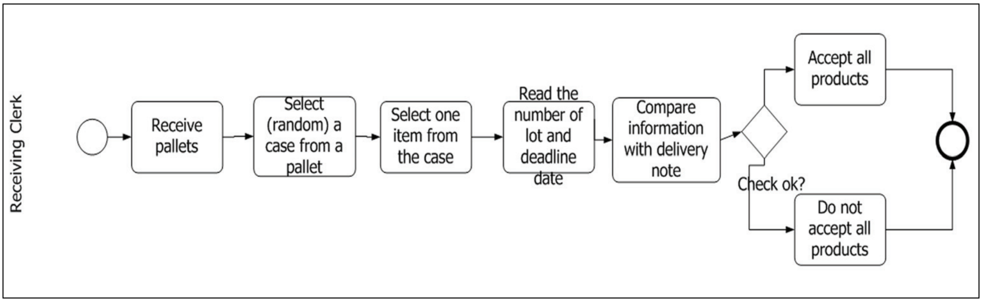


Fig. 6(a). AS IS model of the Product Receiving subprocess

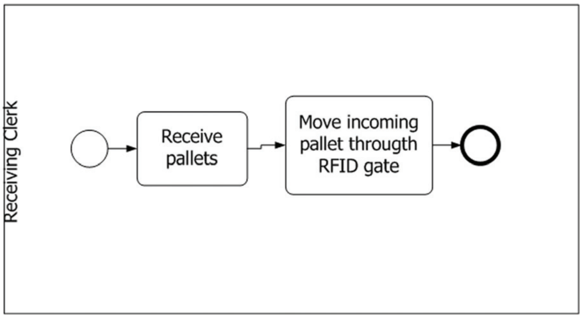


Fig. 6(b). TO BE model of the Product Receiving subprocess

- Cases accepting (PR2): In order to guarantee an efficient item-level tracing system, a particular equipment, similar to that shown in Fig. 3, can be used. It is composed of a conveyor belt, equipped by a line speed regulator, a double containment edge to keep cases in the same position throughout the belt, one RFID reader (e.g. Impinj Speedway), and four near field reader antennas (e.g. Impinj Brickyard) installed within a metallic tunnel. A worker has just to take every case and to put it on the moving conveyor belt. By using this solution, all products contained within each case will be automatic identified. Let us observe that the case remains closed. Furthermore, if a software infrastructure compliant with EPCglobal standard is adopted, the IS of the wholesaler will receive a complete e-pedigree for each received product. Also for this activity, the combined use of RFID and EPC overcome the previous problems and, furthermore, it is also able to optimize also other processes such as the Storage processes.
  The BPMN design of the AS IS and TO-BE model of the Case Accepting sub-process are shown respectively in Fig. 7(a) and Fig. 7(b).
  It has to note that the only operation that the receiving clerk has to do are to take the case and to put it on the moving conveyor belt: the system will do all it is necessary to add the products' information in the information system.

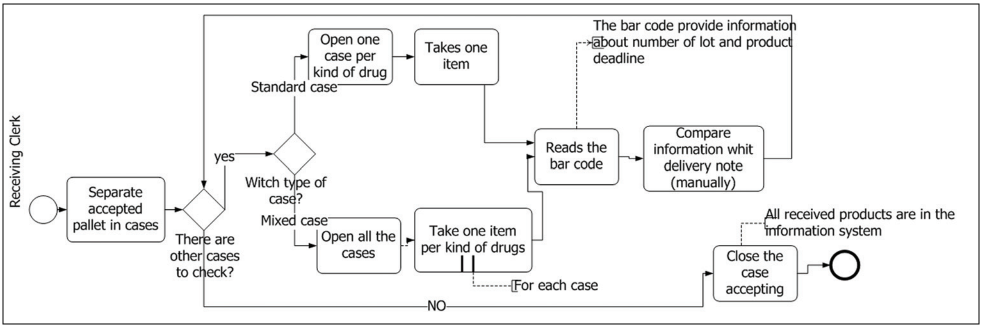


Fig. 7(a). AS IS model of the Case accepting subprocess

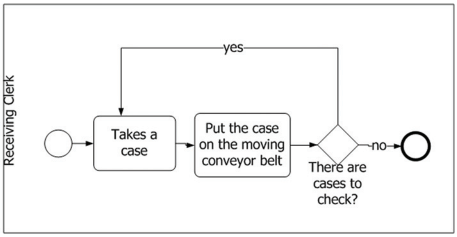


Fig. 7(b). TO BE model of the Case accepting subprocess

The *Storage* (S) process is re-engineered as follow:

- Tasks planning (S1): this activity can use the current knowledge, obtained by RFID and EPC innovations in the previous process, of the information system to optimize the preparation of the positioning lists.
- Setting up of positioning units (S2): This activity could be mainly performed in an automatic way hypothesising the use of different roller conveyors after the RFID tunnel and a software controller that ables to route cases on different carts taking into account the product localization.
- Moving and storing of products (S3) and Inventory management (S4): the worker could wear smart gloves equipped with a portable UHF RFID reader and a near field reader antenna. Let us observe that there are some prototypal models (Muguira, 2009) of these special RFID readers. The use of this special kind of RFID reader allows to optimize storing and inventory management procedures. Another import hypothesis is related to the use of passive UHF RFID tags to identify every location (e.g. every floor of the shelf) of the warehouse. By adopting this technological approach, a simple movement of the worker's hand is sufficient to communicate the exact location and quantities of every product that is in warehouse of the wholesaler. Also for all activities of the process S, the combined use of RFID and EPC is able improve both timeliness and correctness.

  It is important to note that all the random activities made up manually on single item of one case are, in TO BE model, automatic and the only task of the receiving clerk is to move the incoming pallet through the RFID gate. In this case, the IS will be automatically update.

  The combined use of the passive UHF RFID tags applied on every secondary package of medicines and the other enhancements suggested for the activity S3 is able to improve

also the main activities of the *Order Picking* (OP) process. In fact, the activity OP3 may be closed guaranteeing the exact composition (i.e. no errors) of boxes related to orders.
It is important to understand how the business processes change in the reengineered version for the Order Preparing and Order Closing sub-processes of the Order Picking process.
Fig. 8(a) and Fig. 8(b) show the BPMN design of the AS IS and TO BE models of the Order Preparing sub-processes.

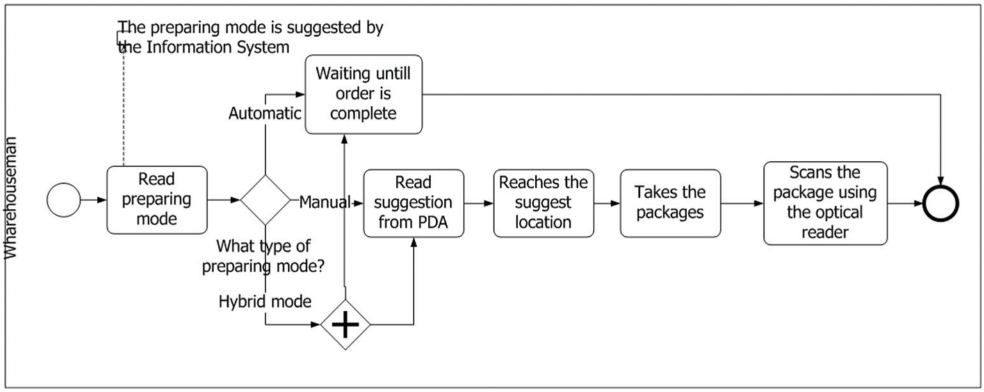


Fig. 8(a). AS IS model of the Order Preparing subprocess

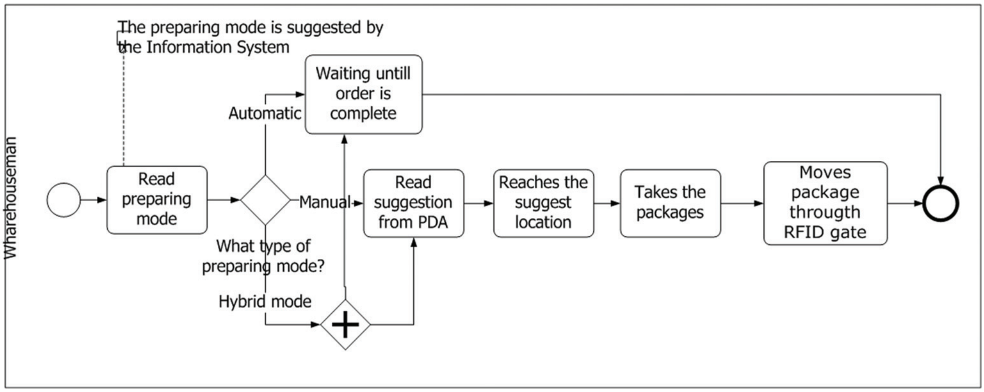


Fig. 8(b). TO BE model of the Order Preparing subprocess

It is important to note that, although, the unique difference between Fig. 8(a) and Fig. 8(b) is related to last task, the effort need to complete this task it is very different: while in the AS IS model the wharehouseman will scan each package in order to add information about the order in the information system, in the TO BE model the wharehouseman has just to put the package through the RFID gate.
Same considerations are valid also for the sub-process Order closing (Fig. 9(a) and Fig. 9(b)). The only difference is in the fourth task that is manual in the AS IS and it is supported by the technology in the TO BE. The wharehouseman has just to move the

box through RFID gate: the execution of the task is more immediate and the information in the information system is more accurate.

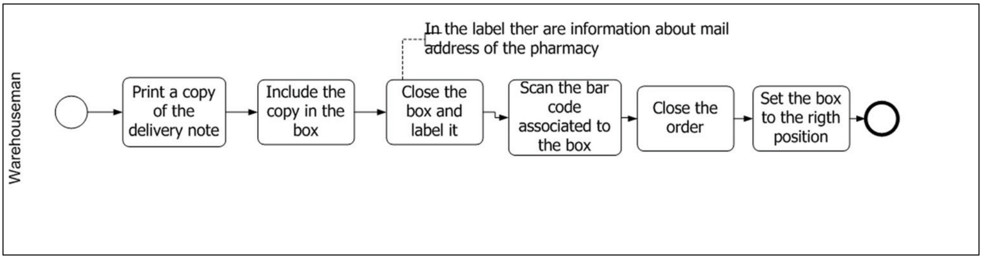


Fig. 9(a). AS IS model of the Order closing subprocess

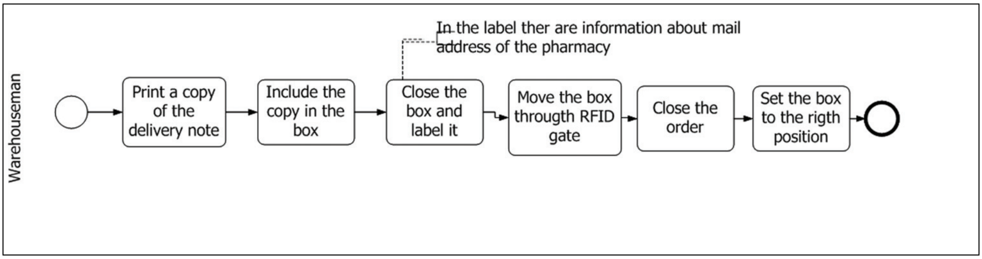


Fig. 9(b). TO BE model of the order closing subprocess

The adoption of the ad hoc re-engineered solutions, able to combine RFID, EPC and B2B, could optimize also the main activities of the *Products Deadline Management* (PDM) process. In fact, the IS should be able to guarantee a complete management dashboard and to minimize the quantity of products that exceed their sell-by date. Furthermore, every manual activity could be avoided.

The use of item-level tracing system based on EPCglobal standard is also able to optimize the main activities of the Return Flows Management (RFM) process. It is sufficient just one instance to demonstrate this. All products returned from pharmacy retailers are easily identified and tracked by using RFID and EPC. A wholesaler could know exactly which products were sold to the same wholesaler. This could improve substantially the RFM process.

7. Discussion about the used performance evaluation method

An analysis based on business processes is a key point to evaluate the effectiveness of modern companies in terms of the added value due to the employment of human and machine resources. The design of the business process is important but not sufficient to appreciate the dynamics that determine how to operate of a company. For this reason, it is also important to be able to measure how the business process is performed.

The measurements of the business process can be useful for several reasons:

- To understand if the business process is effectiveness and, if not, to take some action to improve it (re-engineering);

- To perform comparisons among different companies operating in the same sector (e.g. benchmarking) and thus to study and propose improvements in order to achieve the best practice;
- To evaluate the impact of new technologies in business processes in terms of trade-off between cost and benefits.

The measurement of business process is a delicate task because it is strategic to define indicators and metrics useful for a given applicative scenario. The choice of indicators has to satisfy the following requirements:

- Not many indicators but relevant enough to have a low effort analysis;
- Simple and shared in the whole company in order to make easier the survey and the analysis;
- Unambiguous;
- Able to guarantee a clear and complete vision of the company.

In this chapter, a set of indicators for each business process has been defined in order to evaluate the impact of the use of innovative technologies such as RFID, EPC and B2B. The KPIs (Franceschini, 2009) analysis combined with the CSFs method has been chosen for this kind of study.

The CSF method was presented in (Rockart, 1979). CSF was defined as "few, but important areas where the company must work perfectly in order to have success in business". In other words, the CSFs are defined as the excellence areas where the same company should increase its technological investments in order to reach the business goals. This kind of analysis allows mapping each KPI to one or more CSFs. In this way, main factors where the new technologies could play a very important role are easily identified.

The adopted approach may be synthesized as below reported:

- AS IS analysis of the company aims to identify the main business process of the wholesaler.
- The defined CSFs highlight the key points where the company (in our case the wholesaler) aim to excel in order to obtain its long terms goals.
- Definition of the main KPIs. KPIs are able to show real measurements of efficiency, service level and quality performance of the business processes.
- Mapping between KPIs and CSFs.
- Measurement of the identified KPIs in the AS IS model.
- Design of the re-engineered TO BE model.
- Measurement of the KPIs for the TO BE model.
- Discussion about the potential improvements on the identified KPIs due to the use of the innovative technologies in the business processes.

The cross analysis between KPIs and CSFs is proposed to obtain fundamental information about the quality of the final product and about the effectiveness and correctness of the main business processes.

Taking into account the AS IS analysis reported in Section 5, the main CSF for the wholesaler have been defined in order to understand where the company aims to excel.

An intensive brainstorming and interview activities between the company and the authors allow identification of the following CSFs:

- *CSF 1: to acquire new customers*. In order to acquire new customers it is important to speed up the entry of the drugs into the wholesaler and the management of the recalls;
- *CSF 2: customer's satisfaction*. Customer satisfaction is a priority for all types of companies;

- *CSF 3: quality of drugs delivered to the pharmacy retailers*. This CSF is focused on the activities useful to completing the order;
- *CSF 4: quality of the management of the drugs at the wholesaler*. This CSF is mainly related to inventory procedures and management of the drugs expiration date;
- *CSF 5: human capital*. It is important to make efficient the human capital efficient by minimizing the working hours and maximizing production;
- *CSF 6: interaction with pharmacy retailer*. It is important to answer as soon as possible to the requirements of the pharmacy.

The defined KPI for each sub-process described in the previous sections are reported below in Table 1.

Sub-process name	KPI
Pallet receiving	Item level checking average time
	Case level checking average time
	Pallet level checking average time
	Average errors at drug type level
	Average number of losses at drugs type level
	Item level average errors
	Item level average losses
	Workers for product receiving step
Storage	Item level unit storage average time
	Item level unit preparation average time
	Workers for item level unit preparation step
Order picking	Average fulfilment time per order including release
	Average preparation time per order
	Average number of missing items by using manual picking
	Average number of missing items by using automatic picking
Return flow management	Average number of returned drugs from pharmacy
	Average time for the recall of a drugs
	Average number of returned item for expiration
	Average number of lost drugs
Product deadline management	Average workers to check expiration
	Average number of hours to check expiration
Products outcoming	Average number of incorrect deliveries to pharmacy retailer

Table 1. The defined KPI for each subprocess

The next step of the analysis is to define what KPIs are important in order to obtain each specific CSF. This is a key point for the analysis and was carried out after a brainstorming with the top management and authors. The result of this analysis is showed in the Table 2.

Let us observe that the most indicators related to the sub-process Pallet receiving are mapped with CSF 1 and CSF 2. An efficient management of the pallet receiving sub-process increases the quality of incoming items contributing to improve the quality of the product delivered to the pharmacy retailers. This could impact on the decision of new pharmacy retailers to be served to a particular wholesaler. Furthermore, this could improve the customer.

Sub-process	KPI	CRITICAL SUCCESS FACTORS (CSF)					
		1	2	3	4	5	6
PALLET RECEIVING	Item level checking average time	X	X				
	Case level checking average time	X					
	Pallet level checking average time	X					
	Average errors at drug type level	X	X	X			
	Item level average errors	X	X	X			
	Item level average losses	X	X	X			
	Workers for product receiving step					X	
STORAGE	Item level unit storage average time				X	X	
	Workers for item level unit preparation step					X	
	Item level unit preparation average time		X				X
ORDER PICKING	Average fulfilment time per order including release	X	X				
	Average preparation time per order	X	X				
	Average number of missing items by using automatic picking		X	X			X
	Average number of missing items by using manual picking		X	X			X
RETURN FLOW	Average number of returned drugs from pharmacy		X				X
	Average time for the recall of a drugs		X				X
	Average number of returned item for expiration				X		
	Average number of lost drugs				X		
PRODUCT DEADLINE MANAG.	Average workers to check expiration		X			X	
	Average number of hours to check expiration		X			X	
PRODUCTS OUTCOMIG	Average number of incorrect deliveries to pharmacy retailer		X			X	X

Table 2. KPI – CSF cross analysis

The KPIs related to the order picking are mapped mainly to the CSF 2. As discussed for the pallet receiving case, the order picking sub-process could improve the quality of the product

delivered. The CSF 5 is related to all the indicators that allow measuring the number of workers employed in the related sub-processes. A reduction of the workers effort allows to move the same workers on other activities, more intellectual, and thus to improve the human capital of the company.
In order to evaluate a performance comparison between AS IS and TO BE models exploiting the KPI-based analysis, an intensive measurements campaign is needed. This activity is vey complex because it requires an accurate knowledge of business processes. Furthermore, the estimation of the defined indicators for the TO BE model is often carried out exploiting a simulation approach or past experimental experiences. This comparison is not reported here because its goal was to illustrate a useful approach able to evaluate potential benefits due to the combined use of the three innovative technologies in the pharmaceutical supply chain. Let us observe that the KPI analysis is still in progress when authors are writing this chapter. For this reason, only few experimental results are mentioned here in order to report some examples that are able to anticipate the substantial improvements derivable by a combined use of these innovative technologies (i.e. RFID, EPCglobal, and ebXML) in the pharmaceutical supply chain. For example, the item-level checking time in the AS IS analysis is equal about to 7 min and the Average Errors at level of drug type is about 70 errors on 109 total product types. The TO BE analysis allowed to estimate that the time and errors related to the products receiving process could be significantly reduced. The average time need to carry out the several checks is almost zero because in the re-engineered model workers are involved just in the moving activities. The checks at every level (i.e. pallet, case, and item) are performed by auto-identification systems based on the RFID technology. Furthermore, the combined use of RFID, EPCglobal e B2B will provide the possibility to remove all errors that in the AS IS model have been measured in the Product Receiving process. Also the number of workers needed for the activities in the several sub processes could be significantly reduced. Furthermore, the re-engineered TO BE model is able to guarantee that the orders prepared to be delivered to pharmacy retailers are error-free because the last point to check, characterized by a RFID gate connected to IS, is able to identify any discrepancies avoiding to get out from wholesaler orders not fully comply with the requests done by retailers through the B2B system.
Finally, the comparison in terms of defined KPIs for Return Flow Management (RFM) and Product Deadline Management (PDM) hypothesises that KPIs for the TO BE model converge to zero. A last significant data is related to the number of workers employed to check the expiration date of drugs that passes from 28 to 1 in the re-engineered model. These few examples are useful to confirm the encouraging indications reported in the cross analysis KPI-CSF in Table 2. These innovative technologies, used in combined mode, are able to guarantee a great boost for the company improving the interaction between wholesaler and pharmacy retailer. There is a valorisation of the human capital. The re-engineering activity, in fact, allow to reduce the average numbers of workers both in the pallet receiving sub-process and in the product deadline management and thus there is a reduction of the average time useful to complete the task of each worker. This will provide to the company the possibility to define a requalification programme for workers.

8. Conclusion and future works

This chapter represents a first attempt to evaluate potential benefits of the combined use of the innovative technologies, such as RFID and EPCglobal, in item-level tracing systems in the pharmaceutical supply chain.

In particular, a processes analysis has been performed on the wholesaler that represents a stakeholder very interesting, characterized by many constraints and high product flows. The current vision of the main business processes of the wholesaler has been described through the definition of the AS IS model by using the BPMN notation. This analysis allowed defining a possible re-engineered (TO BE) model based on the assumption of a complete installation of the combined use of RFID, EPCglobal, and ebXML in order to improve traceability and business messages interchange in the pharmaceutical supply chain. Furthermore, significant KPIs and CSF have been defined for the wholesaler in order to make easier a future quantitative analysis of the benefits due to the re-engineering by the innovative technologies described above. At this regard, a combined analysis between KPI and CSF allowed to understand what factors, important for the wholesaler, could be improved. In particular, the analysis carried out promises significantly benefits on the main business processes of the wholesaler, mainly, in terms of increase of correctness and timeliness and reducing of the number of workers.

The next step is to evaluate the performance comparison between AS IS and TO BE models exploiting the defined KPIs. This comparison will be able to demonstrate how the combined use of these technologies is able to guarantee significant improvements of the main business processes in terms of increase of correctness and timeliness and reducing of the number of workers. Realistic estimates of the selected performance indicators will be derived exploiting both consolidated experimental experiences in the use of EPC-aware solutions and ad hoc simulation tool able to reproduce accurately the re-engineered (TO BE) model.

9. Acknowledgment

The authors wish to acknowledge the wholesaler Farpas (Bari, Italy) for their practical contribution to research, and Dr. Gabriella Spalluto, collaborator of the IDA Lab group (Salento University, Italy), for her efforts in the processes analysis of the wholesaler.

10. References

Acierno, R., De Riccardis, L., Maffia, M., Mainetti, L., Patrono, L., Urso, E. (2010). Exposure to Electromagnetic Fields in UHF Band of an Insulin Preparation: Biological Effects. *Proceeding of IEEE International Conference on Biomedical Circuits and Systems (BIOCAS2010)*. November 3-5, 2010, Paphos, Cipro.

Acierno, R., Maffia, M., Mainetti, L., Patrono, L., Urso, E. (2011). RFID-based Tracing Systems for Drugs: Technological Aspects and Potential Exposure Risks. *Proceedings of International IEEE Biomedical Wireless Technologies, Networks, and Sensing Systems (RWS2011-BioWireless*). Phoenix, AZ, USA, January 16-20, 2011.

Barchetti, U., Bucciero, A., De Blasi, M., Mainetti, L. and Patrono, L. (2009). Implementation and Testing of an EPCglobal-aware Discovery Service for Item-level Traceability. *Proceedings of IEEE International Conference on Modern Ultra Telecommunications*, St. Petersburg, Russia, October 2009.

Barchetti, U., Bucciero, A., De Blasi, M., Mainetti, L. Patrono, L. (2010). RFID, EPC and B2B convergence towards an item-level traceability in the pharmaceutical supply chain, *Proceeding of IEEE International Conference on RFID-Technology and Applications*, ISBN:978-1-4244-6699-3, Guangzhou, China, June 2010.

Barchetti, U., Bucciero, A., Guido, A.L., Mainetti, L., Patrono, L. (2011). Supply Chain Management and Automatic Identification Management convergence: Experiences in the Pharmaceutical Scenario. In: Pengzhong Li ED. *Supply Chain Coordination and Management.* ISBN: 978-953-307-437-5. VIENNA: IN-TECH Education and Publishing. (April 2011)

Bottani, E. (2008). Reengineering, Simulation and Data Analysis of an RFID System. *Journal of Theoretical and Applied Electronic Commerce Research*, vol. 3, issue 1, April 2008, pp. 13-29.

Bottani, E. (2009). On the impact of RFID and EPC Network on traceability management: a mathematical model. *International Journal of RF Technologies: Research and Applications*, Taylor&Francis, Vol. 1, No. 2, June 2009, pp. 95-113.

Bottani, E., Ferretti, G., Montanari, R., Rizzi, A. (2009). The impact of RFID technology on logistics processes of the fashion industry supply chain. *International Journal of RF Technologies: Research and Applications*, Taylor&Francis, Vol. 1, No. 4, Dec. 2009, pp. 225-252.

Business Process Modeling Notation Specification, OMG (2006). Availaible on: http://www.bpmn.org/

Catarinucci, L., Colella, R., De Blasi, M., Patrono, L., Tarricone, L. (2010). Improving Item-Level Tracing Systems through Ad Hoc UHF RFID Tags, *Proceeding of IEEE Radio and Wireless Symposium*, New Orleans, LA (USA), January 2010, pp. 160-163.

Cox, F. C. A. I., Sharma, V. K., Klibanov, A. M., Wu, B.-I., Kong, J. A., & Engels, D. W. (2006). A method to investigate non-thermal effects of radio frequency radiation on pharmaceuticals with relevance to RFID technology. *Proceedings of IEEE International Conference Engineering in Medicine and Biology Society. Vol 1*, 2006, pp. 4340-4343.

De Blasi, M., Mighali, V., Patrono, L., Stefanizzi, M.L. (2009). Performance Evaluation of UHF RFID tags in the Pharmaceutical Supply Chain, *Paper presented at The Internet of Things - 20th Tyrrhenian International Workshop on Digital Communications*, ISBN 978-1-4419-1673-0, pp. 283-292, Sardinia(Italy), September 2009.

EPCglocal Inc. (2005). *EPCglobal standard overview.* http://www.gs1.org/gsmp/kc/epcglobal.

FDA (2004). Radiofrequency Identification Feasibility Studies and Pilot Programs for Drugs, *CPG. Sec. 400.210 U.S. FDA*, November 2004.

Finkenzeller, K. (2003). RFID *Handbook, Fundamentals and Applications in Contact-less Smart Cards and Identification*, Wiley & Sons, ISBN 978-0-470-84402-1.

Franceschini, F., Galetto, M., Maisano, D. (2009). Management by Measurement: Designing Key Indicators and Performance Measurement Systems. *Springer Berlin Heidelberg,* ISBN: 978-3642092275.

Fuhring, S. (2009). Interview on the new legal requirements relatedto the secure european pharmaceutical supply chain. *European Commission*, Brussels, Belgium.

Gaukler, G.M. (2005). RFID in supply chain management. *Dissertation, Standford University, 2005*.

Gandino, F., Montrucchio, B., Rebaudengo, M., Sanchez, E.R. (2007). Analysis of an RFID-based Information System for Tracking and Tracing in an Agri-Food chain. *Proceedings of the 1st Annual on RFID Eurasia*, Instanbul, 5-7 Sept., 2007.

Gunasekaran, A., Ngai, E.W.T. (2005). Build-to order supply chain management: a literature review and framework for development. *Journal Oper. Manag.*, vol. 23(5), 2005, pp. 423-451.

Hardgrave, B.C. (2009). RFID in Transportation and Logistics. *McGraw-Hill 2009 Yearbook of Science & Technology*, New York, NY, McGraw-Hill, 2009, pp. 17-19.

Hardgrave, B.C., Langàord, S. , Waller, M., Miller, R.E. (2008). Improving the Retail Supply Chain with RFID: Reducing Out of Stocks. MIS Quarterly Executive, 7 (4), December 2008, pp. 113-124.

Hou, J.L., Huang, C.H. (2006). Quantitative performance evaluation of RFID applications in the supply chain of the printing industry. *Ind. Manag. Data Syst.*, Vol. 106(1), 2006, pp. 96-120.

Lee, Y.M., Cheng, F., Leung, Y.T. (2004). Exploring the impact of RFID on supply chain dynamics. *Proceedings of the 36th conference on Winter simulation*, ISBN:0-7803-8786-4, R .G. Ingalls, M. D. Rossetti, J. S. Smith, and B. A. Peters, eds.

Loebbecke, C. (2005). RFID Technology and apllication in the retail supply chain: the early metro group pilot. *Proceedings of the 18th conference on eIntegration in action*, Bled, Slovenia, June 6-8, 2005.

Mirowski, L., Hartnett, J., Williams, R. (2009). An RFID Attacker Behavior Taxonomy. *IEEE Pervasive Computing Magazine*, Oct-Dec. 2009, pp.79-84.

Muguira, L., Ruiz-de-Garibay, J. Vazquez, J.I. (2009). Interacting with the digital world through RFID-powered gadgets. *Proceedings of International IEEE SoftCOM 2009*, September 2009, Split, Croatia.

Niktin, P.V., Rao, K.V. (2006). Performance Limitations of Passive UHF RFID Systems. *Proceeding of IEEE International Symposium on Antennas and Propagation Society.* Albuquerque, NM, 9-14 July 2006, pp. 1011-1014.

Pramataris, K.C., et al. (2005). Towards Smarter supply chain and demand-chain collaboration practices enabled by RFID technology. *The Hermes Newsletter, Eltrum*, March-April 2005.

Rockart, J. (1979). Chief executive define their own data needs. *Harward business Review*, 57(2) March-April, 1979.

Schroeter, J. (2008). *Pharma Serialization and Data Carrier Choices, Tracking & Tracing Pharmaceutical Products*, Spring 2008.

Srivastava, B. (2004). Radio frequency ID technology: the next devolution in SCM. *Business Horizons, Elsevier*, vol. 47(6), 2004, pp. 60-68.

Thiesse, F., Floerkemeier, C.; Harrison, M.; Michahelles, F.; Roduner, C. (2009). Technology, Standards, and Real-World Deployments of the EPC Network. *IEEE Internet Computing Magazine*, *13*(2), pp. 36-43.

Ustundag, A. Cevikcan, E. (2007). Return on Investment Analysis for Evaluation of RFID Implementation on Cargo Operations. *Proceedings of the 1st Annual on RFID Eurasia*, Instanbul, 5-7 Sept., 2007.

Uysal, D. D., Emond, J.-P.; Engels, D.W. (2008). Evaluation of RFID performance for a pharmaceutical distribution chain: HF vs. UHF, *Proceedings of IEEE international conference on RFID*, Las Vegas, Nevada, USA, April 2008.

Uysal, I., DeHay, P.W.; Altunbas, E.; Emond, J.-P.; Rasmussen, R.S.; Ulrich, D. (2010). Non-thermal effects of radio frequency exposure on biologic pharmaceuticals for RFID applications. *Proceedings of IEEE International Conference on RFID*, Orlando, FL, USA, April, 2010, pp. 266-273.

Yue, D., Wu, X., Bai, J. (2008). RFID Application Framework for Pharmaceutical Supply Chain. *Proceedings of the IEEE International Conference on Service Operations and Logistics, and Informatics*, Beijing, Oct. 2008, pp. 1125 – 1130.

8

Business and Environment Performance Evaluation in Supply Chains: A Formal Model-Driven Approach

Gabriel Alves Jr., Paulo Maciel, Ricardo Lima and Fábio Magnani
Federal Univestity of Pernambuco, Recife-PE, Brazil

1. Introduction

While economic and service level indicators were adequate to show the performance of supply chains (SCs) in the past, nowadays, environment indicators are gradually becoming more relevant (Beamon, 1999). Many prominent companies and academic research groups around the world are making efforts to provide environmentally responsible products and services. These topics are subjects of intensive study not only due to the respective impact of the production and transport systems in our planet but also particularly related to the image these companies aim to project to the society (Beamon, 1999; Srivastava, 2007). Moreover, supply chains' managers must carry about optimizing an endless number of variables that might impact costs and operational performance. These variables usually get in conflict between themselves. For instance, increasing the amount of stored goods might reduce the lead time to customers, but also increase storage costs and environment impacting resources like energy. Modelling is quite often employed for quantitative analysis of SCs (Simchi-Levi et al., 2000). One of the main advantages in use modelling techniques is the possibility of analyse "what-if" questions. Thereby, it is possible to evaluate different scenarios looking for the most optimized ones. Although the strict mathematical modelling is one of the most used approaches in the evaluation of SCs (Cohen & Lee, 1988; Sabri & Beamon, 2000; Simchi-Levi et al., 2005), it is not always the best option. Such a method requires some simplifications that might incur inaccurate results. Other modelling techniques, like queueing networks (Gross, 2009), Markov Chains (Norris, 1998), and Petri Nets (Bolch et al., 2006; Desrochers & Al-Jaar, 1994; Jensen, 1997), might be adopted so as to overcome this problem.
Petri nets were proposed by Carl Adam Petri in 1962 (Petri, 1962), and have evolved into a formalism employed in different areas such as informatics, electronics and chemistry since then. This modelling technique has a graphical representation that supports the specification and design of systems. Having a solid mathematical foundation, Petri nets are very well suited for the numerical evaluation of complex systems. Different extensions were proposed to this formalism, including the concept of time (Ramchandani, 1994) after Carl Petri's initial work. Petri nets have been already adopted for evaluating manufacturing systems and SCs (Alves et al., 2010; Desrochers & Al-Jaar, 1994; Makajic-Nikolic et al., 2004; Silva & Maciel, 2005; Viswanadham & Raghavan, 2000). Stochastic Petri nets (SPNs) (Bolch et al., 2006; German, 1994; Haas, 2002; Marsan et al., 1995) deals with probabilistic distributed times, which are approximated to distribution functions like exponential, Erlang and uniform.

The framework that is going to be presented in this chapter uses stochastic reward nets (SRNs) (Bolch et al., 2006), which are a specific type of SPN, for modelling and evaluating SCs. The SCs are modelled using a bottom-up approach, based on pre-defined components (Alves et al., 2010), that model specific entities and processes of the real system, focusing on the product/information flows. This approach allows using SRNs as the modeling technique even without further knowledge on it. This is advantageous for industrial users that are not familiar with Petri nets.

The library of models allows making experiments by changing variables like the transportation and production delays, supply chains' facilities relationship, replenishment policies and energy sources. The component-based modelling together with a well-defined composition process guarantee that the final model will have some desired Petri net properties (Murata, 1989). A numerical solution based on the continuous-time Markov chain (CTMC) (Bolch et al., 2006; Norris, 1998) is thus possible, either for obtaining transient or steady state solutions. The component-based modeling tackles the requirement of verifying the model's correctness. However, a validation of the model might still be required. While the the components guarantee that the structure of the systems will be correctly represented in the Petri net notation, there is no guarantee that the model's parameters (e.g. mean time between failures and tasks delays) were assigned correctly in the model.

Finally, this chapter will depict how to use a single model to assess business and environment indicators. This facet helps on evaluating possible business and environment trade-offs. Besides, we will show the advantage of using the exergy concept (Kotas, 1985; Szargut et al., 1988) to quantify the impact of alternative energy sources.

The remainder of this chapter is organized as follows. Section 2 presents a brief introduction to supply chains and sustainability. Some models that are usually adopted when evaluating performance of systems are discussed in section 3. This section will be focused on SRNs, since the proposed framework uses this model. Section 4 details metrics, evaluation process of the framework. The library of models is presented in section 5. Section 6 shows a case study conducted using the framework. Finally, concluding remarks are done in section 7.

1.1 Related works

A brief review of some related works is now going to be presented. An approach for modeling logistics networks based on high-level timed colored Petri nets is proposed in van der Aalst (1992). Some components are proposed to model supply chain entities, and analysis methods are proposed for this kind of Petri nets. However, time is associated with tokens and represented by an interval specified by its lower and upper bounds in this type of model, making it hard to follow the natural association of time to activity delays (transitions) as followed in most other timed Petri nets.

Stochastic colored Petri nets are used to model and evaluate logistics systems in Zimmermann (2007); Zimmermann et al. (2007). In such colored Petri nets, the metrics are almost often computed through the simulation of a program resulting from the model specification. Another kind of Petri nets, called Batch Deterministic Stochastic Petri Nets (BDSPN), is proposed in Chen et al. (2005) to model and evaluate supply chains. It extends Deterministic and Stochastic Petri nets (DSPNs) (Marsan & Chiola, 1987) including batch places and tokens. Few works have followed using this kind of net so far (Labadi et al., 2007). Using such nets is unfeasible due to the lack of supporting tools.

In Viswanadham & Raghavan (2000), the authors evaluate a supply chain considering make-to-stock (MTS) and assembly-to-order (ATO) policies. To achieve their goals, authors consider that operations occur in pipeline and not in parallel such as in most supply chains. A multi-echelon make-to-stock supply chain is evaluated in Raghavan & Roy (2005) using Stochastic Petri Nets.

One of the few proposals for performance evaluation of supply chains with SPN modules is presented in Dotoli & Fanti (2005). The entities and flows are represented through the composition of these modules, but such process requires some changes on basic models. Although the use of modules supports the supply chain modeling, the lack of a well-defined composition process restrains an automatic parsing from a high-level representation into an SPN model.

Inventory management of supply chain nodes is closely related to distribution strategies. The inventory replenishment policy of intermediary entities significantly influences the overall supply chain's QoS. A well-known problem that can occur in a supply chain is the *Bullwhip Effect* (Lee et al., 1997). The *Beer Game* (Lee et al., 1997; Simchi-Levi et al., 2000) aims at representing such a problem. Makajic-Nikolic et al. (2004) model this game via a timed hierarchical colored Petri Net (Jensen, 1997). The work also conducts experiments to evaluate the impact of different replenishment strategies over individual participants and the entire supply chain.

An extensive state-of-the-art review for the green supply chain management is presented in Srivastava (2007). The author classifies the existent works about green supply chains (GrSCs) according to the sub-areas of this discipline and the used evaluation technique. Some of the classified sub-areas are: products manufacturing and remanufacturing, life cycle assessment (LCA), reverse logistics, network design, and waste management. Regarding the technique used, the author classifies works from empirical methods to the mathematical modeling, including the linear programming (Louwers et al., 1999), queueing theory (Guide et al., 2005; van der Laan et al., 1996), Markov chains (MCs) (Fleischmann et al., 2002; van der Laan & Salomon, 1997), and Petri nets (Moore et al., 1998).

Veleva proposes a methodology for monitoring and evaluating indicators in sustainable production systems (Veleva & Ellenbecker, 2001). The author determines a five-level evaluation system, where different sustainability indicators are addressed by each level. The first level checks the compliance to standards and laws. The second level assess the performance of the consumption and disposal of resources. The third level is concerned about the effects of the system over workers, public health and environment. The fourth level the evaluation goes beyond the system boundaries, checking the product life cycle and the supply chain impacts on environment. Finally, the fifth level evaluation measures indicators regarding the impacts of the system on the economy, society and environment of the local (where the company is located) and global (where the company sells its products) communities.

The Life Cycle Assessment (LCA) is a well known method for evaluating the environment impacts owing to the product existence (Cascio, 1999; Heijungs et al., 1992; ISO, 2006). Currently, there are some commercial tools used for LCA (e.g. GaBi (GaBi Software – product sustainability, 2010) and SimaPRO (SimaPRO LCA Software, 2010)). Within these tools, metrics like the Global Warming Potential (GWP) (IPCC, 2001) are estimated based on a conversion database of resources' consumption. Nevertheless, these tools are not well suited to conduct a performance evaluation of the activities involved in the product life cycle (e.g. machines utilization, reliability analysis), since it is not adressed by LCA.

The exergy analysis have also been employed to measure and compare the use of different energy sources in systems and processes (Oliveira Filho, 1995). This kind of analysis aims at comparing the energetic efficiency and destruction considering the Second Law of Thermodynamics (Kotas, 1985).
Some efforts have also been made with the objective of combine exergy and LCA. These efforts have resulted in evaluation methods like the *Exergetic Lyfe Cycle Assessment* (ELCA) (Cornelissen & Hirs, 2002) and the *Lyfe Cycle Exergy Analysis* (LCEA) (Gong & Wall, 2001). These methods have been employed in different areas like electricity production (Rosen & Dincer, 2003), supply chains (Apaiah et al., 2006), and IT companies (Lettieri et al., 2009).

2. Green supply chains

This section provides a brief introduction to some sustainability issues in supply chains. The beginning of this section describes some traditional approaches that are usually used when assessing sustainability in supply chains. Section 2.1 presents the exergy concept and its applications in the field of sustainability.
A supply chain (SC) manager must carry out all the activities necessary for producing and delivering goods to customers. Acquisition of raw materials, manufacturing, assembling and transportation are some of those activities. The Green Supply Chain (GrSC) extends the supply chain by considering the backward flow and the environment impacts of the SC's activities. The backward flow is known as reverse supply chain. The GrSC schema is presented in Figure 1, which was adapted from Beamon (1999) and Cash & Wilkerson (2003).

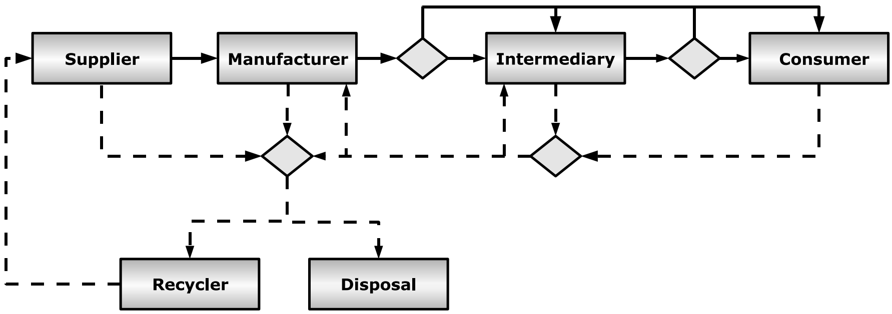


Fig. 1. Green Supply Chain schema.

Regarding the schema of Figure 1, the dashed lines represents the reverse flow of the green supply chain (Beamon, 1999; Cash & Wilkerson, 2003). The self-loop in the intermediary was included to represent a *n-level* supply chain (Simchi-Levi et al., 2000), that can have several intermediaries (e.g. distributors and wholesalers). Each line represents the movement of goods, which might include the transportation activity. The "disposal" rectangle represents the final disposal of the goods in landfills or for composting.
Several organizations moved towards the proposal of practices and management techniques that could help companies to provide environmentally conscious products and services. The *International Organization for Standards* (ISO) developed the ISO 14000 series standard with this objective (Cascio, 1999; ISO, 2006). Environmental management systems (EMS), environmental performance evaluation (EPE), and life cycle assessment (LCA) are some of the areas covered by this series. This chapter will be focused on EPE and LCA.

The ISO 14031 provides guidelines for the selection and use of environment performance indicators (EPIs) in the EPE of organizations. This standard defines an EPI as and *expression that is used to provide information about environmental performance or the condition of the environment*. The EPIs can be expressed as relative or absolute measurements and can also be aggregated and/or weighted. These indicators can be classified as: *Absolute indicators* are directly obtained from an input-output analysis. *Relative indicators* are expressed as a reference to other variables like the production in tons, number of employees, etc. *Indexed indicators* are expressed as a percentage with respect to a total, or a percentage change to previously assessed values. *Aggregated indicators* sums indicators that have the same unit, which are assessed over more than one production stage. *Weighted indicators* assigns different weights to assessed variables of a productions stage depending on its importance.

Absolute EPIs must be used carefully. An increment on the demand or production of a company almost often incurs in an expected increment on these indicators. For instance, increasing the production implies an increment on the consumption of raw materials. In such a sense, relative indicators are usually more accurate to depict the environment performance than absolute indicators. Following are some examples of EPIs (Beamon, 1999; Cascio, 1999): *relative/absolute quantity of specific pollutant emitted (e.g.* CO_2, SO_2, *CFCs)*; *relative/absolute quantity of hazardous substances emitted*; *relative/absolute kWh of electricity consumed*; *relative/absolute amount of waste produced*; *percent of raw materials from renewable resources*; *percent of waste recycled*; *investment in environmental programs*; *amount of regulatory violations or fines*; *number of environmental incidents/acidents*.

A life cycle assessment (LCA) intends to measure the social, environmental and economical impacts of a product or service (Cascio, 1999; ISO, 2006). This assessment must be accounted for the extraction/production of raw materials, manufacture, distribution, use, and disposal including the transportation necessary for any of the stages of the product's life cycle. LCA can be conducted for a single product or for an entire company. Regarding the boundaries of the LCA, it can be classified as follows:

gate-to-gate: looks at a single value-added process in the entire supply chain;

cradle-to-gate: looks at the product life cycle from raw materials and manufacture ("cradle") until the product leave the factory's gate;

cradle-to-grave: beyond that steps considered in the cradle-to-gate, this type of LCA considers the remaining life cycle until the disposal of the product;

cradle-to-cradle: beyond that steps considered in the cradle-to-grave, this type of LCA considers reverse and recycling processes of the product;

The framework presented in this chapter uses the *gate-to-gate* LCA. This type of LCA can be composed for each stage of the supply chain in order to achieve a complete LCA. One of the units that can be used in the LCA is the *Global Warming Potential* (GWP). It was proposed by the *Intergovernmental Panel on Climate Change* (IPCC) in order to allow comparing the radiative effect of different substances considering a time horizon (IPCC, 2001). The CO_2 equivalent (CO_2e or $CO_2Eq.$) is the unit that measures the GWP. It expresses the radiative effect of a substance considering the GWP of the CO_2 as reference (DEFRA - Department for Environment, Food and Rural Affairs, 2009; Frischknecht et al., 2005; IPCC, 2001). The GWP of the CO_2 is thus 1. The framework presented in this chapter will be focused on the GWP measurement, despite of other environment impacts like noise, acidification, and desertification.

2.1 Exergy and sustainability

The *Second Law of Thermodynamics* (SLT) asserts that there will always be loss of quality when converting a type of energy into another type. The concept of *exergy* is linked to the SLT, since it assess the amount of energy that can be converted into useful work, that means the quality of the energy (Kotas, 1985; Szargut et al., 1988). Because of that *available energy*, *available work* or simply *availability*, are also synonyms of exergy. The amount of energy that is not available is called *anergy* (Sato, 2004).

Let E, X and A be the respective amounts of energy, exergy and anergy, thus the equation $E = X + A$ depicts the relation between these amounts. Such a relation can also be expressed as in Equation 1, by using an energy efficiency factor α.

$$X = \alpha E \therefore A = (1 - \alpha)E \tag{1}$$

Let X_{in}, X_{out}, X_{diss} and X_{dest} be the amount of input, output, dissipated and destroyed exergy in a process. Since $X_{dest} = (1 - \eta_{II})X_{in} - X_{diss}$, where η_{II} is the exergetic efficiency of the process, the SLT is mathematically represented by Equation 2.

$$X_{in} = X_{out} + X_{diss} + X_{dest} \therefore \eta_{II} = \frac{X_{out}}{X_{in}} \tag{2}$$

The chemical exergy x_{ch} of a material can be calculated in function of its mass composition (Kotas, 1985). It represents the amount of useful energy in any kind of material, including energy sources. Equation 3 depicts the total chemical exergy X (in kJ) for a mass m (in kg) of a material whose chemical exergy is depicted by x_{ch} (in kJ/kg). The physical and chemical exergies fully defines the total exergy of a system. Thereby, Equation 4 expresses the exergy of a system with kinetic energy ke, potential energy pe, enthalpy h, entropy s and j elements in its chemical composition, at a reference environment with enthalpy h_0, entropy s_0, and temperature T_0. Considering that the system is in physical equilibrium with the reference environment, the total exergy is its chemical exergy.

$$X_{ch} = m x_{ch} \tag{3}$$

$$X = ke + pe + [(h - h_0) - T_0(s - s_0)]m + \sum_j X_{ch,j} \tag{4}$$

Szargut et al. (2005) proposes several values for the chemical exergy of chemical elements. These values were calculated based on a reference environment, which the authors claim to become an international reference for evaluating the natural resources on Earth. These values can be used in order to calculate the chemical exergy of any resource of a supply chain, including waste and raw materials. Although, it might be cumbersome to identify the exact chemical composition of each material used in the supply chain. To overcome this problem, some authors proposes approximations to calculate the chemical exergy of wasted materials (Ayres et al., 1998). Despite of this, using exergy for any sort of resources is a awkward task.

There are several proposals that consider the exergy analysis for measuring sustainability performance. Extended Exergy Account (EEA) (Sciubba, 2003), Cumulative Exergy Consumption (CEC) (Szargut & Morris, 1985), Life Cycle Exergy Analysis (LCEA) (Gong & Wall, 2001), Exergetic Life Cycle Assessment (ELCA) (Ayres et al., 1998; Cornelissen & Hirs, 2002) are some of these approaches, which usually measure the amount of exergy consumed, or destroyed, in a process. Thus, the less exergy a process consumes, or destroys, the most sustainable it is. Some proposals also joins exergy, cost and

other aspects to provide a general insight of the analysed process (Rosen & Dincer, 2003; Sciubba, 2003).
The *life cycle exergy analysis* (LCEA) (Gong & Wall, 2001) aims at measuring the total input and output exergy in the product life cycle, also differing renewable and non-renewable resources. It divides a system in three stages: construction, operation, and clean up. In the construction and clean up stages, the system indirectly consumes exergy ($E_{indirect}$). During the operation the system indirectly consumes exergy for its maintenance ($E_{indirect}$) and directly consumes it in order to produce finished goods (E_{in}). Besides, the finished good also has an amount of exergy (E_{pr}).
When the system uses non-renewable resources, there will be a degradation of such resources, thus $E_{pr} < E_{indirect} + E_{in}$. When renewable resources are used, the LCEA does not consider the input exergy of these resources. Thus, in a time $t_{payback}$, all the exergy that was indirectly consumed will be compensated by the product. In this case the net exergy product ($E_{net,pr}$), is the amount of exergy generated beyond $t_{pay\,back}$ and is measured as: $E_{net,pr} = E_{pr} - E_{indirect}$.
The *exergetic life cycle assessment* (ELCA) (Cornelissen & Hirs, 2002), aims at measuring the exergy destruction due to the irreversibility of processes, quantifying the depletion of natural resources. The ELCA allows expressing the resources depletion when renewable resources are not used. But, even when these resources are used, a high irreversibility may represent an inefficient consumption of these resources. In such a sense, the depletion of non-renewable resources is measured by subtracting the exergy from renewable resources from the total irreversibility of the system, as: $D_{natural\,resource} = I_{life\,cycle} - E_{renewables}$, where $I_{life\,cycle}$ is the total irreversibility in the process life cycle and $E_{renewables}$ is the amount of exergy from renewable resources. Besides, the irreversibility of each process as measured as $I = X_{out} - X_{in}$, where X_{out} and X_{in} are the respectives output and input chemical exergy of each process.
Due to the difficulty in obtaining reliable exergetic values for any sort of material (Ayres et al., 1998), we adopt the exergy analysis (LCEA) just for resources that are consumed for energetic purposes. The GWP analysis (LCA) is used for the other resources instead. Furthermore, the LCEA provides reliable results when comparing the environment impacts of using different energy sources. Such an approach supports the evaluation of "what-if" questions when conducting an EPE without increasing the complexity of this activity.

3. Performance models

This section aims at providing some insights about different evaluation methods that are often used when measuring systems performance. A performance evaluation model aims at representing a real system, through mathematical or simulation methods, in order to assess measures. Experiments that can be easily conducted in a model could be hardly, or even impossible, to be done in the real system. The evaluation model can be grouped into: analytical, numerical, and simulation. These methods will be discussed in the following subsections.

3.1 Analytical solution

Analytical solution methods try to represent the real system using mathematical expressions. This kind of solution is well-suited for simple systems. Although, the complexity of a real system can forbid an analytical solution. There are several manners of analytically representing a system. In the specific case of supply chains there are models to evaluate problems like that ones related to inventory replenishment policies (Ballou, 2004;

Simchi-Levi et al., 2000), the logistics network (Narahari & Biswas, 2007; Simchi-Levi et al., 2005), and also to support the decision making based on different variables (e.g. cost, service level, environment) (Louwers et al., 1999). But, these methods tend to make several simplifications. For instance, defining the best lower inventory level of a facility in a multi-echelon supply chain can be cumbersome using analytical models.

Queueing theory (Gross, 2009) is an analytical method that was adopted in different areas, including supply chains (Guide et al., 2005; van der Laan et al., 1996). This method aims at representing systems through queues. A queue system is represented by 6-tuple $A/S/m/B/N/SD$, where A is the interval between arrivals, S is the service time, m is the number of servers, B is the maximum size of the queue, N is the population (can be infinity) and SD is the service policy of the system. The times related to A and B can follow distributions like the Erlang, exponential, deterministic, etc. Service policies related to SD can be, for instance, *First-Come-First-Served*, *Last-Come-First-Served*, *Round Robin*, and *Infinite Server*.

The queue theory allows assessing metrics like *servers utilization*, *system's throughput*, *response and waiting times*, which are the time that a task spent in the system and that it waits before being processed, *queue length*, and the *amount of tasks in the system*. For instance, considering that orders (*tasks*) arrive to a factory (*server*) with a given interval (*rate*), the queue theory can provide measures like, the amount of orders waiting for being processed (*queue length*) and the average time that an order waits until be processed and delivered (*waiting and response times*) to the client.

3.2 Numerical solution

This section will be focused on numerical solution of system's performance. The numerical solution methods are well suited for evaluating systems that are too complex to be represented using the analytical methods. The stochastic Petri nets (SPNs) will be the numerical solution method covered in this section.

Since the first Petri nets proposition, different extensions were made. Nowadays, there are several types of Petri nets, each of them considering different aspects, like deterministic (Marsan & Chiola, 1987) and stochastic times (Molloy, 1981), the differentiation between tokens (Jensen, 1997) and the hierarchical modeling (Jensen, 1991).

Stochastic Petri nets (SPNs) concepts (Marsan et al., 1995; Molloy, 1981) is a Petri net extension that associates probabilistic distributed times with transitions. *Inhibition arcs*, *immediate transitions* (Marsan et al., 1995), *deterministic transitions* (Marsan & Chiola, 1987), *general distribution functions* (German, 1994), *transitions' guards*, *marking-dependent features* (transitions' weights and rates, arcs' multiplicity) (Ciardo et al., 1993) are some of the extensions proposed over the early SPN models. Such extensions grants to the SPNs the power of a Turing machine to describe the structural behaviour of the system (Ciardo et al., 1993). Some of the performance measures of SPNs are the average number of tokens in a place, the throughput of a transition, and average sojourn delay of a token in a place (Marsan et al., 1995).

These extensions resulted in several types of SPNs, like generalized stochastic Petri nets (GSPNs) (Balbo, 2001; Marsan et al., 1995), deterministic and stochastic Petri nets (DSPNs) (Marsan & Chiola, 1987) , extended deterministic and stochastic Petri nets (eDSPNs) (German, 1994) and stochastic reward nets (SRNs) (Ciardo et al., 1993; Muppala et al., 1994). A SRN is a 10-tuple $N = (P, T, I, O, H, \Pi, G, M_0, W, \mathcal{R})$, where (Ciardo et al., 1993):

- P is the ordered set of places;
- T is the ordered set of transitions, $P \cap T = \emptyset$;

- $I \in (\mathbb{N}^{|P|} \rightarrow \mathbb{N})^{|P| \times |T|}$ is the matrix of marking-dependent multiplicities of input arcs. If place p_j is an input place of transition t_k, then $i_{jk} \geq 1$ else $i_{jk} = 0$;
- $O \in (\mathbb{N}^{|P|} \rightarrow \mathbb{N})^{|P| \times |T|}$ is the matrix of marking-dependent multiplicities of output arcs. If place p_j is an output place of transition t_k, then $o_{jk} \geq 1$ else $o_{jk} = 0$;
- $H \in (\mathbb{N}^{|P|} \rightarrow \mathbb{N})^{|P| \times |T|}$ is the matrix of marking-dependent multiplicities of inhibition arcs. If place p_j is an inhibition place of transition t_k, then $h_{jk} \geq 1$ else $h_{jk} = 0$;
- $\Pi \in \mathbb{N}^{|T|}$ is the vector of transitions' priorities function. If transition t_k is an immediate transition, then $\pi_k \geq 1$ else $\pi_k = 0$;
- $G \in (\mathbb{N}^{|P|} \rightarrow \{true, false\})^{|T|} \rightarrow \{true, false\}$ is the vector of marking-dependent transitions' guards. If t_k is enabled within $\mathbb{N}^{|P|}$, then $g_k = true$ else $g_k = false$;
- $M_0 \in \mathbb{N}^{|P|}$ is the vector of places' initial markings, where $\mu_{0_j} \geq 0$, $\forall p_j \in P$;
- $W \in (\mathbb{N}^{|P|} \rightarrow \mathbb{R}^{+})^{|T|}$ is the vector of marking-dependent immediate transitions' weights and timed transitions' rates. For immediate transitions the $k-th$ element of W is denoted by w_k, representing its weight. Regarding timed transitions, λ_k is the $k-th$ element of W and depicts its rate, which in turn must be greater than zero;
- $\mathcal{R}$ is a finite ordered set of rewards of N. Each element $\nabla_i \in \mathcal{R}$ is a triplet (ρ, r, ψ) representing the *i-th* reward of the SRN, where: ρ is a reward rate, r is a reward impulse and ψ is a reward based on the results of other rewards.

Elements P, T, I, O, H, Π, G, M_0, W of the SRN describe a regular SPN. Considering that λ is exponentially distributed for timed transitions, those elements describe a trivariate discrete-time stochastic process: $\{(t^{[n]}, \theta^{[n]}, \mu^{[n]}), n \in \mathbb{N}\}$, with $t^{[0]} = NULL$, $\theta^{[0]} = 0$, and $\mu^{[0]} = M_0$. For $n > 0$, $t^{[n]} \in T$ is the n-th transition to fire, at marking $\mu^{[n-1]}$ leading to a new marking $\mu^{[n]}$ at time $\theta^{[n]}$. This stochastic process fully defines the SPN's underlying semi-Markov process (SMP) (Bolch et al., 2006; Ciardo et al., 1993; Muppala et al., 1994), where $\mu^{[n-1]}[t^{[n]} > \mu^{[n]}$ represents the transition from marking $n-1$ to n and $\theta^{[n]} - \theta^{[n-1]} \geq 0$ is the sojourn time at marking $\mu^{[n-1]}$. In this SMP, a sojourn times equal and greater than zero represent vanish and tangible markings, respectively (Bolch et al., 2006; Marsan et al., 1995). Furthermore, $\theta^{[n]} - \theta^{[0]}$ represents the total time spent from marking 0 until reaching marking n (Ciardo et al., 1993).

The set with all possible values of $\mu[n]$ is the reachability set (RS) of the SRN. Each element $\theta^{[n]}$ represents a discrete time at wich transition $t^{[n]}$ fires. The continuous-time Markov chain (CTMC) can thus be fully described by the depicted stochastic process, considering just the tangible markings of the Markov chain (Ciardo et al., 1993). Regarding to the depicted stochastic process, the marking at any time $x \geq 0$ is: $\mu(x) = \mu_{max\{n:\theta^{[n]} \leq x\}}$. Thus, $\mu(x)$ is the marking $\mu^{[n]}$, where $\theta^{[n]}$ is at most equal to time x.

SRNs allows defining business-centric metrics beyond traditional SPNs' metrics, since they associate rewards with transitions firings and places markings at the net level. The underlying SPN's Markov chain is thus transformed into a Markov reward model (MRM). An MRM associates rewards with each state of the Markov chain (Tijms, 2003). In MRMs, *Reward rates* relate to the rate that the reward is accumulated while the system is in a state s_i. *Reward impulses* determines the amount of a reward that is instantaneously accumulated when the system goes from a state s_i to a state s_j. MRM rewards are respectively represented by ρ and r components of each SRN's reward $\nabla_i \in \mathcal{R}$.

Regarding $\mathcal{R}$, a reward rate function ρ_i of a SRN depends on its markings, and is defined as $\rho : \mathbb{N}^{|P|} \rightarrow \mathbb{R}$, where P is the set of places of the SRN. Thus, $\forall \mu \in RS$, $\rho_i(\mu)$ depicts the rate in which reward i is accumulated while the system is in marking μ, where RS is the reachability set (Marsan et al., 1995).The reward impulse function $r_{i,t}$ regards to the amount of reward i accumulated when a transition t fires. Let P and T be the respective sets of places and transitions of a SRN, the reward impulse is a function $r_{i,t} : \mathbb{N}^{|P|} \rightarrow \mathbb{R}$. Thus, $\forall \mu \in RS$, $r_{i,t}(\mu)$ depicts the amount of reward i that is accumulated in marking μ when transition t fires. The stochastic process $\{(t^{[n]}, \theta^{[n]}, \mu^{[n]}), n \in \mathbb{N}\}$ among the rewards defined by ρ and r defines a new continuous stochastic process $\{Y(\theta), \theta \geq 0\}$ which relates to the SRN. The reward accumulated until a time θ is measured as described in Equation 5 (Ciardo et al., 1993).

$$Y(\theta) = \int_0^\theta \rho(\mu(u))du + \sum_{j=1}^{max\{n:\theta^{[n]} \leq \theta\}} r_{t^{[j]}}(\mu^{[j-1]}) \tag{5}$$

The SRN's definitions presents each element of $\mathcal{R}$ as a triplet (ρ, r, ψ). The third element of the triplet, ψ, is a function that computes a single value from the stochastic process $\{Y(\theta), \theta \geq 0\}$ described above. This function is defined as $\psi : R \rightarrow \mathbb{R}$, where R is a set of real-valued stochastic processes. Considering the rewards triplets (ρ, r, ψ), some of the measures that can be assessed with SRNs are presented in Table 1 (Ciardo et al., 1993).

Description	**Steady State**	**Up to θ**
Accumulated reward	$E\left[\lim_{\theta \to \infty} Y(\theta)\right]$	$E\left[Y(\theta)\right]$
Time-averaged reward	$E\left[\lim_{\theta \to \infty} \frac{Y(\theta)}{\theta}\right]$	$E\left[\frac{Y(\theta)}{\theta}\right]$
Instantaneous reward	-	$E\left[\lim_{\delta \to 0} \frac{Y(\theta+\delta)-Y(\theta)}{\delta}\right]$
Number of transitions firings	-	$E\left[Y(\theta)\right]$, $where\ \rho = 0\ and\ r = 1$
Prob. of acc. reward be greater than x	$P\left[\lim_{\theta \to \infty} Y(\theta) > x\right]$	$P\left[Y(\theta) > x\right]$
Prob. of time-averaged reward be greater than x	$P\left[\lim_{\theta \to \infty} \frac{Y(\theta)}{\theta} > x\right]$	$P\left[\frac{Y(\theta)}{\theta} > x\right]$
Supremum reward rate	$\sup_{n \geq 0} \left\{\rho(\mu) : Pr(\mu^{[n]} = \mu) > 0\right\}$	-

Table 1. Some SRNs measurements

Some elements (e.g. arc cardinality, transition rate) of a SRN are defined in function the current marking ($\mathbb{N}^{|P|}$). SRNs uses only exponentially distributed functions for timed transitions. Nevertheless, it is still possible to represent other types of distributions. A well-known technique called *phase approximation* (Desrochers & Al-Jaar, 1994) can be applied to represent poly-exponential distribution functions like Erlang, Hypo- and Hyper-Exponential distributions.

Since the timed transitions' rates are marking-dependent, they can be defined as single-, k-, or infinite-server, in the same sense as queueing networks. Let N be a SRN, where $p_j \in P$ is the only input place of a transition $t_k \in T$, with rate 0.5. The depicted server semantics are respectively represented by $\lambda_k = 0.5$, $\lambda_k = 0.5 \times min(m_j, L)$ and $\lambda_k = 0.5 \times m_j$, where m_j is the marking of place p_j in a given state and L is the upper limit of the k-server semantics.

In an SPN (and SRN), when two or more conflicting timed transitions are enabled at the same time, this conflict is solved through a *race policy* (Marsan et al., 1995). If immediate transitions are in conflict, the choice of which to fire takes into account the respective *priority* and *weight* levels. Suppose two immediate transitions $t1$ and $t2$ in conflict. If the *priority* of $t1$ is greater than $t2$, it will always fire first. If they have the same priority, the conflict is probabilistically solved considering their *weights*.

Usually, the *Reachability Set* and the *Reachability Graph* are simply referred as RS and RG, respectively. When the Petri net is not *bounded*, that is, there is a place that can have an infinite number of tokens, its RS and RG are also infinite. The RS and RG considering just the set of *tangible* markings are respectively known as *Tangible Reachability Set* (TRS) and *Tangible Reachability Graph* (TRG). This TRG can be converted to a continuous time Markov chain (CTMC), from which metrics could be calculated (Bolch et al., 2006). When the RG is too large, a subset of this graph can be explored using simulation.

3.3 Simulation

Chung (2004) defines the "*simulation modeling and analysis is the process of creating and experimenting with a computerized mathematical model of a physical system*". The simulation analysis allows modeling more details and variables of the real system. Metrics can thus be assessed based on a wider range of variables, when compared to analytical models. Since the analytical solution represents the real system using mathematical equations, it cannot take into account every variable that can directly or indirectly affect the real system. Otherwise, the equations could become to complex to be solved (Chung, 2004).

The simulation analysis does not provide exact results. Instead, it often adopts one or more stopping criteria. Once the evaluation reaches these criteria, the simulation stops and the metrics are considered to be found. The confidence interval, simulation length, simulated system time, amount of iterations for solving the problem, are examples of these criteria. Thus, if the stop criteria is not correctly defined, the results will not be reliable. The simulation analysis can also be used in conjunction or to replace analytical and numerical methods. For instance, it can support the evaluation of queueing networks and Petri nets, especially when the analytical or numerical solution is not possible due to the size of the model.

4. An evaluation methodology

This section presents an approach to assess environmental and cost indicators using SRN models. In order to achieve this assessment, reward functions should be associated to transitions and places of a SRN. These functions are calculated for each state of the SRN model returning a result that represents an environmental, cost or performance indicator.

The places and transitions of a Petri net are considered to be its respective passive and active elements. Input and output places of a transition often represent: preconditions and postconditions; input and output data; resources needed and resources released; input and output buffers. The amount of tokens in a place can thus represent the amount of resources located in such a place. Transitions often represent events, actions, a processor, etc.

Considering the presented semantics of places and transitions of a Petri net, it is possible to infer that the amount of stored products, could be represented by the number of tokens in a place that represents a store. In turn, the amount of goods produced per hour could be derived from a transition throughput that represents the producing rate.

The respective production and storage of goods might have other associated issues. For instance, producing goods may require energy and expel green house gases (GHG). As observed, it is possible to have several indicators associated with a single action. One might notice that these issues could be modeled as output places of a transition. But, it would

increase the number of reachable states, hence demanding more computational resources for calculating measures, or even leading to a state-space explosion (Valmari, 1998).
Before the evaluation of a system, it is important to collect data to calculate the environmental indicators. After identifying the system's components (e.g.: machines, entities, processes) that are going to be represented in the model, the modeler should gather information about:

- **Energy** - The amount of resources consumed for energetic means. It is important to define the energy source (e.g. electricity, biomass, gasoline, diesel);
- **Raw Materials** - The amount of resources used to produce a good or realize an activity. Raw materials should be categorized by type (e.g. water, wood, hazardous, non-hazardous) and its origin (e.g. first use, reuse, recycled);
- **Waste** - The amount of waste generated by system's activities. This information should be structured by the type of the waste (e.g. wood, card, plastic) and by its destination (e.g. recycling, landfill, composting).

It is important to stress that a resource might be used as energy source, raw material or be a waste of an activity. For instance, a piece of wood can be used as energy source, as raw material in the production of a good, and some of it can also be wasted.
The proposed classification aims at providing means to separately measure GWP and exergy outputs of each activity/process, without being over-detailed avoiding a complex and inefficient evaluation process. Furthermore, a different value of GWP or exergy efficiency can be assigned to the same substance depending on its classification. For instance, a block of wood has a different GWP value when used as raw material of a good, disposed for recycling, or disposed in landfill. We chose this categorization based on the conversion factors usually adopted in LCA (Bösch et al., 2007; DEFRA - Department for Environment, Food and Rural Affairs, 2009; Goedkoop et al., 2000), in order to provide detailed description of the GWP of consumed/disposed resources.
Let N be a SRN that models the evaluated system, $\mathcal{I}$ is its set with the classified energy, raw material, and waste items. For each element of $\mathcal{I}$ a reward $\nabla_i \in \mathcal{R}$ related to the consumption/disposal (in kg) of the item should be defined. For convenience, the set with these basic rewards is denoted $\mathcal{R}_{\mathcal{I}}$, where $\mathcal{R}_{\mathcal{I}} \subseteq \mathcal{R}$.
An important remark considering the rewards definition is that they do not distinguish between places of the SRN. Instead, reward rates are based on the state of the SRN. But, sometimes it is wanted to have an insight of a specific process or a set of processes of the modeled system. In such cases, the rewards should be defined separately for each place and transition.
If such strategy is used, the total reward of a classified item should be derived from the sum of the rewards for each (or some) place and transition of the SRN. Let N, $P' \subseteq P$ and $T' \subseteq T$ be a SRN and its respective sets of places and transitions of N, for which it is intended to obtain the expected time-averaged reward of $\nabla_i \in (\mathcal{R} - \mathcal{R}_{\mathcal{I}})$. ∇_i is measured as depicted in Equation 6.

$$\nabla_i = \sum_{j=0}^{j=|\mathcal{R}'|} \nabla_j \tag{6}$$

where $\mathcal{R}_{\mathcal{I}}{}' \subseteq \mathcal{R}_{\mathcal{I}}$ is the set of rewards related to ∇_i that were defined for $p \in P'$ and $t \in T'$.
The SRN presented in Figure 2 is used to exemplify the metrics definition. This SRN models a system where a hotel with 30 available rooms (*pFreeRooms*). The rooms are warmed by two furnaces, each capable of warming 15 rooms. The second furnace is turned on just when there

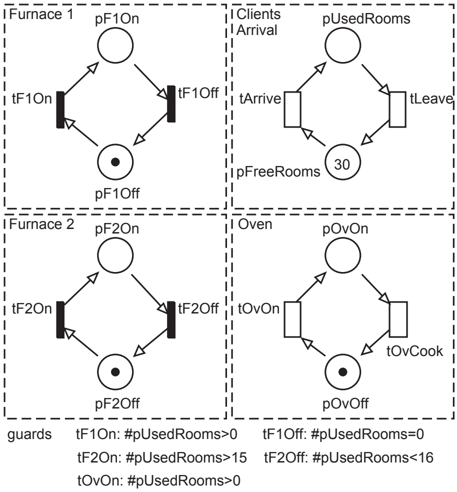


Fig. 2. Example of an SRN.

are more than 15 rooms occupied. These furnaces consumes natural gas at rate $x_0 + n_0\lambda_0$ and $x_1 + n_1\lambda_1$, respectively. Where n_0 and n_1 are factors that depends on the amount rooms occupied. Furthermore, transition *tOvCook* represents the use of an oven that consumes a fixed amount z of the same gas each time it is used. Let $\sharp P$ represent the number of tokens in place P and $\nabla_i = (\rho_i, r_i, \psi_i)$ represent the consumption of natural gas, this reward could be defined as follows:

$$\rho_i = \sharp PF1On(x_0 + (min\{\sharp pUsedRooms, 15\})\lambda_0) + \\ \sharp PF2On(x_1 + (max\{\sharp pUsedRooms - 15, 0\})\lambda_1)$$
$$r_{i,t} = z, t = t_0 \wedge r_{i,t} = 0, t \neq t_0; \quad \psi_i = 0$$

It is important to remark that considering the defined natural gas reward, it is not possible to measure the amount consumed by a particular furnace. Instead the whole consumption is retrieved. If such information is required, these rewards should be defined separately, having their values totalized by another reward as depicted in Equation 6.

Assuming that the evaluated system produces physical goods (not virtual ones, as occurs with most informatics services) a mass balance analysis might be directly derived from the sum of all raw materials inputs and output goods (Equation 7).

$$\nabla_i = \frac{Qty_{good}}{\sum_{j=0}^{j=|\mathcal{R}'|} \nabla_j} \tag{7}$$

where $\mathcal{R}' \subseteq \mathcal{R}$ is the set rewards that represents the input of raw materials (in kg/time) used in the production of the good and Qty_{good} is the amount of goods produced per unit of time (in kg/time). Qty_{good} could be obtained from the throughput of a SRN transition that represents the production of goods.

There are more three important rewards that should be defined in terms of each classified item. These rewards are: cost, global warming potential, and exergetic input/output. For each reward $\nabla_i \in \mathcal{R}_\mathcal{I}$, a cost reward $\nabla_j \in (\mathcal{R} - \mathcal{R}_\mathcal{I})$ must be defined. The cost reward should assign a financial profit (positive signal) or expense (negative signal) related to the classified item. This reward is defined as

$$\nabla_j = K + \beta \times \nabla_i \tag{8}$$

where K is a constant and β is the unitary cost/profit for the classified item. The total financial cost/reward is simply depicted by the sum of the financial rewards.
For each reward $\nabla_i \in \mathcal{R}_{\mathcal{I}}$, a global warming potential reward $\nabla_j \in (\mathcal{R} - \mathcal{R}_{\mathcal{I}})$ can also be defined as

$$\nabla_j = g \times \nabla_i \tag{9}$$

where g is the GWP for each unit of the classified item. The total GWP is thus simply depicted by the sum of the GWP rewards.
For each reward $\nabla_i \in \mathcal{R}_{\mathcal{I}}$, that refers to energy consumption, an exergy input, output, and lost reward $\nabla_j, \nabla_k, \nabla_l \in (\mathcal{R} - \mathcal{R}_{\mathcal{I}})$ can be respectively defined as

$$\nabla_j = x_{ch} \times \nabla_i \tag{10}$$

$$\nabla_k = \eta_{II} \times \nabla_j \tag{11}$$

$$\nabla_l = \nabla_k - \nabla_j \tag{12}$$

where η_{II} and x_{ch} are the weighted-average exergetic efficiency and chemical exergy of the used energy. The total exergy is thus simply depicted by the sum of the exergy rewards.
For each type of energy source consumed, the estimated exergetic efficiency of fuel f regarding activity/location act represented by the SRN's transition/place should be informed ($\eta_{II,act,f}$). This efficiency factor in conjunction with the already known fuel's chemical exergy ($x_{ch,f}$) allows calculating the exergy output in the activity $X_{out,act}$. Based on the exergy output (Equation 13), it is possible to compare the adoption of different types of energy sources. This comparison is carried out by considering that the exergy output of each activity must be the same regardless of the energy source. The amount (in kg) of the energy source of the new energy source could be calculated using Equation 14. It is important to stress that changing the energy source would probably vary the exergetic efficiency η_{II} in the activity.

$$X_{out,act_i,f_1} = \eta_{II,act_i,f_1} \times x_{ch,f_1} \times Qty_{act_i,f_1} \tag{13}$$

$$X_{in,act_i,f_2} = \frac{X_{out,act_i}}{\eta_{II,act_i,f_2}} \therefore Qty_{act_i,f_2} = \frac{X_{out,act_i}}{x_{ch,f_2} \times \eta_{II,act_i,f_2}} \tag{14}$$

The cumulative exergy consumption could be directly derived from the sum of exergy inputs. Based on these inputs, the Life Cycle Exergy Analysis (LCEA) can be applied in the evaluated process, by accounting the exergy losses and the input exergy. The measured exergy outputs might be used in order to compare different energy sources considering Equation 14. Since each energy source might have a different GWP, this comparison provides insights about the environment impact resultant from the use of different energy sources.

5. Modeling

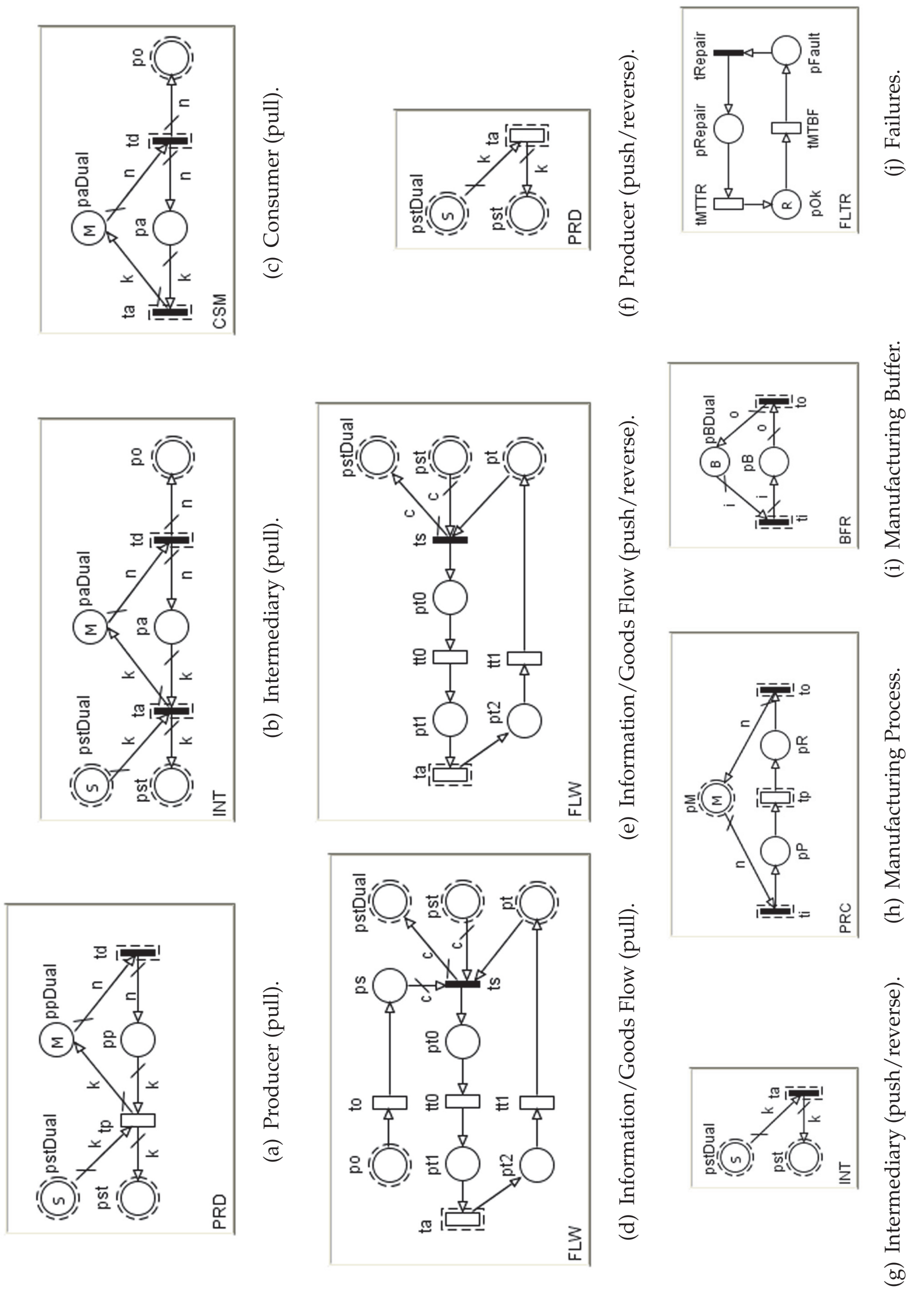
This section presents some SRN models that were conceived to represent facilities and processes of a supply chain and manufacturing systems. The manufacturing systems models were based on Desrochers & Al-Jaar (1994). This library of components allows a bottom-up

modeling. It also guarantees that the final model has some properties like boundedness, allowing either a steady state or transient evaluation (Alves et al., 2010).
Figure 3 presents the proposed components for modeling pull, push and reverse supply chains networks (Ballou, 2004; Fleischmann et al., 1997; Simchi-Levi et al., 2000) and manufacturing systems. The consumer component is not explicitly modeled in the *push* and *reverse* supply chains. It is represented by transition ta of the flow model, which models the arrival of goods in the destination. Places named $pxDual$ are the dual places of places named px. These places aim at guaranteeing that the final model is *structurally bounded* (Marsan et al., 1995), allowing a stationary analysis. The initial marking M of these places should be high enough to guarantee that the marking of these places does not reach zero in any state, since these places cannot interfere in the system's behavior. Nevertheless, the higher these initial markings are, the larger the state space of the SRN will be. Therefore, the simulation can be required when evaluating the model. In order to tackle this problem, experiments can be conducted increasing these initial markings until the metrics remains statistically equals.
Table 2 lists typical business indicators that can be extracted from the proposed models. The entity column refers to the model from which the metric can be extracted, including factories (**F**), intermediaries (**I**), consumers (**C**), flows (**FL**), buffers (**B**), processes (**P**), and failures (**FLT**).

Entity	**Performance Indice**	**Reward***
F or I	Expected inventory	$\sharp pst$
F or I	Prob. empty inventory	$\sharp pst = 0?1:0$
F or I	Prob. full Inventory	$\sharp pstDual = 0?1:0$
F or I	Available vehicles of kind pt	$\sharp pt$
F or I	Prob. more than V vehicles of kind pt available	$\sharp pt > V?1:0$
F or I	Prob. using all vehicles of kind pt	$\sharp pt = 0?1:0$
C or I	Pending orders	$\sharp pa$
C or I	Delivery throughput to customer	$\lambda(ta)$
C or I	Customer order cycle time	$\sharp pa/\lambda(ta)$
FL	Number of recent orders	$\sharp po$
FL	Number of backorders	$\sharp ps$
FL	Prob. have more than n Backorders	$\sharp ps > n?1:0$
FL	Customer service level	$1 - (\sharp ps > 0?1:0)$
FL	N^o of vehicles delivering to destination	$\sharp pt1$
FL	In-transit inventory	$c \times (\sharp pt0 + \sharp pt1)$
B	Buffer size	$\sharp pB$
B	Prob. buffer full	$\sharp pBDual = 0?1:0$
P	N^o of machines in use	$\sharp pP$
P	N^o of idle machines	$\sharp pM$
P	N^o of machines being released	$\sharp pR$
P	Prob. more than x machines in use	$\sharp pP > x?1:0$
FLT	N^o of resources not in fail	$\sharp pOk$
FLT	N^o of resources waiting for repair	$\sharp pFault$
FLT	N^o of resources being repaired	$\sharp pRepair$
FLT	Prob. of resources waiting for repair	$\sharp pFault > 0?1:0$
FLT	Prob. of resources not in fail lower than x	$\sharp pOk < x?1:0$

*Rewards are expressed based on the SPNP tool syntax (Hirel et al., 2000).

Table 2. Some metrics that can be extracted from models.



(a) Producer (pull). (b) Intermediary (pull). (c) Consumer (pull).

(d) Information/Goods Flow (pull). (e) Information/Goods Flow (push/reverse). (f) Producer (push/reverse).

(g) Intermediary (push/reverse). (h) Manufacturing Process. (i) Manufacturing Buffer. (j) Failures.

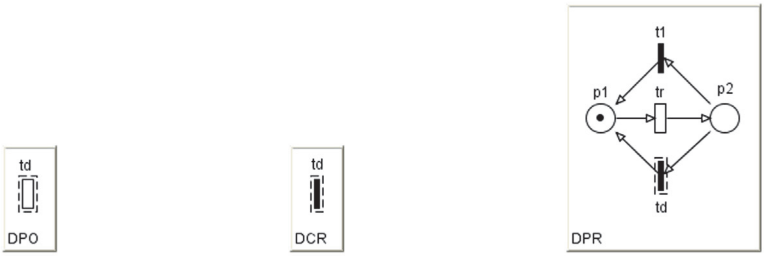
Fig. 3. SRN models for entities and flows of a GSC.

5.1 Failures

Failures occur quite often in supply chains. Delivering problems, broken products, vehicles or machines breaks are some of these failures that might partially or totally interfere with activities and processes. Depending on the failure and repair rate, the overal system's performance might also be affected. Figure 3(j) pictures the SRN that represents a failure.
The initial marking R of pOk^{FLTR_i} denotes the maximum amount of resources that might be used in an activity that is susceptible to failures. Transitions $tMTBF^{FLTR_i}$ and $tMTTR^{FLTR_i}$ respectively depict the mean time between failures and the mean time to repair. The rate of these transitions can be marking-dependent, allowing representing the server-semantics for the failures and repairing activities.
The failure rate can depend on the marking of pOk^{FLTR_i} which represents the amount of resources being used. The repair rate can represent a limitation on the maintenance team. For instance, if the system has limited amount of resources n in the maintenance team. Thus, if there are more than n machines broken, just n of these machines will be fixed in turn. Thus, the repair rate could be defined as $\lambda \times min(n, pRepair^{FLTR_i})$, where λ is the time required to fix a single machine. If a machine could be fixed by more than one resource at the same time, the repair rate could be even lower, being defined as $\lambda \times n$.
This model can also represent failures occurring in more than one activity. The rate of transition $tMTBF^{FLTR_i}$ represents the failure rate when a set of activities are being executed, or the absolute time between failures. In the first case, it is necessary to assign a guard $[t_k >, \forall t_k \in T'$ to transition $tMTBF^{FLTR_i}$, where T' is the set of transitions that represents activities susceptive to the modeled failure.
The guards and rates of such transitions must also depend on the failure model. If a transition $t_k \in T'$ must have at least n resources working to be fired, it must have a guard $\sharp pOk^{FLTR_i} \geq n$, where n is an integer. In the case of $n = R$ if a single resource is in the fail state, the activity represented by t_k halts. Alternatively, the $FLTR$ can be reduced by removing transition $tRepair^{FLTR_i}$ and place $pRepair^{FLTR_i}$. It can be done when it is not necessary to represent the limited maintenance resources.

5.2 Replenishment policies

Replenishment policies are considered for changing the way that intermediaries order goods and manufacturers produce them. *Make-to-order* (MTO) policy means that finished goods are manufactured only when an order from a customer is received. Under *make-to-stock* (MTS) policies, finished goods are manufactured and stored. Customers orders are thus supplied from storage. The proposed models supports the following replenishment policies(Simchi-Levi et al., 2000): **(r,Q)**, **(r,s,Q)**, **(r,S)**, **(r,s,S)** and **(s,S)**, where **r** is the review interval, **Q** is the amount of goods per order, **s** and **S** are the minimal and target inventory level, respectively.
For the sake of simplicity, the models in Figure 3 use the (r, Q) replenishment policy. The replenishment policy of factories and intermediaries can be changed considering the models pictured in Figure 4.
The periodical ordering component models either the (r, Q) and (r, S) policies. The (r, Q) policy is modeled assigning an integer value Q to the arc weight n and $1/r$ to the rate of transition td. The (r, S) policy is modeled assigning the same rate to transition td and a marking dependent function $S - I$ to the arc weight n, where I is the current inventory position $(\mu(pa) + \mu(pst))$.



(a) Periodic Ordering. (b) Continuous Review. (c) Periodic Review.

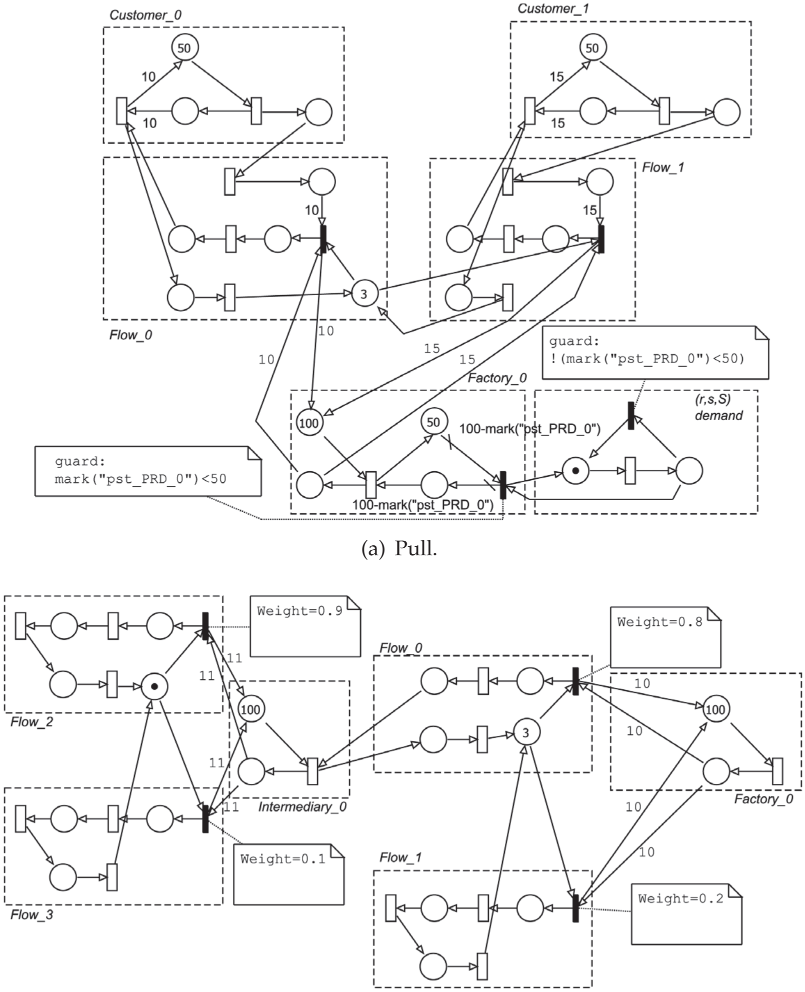
Fig. 4. Replenishment policies models.

The continuous review component models (s, Q) and (s, S) policies. The (s, Q) policy is modeled by setting an integer value Q to the arc weight n and the guard $I < s$ to the transition td, where I is the current inventory position. The (s, S) policy should be modeled in a similar way to (s, Q) policy, but assigning a marking dependent function $S - I$ to the arc weight n.
This model can also be considered for modeling a MTO policy. This policy should be modeled by assigning the arc weight $n = Backlog$ and a guard $Backlog > 0$ to transition td, where $Backlog = Backorders - Stored\ Inventory - Inventory\ on\ Order$ and the $Backorders$ depicts the sum of the backorders of all the facility's customers. For factories, the $Inventory\ on\ Order$ depicts its *work-in-process* (WIP).
The periodic review component models either the (r, s, Q) and (r, s, S) policies. These policies are modeled by setting the guard $I < s$ to the transition td and $1/r$ to the rate of transition tr. A marking dependent function $S - I$ must be assigned to arc weight n when considering the (r, s, Q) policy, whilst an integer value Q must be set to arc weight n, when considering the (r, s, S) policy. The priority of transition td must be greater than that one of transition $t1$. Thus, whenever a conflict occurs between these transitions, td will always be fired, triggering the replenishment order.
It is also possible to adopt a hybrid policy by composing different replenishment models. For instance, a factory can adopt a MTS policy for a set of clients and a MTO policy for other clients. This is especially useful for facilities that faces demands with high variation (Soman et al., 2002). Multiple MTS policies could also be used together with the aim of modeling seasonality on demand.

5.3 Supply chain network

Based on the library of components presented in this section, modelers can design and experiment different configurations for a supply chain (SC). Figure 5 shows the models for two different SCs. The elements' names were intentionally suppressed for a better readability. The model showed in Figure 5(a) represents a pull SC, in which a factory (*Factory_0*) sends its products to two different customers (*Customer_0* and *Customer_1*) . This factory uses an *(r,s,S)* policy, with the minimal and target inventory levels of 50 and 100, respectively. The minimal replenishment policy is depicted by transitions' guards $mark(``pst\_PRD\_0'') < 50$, whilst the target inventory is depicted by arcs' weights $100 - mark(``pst\_PRD\_0'')$.
The transportation of goods is done using 3 vehicles of the same type. This amount is represented by the initial marking of a place represented inside the *Flow_0* component. These

resources are shared between the flows *Flow_0* and *Flow_1*. The customers are respectively supplied with 10 and 15 units of goods per order, as showed by the arcs with such weights.



(a) Pull.

(b) Push.

Fig. 5. SRN models for supply chains.

The model pictured in Figure 5(b) represents a push SC, in wich a factory (*Factory_0*) sends its products both to a customer (*Flow_1*) and to an intermediary (*Intermediary_0*). Besides, the goods are send to the intermediary through the a flow represented by *Flow_0*. The intermediary serves two consumers (*Flow_2* and *Flow_3*). As depicted previously in this section, the final customers are represented by the flow components in models of push supply chains. The factory and the intermediary serve their clients using 3 and 1 vehicle, respectively. Furthermore, they respectively send 10 and 11 goods to their clients per delivery.

When using the models for pull supply chains, the immediate transitions weights represent the probability of sending goods for each client of the producer. In the example, 80% of the factory's deliveries are addressed to the intermediary and 20% are addressed to its consumer.

6. Case study

This section presents a case study conducted in a Brazilian meat processing industry. This study considers a production line composed of different machines and sub-processes. These elements were grouped in stages of the production line. We thus mapped three main stages which will be called *Stage 1*, *Stage 2* and *Stage 3*. These stages consumes 63.68, 102.94, and 22.96 kWh/ton of electricity, respectively. Furthermore, the second production stage also consumes 26.76 m^3/ton of natural gas. This case study focuses on energy consumption. Beyond environment issues, we also model the failures at each stage. We address this issue to assess the impact of failures in the system performance. This impact might provide information for decisions on the maintenance of the production line's machines.

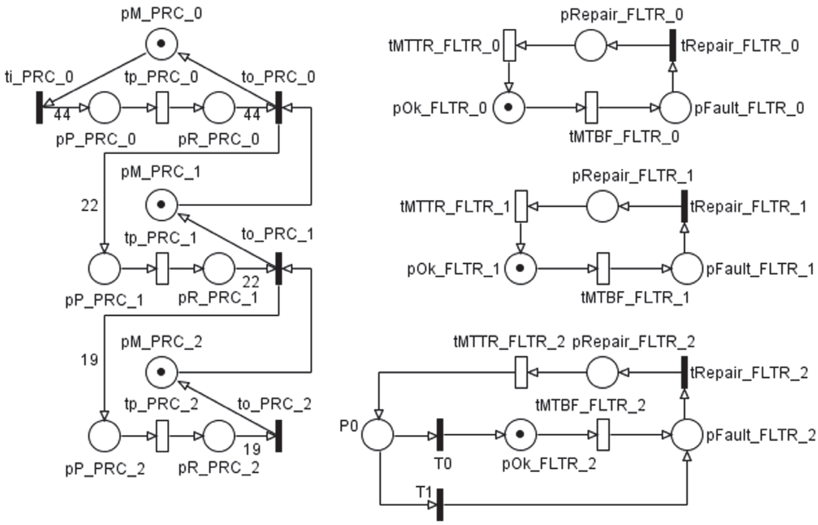


Fig. 6. Stochastic reward net for the production line.

Figure 6 shows the SRN model for the production line. As observed in such a model, the failures were also represented. It is thus possible to compare their effects over performance and environmental metrics. Since for this kind of problem the occurrence of failures may affect not only the availability but also the system performance, they could not be modeled in separate. Considering the data collected, the phase approximation was applied in this model. The rates of the three production stages were approximated to an Erlang distribution with 44, 22, and 19 phases, respectively. The failures occur with a hyper-exponential behavior in the third stage and with an exponential behavior in the other stages.
Table 3 provides a summary of the exergetic values adopted for following calculations (Kotas, 1985). Such efficiencies are used in the exergy/GWP comparison. The natural gas and fuel oil efficiencies considered for powering machines represent the efficiency for converting the energy source into electricity, that in turn could be directly used by machines.

Source	Use	Efficiency (η_{II})	$x_{ch,f}$ (kJ/kg)
Electricity	Power	0.92	3600
Electricity	Cooking	0.115	3600
Natural Gas	Power	0.2931	51702
Natural Gas	Cooking	0.233	51702
Fuel Oil	Power	0.3207	47101
Fuel Oil	Cooking	0.233	47101

Table 3. Exergy efficiency per source and use.

Metric	Stage	Expression	Scenario 1	Scenario 2	Scenario 3
rate1 (un./hour)	1	return rate("tp_PRC_0")/44.0;	4.13629	3.81797	3.82243
rate2 (un./hour)	2	return rate("tp_PRC_1")/22.0;	4.13629	3.81739	3.82111
rate3 (un./hour)	3	return rate("tp_PRC_2")/19.0;	4.13629	3.81551	3.81879
utilization1 (%)	1	return mark("pP_PRC_0")>0?1.0:0.0;	0.94150	0.87566	0.87465
utilization2 (%)	2	return mark("pP_PRC_1")>0?1.0:0.0;	0.79796	0.77152	0.76928
utilization3 (%)	3	return mark("pP_PRC_2")>0?1.0:0.0;	0.83307	0.80724	0.80891
repairing1 (un./hour)	1	return mark("pRepair_FLTR_0");	-	0.00580	0.00573
repairing2 (un./hour)	2	return mark("pRepair_FLTR_1");	-	0.03292	0.03437
repairing3 (un./hour)	3	return mark("pRepair_FLTR_2");	-	0.04039	0.03794
waiting_repair1 (un./hour)	1	return mark("pFault_FLTR_0");	-	0.00000	0.00006
waiting_repair2 (un./hour)	2	return mark("pFault_FLTR_1");	-	0.00000	0.00007
waiting_repair3 (un./hour)	3	return mark("pFault_FLTR_2");	-	0.00000	0.00013
el1 (kWh/hour)	1	return (63.6812*rate1());	263.40376	243.13300	243.41676
el2 (kWh/hour)	2	return (102.9402*rate2());	425.79028	392.96251	393.34586
el3 (kWh/hour)	3	return (22.9600*rate3());	94.96916	87.60421	87.67934
gas2 (m^3/hour)	2	return (26.7559*rate2());	110.67010	102.13761	102.23724
X_in_el1 (MJ/hour)	1	return (3.6*el1());	948.25354	875.27880	876.30034
X_in_el2 (MJ/hour)	2	return (3.6*el2());	1532.84500	1414.66503	1416.04509
X_in_el3 (MJ/hour)	3	return (3.6*el3());	341.88899	315.37515	315.64561
X_in_gas2 (MJ/hour)	2	return (51.702*0.714*gas2());	4085.41194	3770.43302	3774.11120
X_out_power (MJ/hour)	system	return 0.92*(X_in_el1()+X_in_el2()+X_in_el3());	2597.14854	2396.89347	2399.35176
X_out_cooking (MJ/hour)	system	return (0.233*X_in_gas2());	951.90098	878.51089	879.36791

Table 4. Reward functions and results.

Table 4 presents the reward functions adopting the SPNP tool syntax (Hirel et al., 2000). We used this tool to compute these rewards in the steady-state. Table 4 also depicts the results of three scenarios that were carried out. The first scenario disregards system's failures. The second one includes failures but considers an unlimited maintenance team. The third scenario considers that there is only one resource available in this team.
The results presented in Table 4 shows that the inclusion of failures reduces in almost 8% the production rate (from 4.13629 to 3.81551). This rate represents the amount tons of goods are produced per hour. Besides, the lower utilization of the second stage sugests that it is a bottleneck in the system. So, investments in this stage should be prioritized.
The third scenario, which considers a limited maintenance team, presents results that are quite similar to those provided by the second scenario, which disregards this limitation. The difference in the results are due to the errors inherent from the model simulation. Thus, considering the current failures and maintenance rates, a single maintenance team could meet the needs of this production line. But changes in these variables, might require the evaluation of new scenarios to check if this assumption remains true.
The following analysis are based on the second scenario that represents the actual situation of the production line. Assuming the current operation of the industry, it is possible to infer that the consumption of electricity and natural gas assigns a GWP of 72 $kg\ CO_2e/ton$ of goods, considering 0.0959 $kg\ CO_2e$ per kWh of electricity and 2.01330 $kg\ CO_2e$ per kg of natural gas (DEFRA - Department for Environment, Food and Rural Affairs, 2009). The electricity conversion factor is specific for Brazil, the world's average is 0.3827 $kg\ CO_2e$ per kWh. If this conversion factor was adopted, the resulting GWP should be of 126.5 $kg\ CO_2e/ton$ of goods.

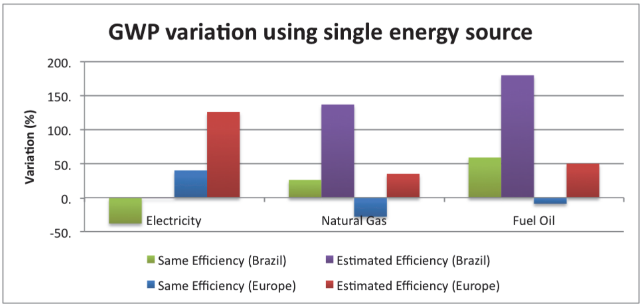


Fig. 7. Impact of energy source over GWP.

We calculated the amount of exergy input necessary to generate the same exergy output (see Table 4) with a single energy source. Based on that exergy input, we calculate the GWP and compared it to the actual operation of the production line. Figure 7 presents that comparison result. The graphs labeled as "Same Efficiency" assume a hypothetical situation where the current efficiency $\eta_{II,a,f}$ is preserved. The "Estimated Efficiency" graphs depict the variation in a real scenario where the exergetic efficiency changes according to the energy source.
It is possible to observe that considering an hypothetical situation where the exergy efficiency is preserved, the use of natural gas as the single energy source decreases the GWP in european countries, whilst in Brazil, this value increases. It occurs due to the fact that in Brazil, the GWP factor of the energy is very low when compared to other countries, due to the extensive use of hydroelectric energy.

Regarding the real efficiencies, despite of the fact that the exergetic efficiency of the electricity for cooking processes is lower than that one of the natural gas, the GWP variation remains almost constant when the electricity is used as the only energy source in Brazil. Furthermore, although the fuel oils have a high chemical exergy, their high GWP concentration make them the worst alternative from the environmental point of view. Analysis of costs might justify their usage in some points of the production line in detriment to environment impacts.

7. Final remarks

This chapter presented a framework based on the stochastic modeling of supply chains for evaluating business and sustainability metrics. Such a framework uses the stochastic reward nets (SRNs) as modeling technique. Furthermore, the GWP and exergy measurements form the basis for the environment performance evaluation (EPE) of this framework. Although, the life cycle assessment (LCA) is a very good tool for measuring static sustainability impacts of a product, it is not well suited for predicting the impacts of a system reengineering. The presented framework reveals itself very useful in such cases.
The case study in the end of the chapter highlights the importance of considering not only the energy source, but also the localities, that means, the effects of the system location (e.g. country, city, etc) over evaluated metrics. Especially for the electricity, the GWP factor might vary substantially according to the country that is using such issue. Together with business metrics like costs, resources utilization and customers backorders, the environment metrics provides information for decision makers.

8. References

Alves, G., Maciel, P., Lima, R. & Zimmermann, A. (2010). Automatic Modeling for Performance Evaluation of Inventory and Outbound Distribution, *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on* 40(5): 1025–1044.

Apaiah, R. K., Linnemann, A. R. & van der Kooi, H. J. (2006). Exergy analysis: A tool to study the sustainability of food supply chains, *Food Research International* 39(1): 1–11.

Ayres, R. U., Ayres, L. W. & Martinás, K. (1998). Exergy, Waste Accounting, and Life-Cycle Analysis, *Energy* 23(5): 355–363.

Balbo, G. (2001). Introduction to Stochastic Petri Nets, *LNCS 2090* pp. 84–155.

Ballou, R. H. (2004). *Business Logistics/Supply Chain Management*, 5 edn, Pearson Education.

Beamon, B. M. (1999). Designing the green supply chain, *Logistics Information Management* 12(4): 332–342.

Bolch, G., Greiner, S., de Meer, H. & Trivedi, K. (2006). *Queueing Networks and Markov Chains: Modeling and Performance Evaluation with Computer Science Applications* , 2 edn, John Wiley & Sons, New York, NY, USA.

Bösch, M. E., Hellweg, S., Huijbregts, M. A. J. & Frischknecht, R. (2007). Applying Cumulative Exergy Demand (CExD) Indicators to the ecoinvent Database, *The International Journal of Life Cycle Assessment* 12(3): 181–190.

Cascio, J. (1999). *The Iso 14000 Handbook*, ASQ Quality Press.

Cash, R. & Wilkerson, T. (2003). GreenSCOR: Developing a Green Supply Chain Analytical Tool. LMI - Logistics Management Institute.

Chen, H., Amodeo, L., Chu, F. & Labadi, K. (2005). Modeling and performance evaluation of supply chains using batch deterministic and stochastic petri nets, *IEEE Trans. on Automation Science and Engineering* 2(2): 132–144.

Chung, C. (2004). *Simulation Modeling Handbook: A Practical Approach*, CRC Press.

Ciardo, G., Blakemore, A., Chimento, P., Muppala, J. & Trivedi, K. (1993). Automated generation and analysis of markov reward models using stochastic reward nets, *IMA Volumes in Mathematics and its Applications* 48: 145–145.

Cohen, M. & Lee, H. (1988). Strategic analysis of integrated production-distribution systems: models and methods, *Operations Research* 36(2): 216–228.

Cornelissen, R. L. & Hirs, G. G. (2002). The value of the exergetic life cycle assessment besides the lca, *Energy Conversion and Management* 43: 1417–1424.

DEFRA - Department for Environment, Food and Rural Affairs (2009). 2009 Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting.

Desrochers, A. A. & Al-Jaar, R. Y. (1994). *Applications of Petri Nets in Manufacturing Systems: Modeling, Control, and Performance Analysis*, Institute of Electrical & Electronics Enginee.

Dotoli, M. & Fanti, M. P. (2005). A generalized stochastic petri net model for management of distributed manufacturing systems, *CDC-ECC05, 44th IEEE Conference on Decision and Control and European Control Conference*, pp. 2125–2130.

Fleischmann, M., Bloemhof-Ruwaard, J. M., Dekker, R., van der Laan, E., van Nunen, J. A. E. E. & van Wassenhove, L. N. (1997). Quantitative models for reverse logistics: A review, *European Journal of Operational Research* 103: 1–17.

Fleischmann, M., Kuik, R. & Dekker, R. (2002). Controlling inventories with stochastic item returns: A basic model, *European Journal of Operational Research* 138(1): 63–75.

Frischknecht, R., Jungbluth, N., Althaus, H., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G. & Spielmann, M. (2005). The ecoinvent Database: Overview and Methodological Framework, *The International Journal of Life Cycle Assessment* 10(1): 3–9.

GaBi Software – product sustainability (2010). Website.
URL: *http://www.gabi-software.com*

German, R. (1994). *Analysis of stochastic Petri nets with non-exponentially distributed firing times*, PhD thesis, Technische Universität Berlin.

Goedkoop, M., Spriensma, R. et al. (2000). *The Eco-indicator 99*, PRé Consultants.

Gong, M. & Wall, G. (2001). On exergy and sustainable development–part 2: Indicators and methods, *Exergy, An International Journal* 1(4): 217–233.

Gross, D. (2009). *Fundamentals of Queueing Theory*, 4 edn, John Wiley & Sons Inc.

Guide, Jr., V. D. R., Souza, G. C. & van der Laan, E. (2005). Performance of static priority rules for shared facilities in a remanufacturing shop with disassembly and reassembly, *European Journal of Operational Research* 164(2): 341–353.

Haas, P. J. (2002). *Stochastic petri nets: Modelling, stability, simulation*, Springer.

Heijungs, R., Guinée, J., Huppes, G., Lankreijer, R., Udo de Haes, H., Wegener Sleeswijk, A., Ansems, A., Eggels, P., Duin, R. & Goede, H. (1992). *Environmental life cycle assessment of products*, Centre of Environmental Science. University of Leiden.

Hirel, C., Tuffin, B. & Trivedi, K. (2000). SPNP: Stochastic Petri Nets. Version 6.0, *Computer Performance Evaluation. Modelling Techniques and Tools*, Vol. 1786, Springer Verlag, pp. 354–pp.

IPCC (2001). *Climate Change 2001: The Scientific Basis*, Cambridge University Press.

ISO (2006). ISO 14040:2006 – Environmental management – Life cycle assessment – Principles and framework, *Technical report*, ISO – International Organization for Standards.

Jensen, K. (1991). Coloured Petri Nets: A High Level Language for System Design and Analysis, *LNCS; Advances in Petri Nets 1990* 483: 342–416. NewsletterInfo: 39.

Jensen, K. (1997). *Coloured Petri Nets: Basic Concepts, Analysis Methods and Practical Use*, Vol. 1, Springer-Verlag.

Kotas, T. J. (1985). *The Exergy Method of Thermal Plant Analysis*, Butterworths.

Labadi, K., Chen, H. & Amodeo, L. (2007). Modeling and performance evaluation of inventory systems using batch deterministic and stochastic petri nets, *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on* 37(6): 1287–1302.

Lee, H. L., Padmanabhan, V. & Whang, S. (1997). The Bullwhip Effect in Supply Chain, *Sloan Management Review* 38(3).

Lettieri, D. J., Hannemann, C. R., Carey, V. P. & Shah, A. J. (2009). Lifetime exergy consumption as a sustainability metric for information technologies, *Sustainable Systems and Technology, 2009. ISSST '09. IEEE International Symposium on*, pp. 1–6.

Louwers, D., Kip, B. J., Peters, E., Souren, F. & Flapper, S. D. P. (1999). A facility location allocation model for reusing carpet materials, *Comput. Ind. Eng.* 36(4): 855–869.

Makajic-Nikolic, D., Panic, B. & Vujosevic, M. (2004). Bullwhip Effect and Supply Chain Modelling and Analysis using CPN Tools, *5th Workshop and Tutorial on Practical Use of Coloured Petri Nets and the CPN Tools*.

Marsan, M. A., Balbo, G., Conte, G., Donatelli, S. & Franceschinis, G. (1995). *Modelling with Generalized Stochastic Petri Nets*, John Wiley & Sons.

Marsan, M. A. & Chiola, G. (1987). On petri nets with deterministic and exponentially distributed firing times, *Advances in Petri Nets 1987, covers the 7th European Workshop on Applications and Theory of Petri Nets*, Springer-Verlag, London, UK, pp. 132–145.

Molloy, M. K. (1981). *On the Integration of Delay and Throughput Measures in Distributed Processing Models*, PhD thesis, UCLA.

Moore, K. E., Gungor, A. & Gupta, S. M. (1998). A Petri net approach to disassembly process planning, *Computers & Industrial Engineering* 35(1-2): 165–168.

Muppala, J., Ciardo, G. & Trivedi, K. (1994). Stochastic reward nets for reliability prediction, *Communications in reliability, maintainability and serviceability* 1(2): 9–20.

Murata, T. (1989). Petri nets: Properties, analysis and applications, *Proceedings of the IEEE* 77(4): 541–580.

Narahari, Y. & Biswas, S. (2007). *Performance Measures and Performance Models for Supply Chain Decision Making*, University Book Series, ICFAI (Institute of Chartered Financial Analysts of India), chapter 7.

Norris, J. (1998). *Markov Chains*, Cambridge University Press.

Oliveira Filho, D. (1995). *Electric Energy System Planning and the Second Principle of Thermodynamics*, PhD thesis, McGill University, Montreal, Canada.

Petri, C. A. (1962). *Kommunikation mit Automaten*, PhD thesis, Bonn: Institut für Instrumentelle Mathematik, Schriften des IIM Nr. 2.

Raghavan, N. R. S. & Roy, D. (2005). A Stochastic Petri Net Approach for Inventory Rationing in Multi-Echelon Supply Chains, *Journal of Heuristics* 11(5-6): 421–446.

Ramchandani, C. (1994). *Analysis of Asynchronous Concurrent Systems by Timed Petri Nets*, PhD thesis, MIT, Cambridge, MA.

Rosen, M. & Dincer, I. (2003). Exergy-cost-energy-mass analysis of thermal systems and processes, *Energy Conversion and Management* 44(10): 1633–1651.

Sabri, E. & Beamon, B. (2000). A multi-objective approach to simultaneous strategic and operational planning in supply chain design, *Omega* 28(5): 581–598.

Sato, N. (2004). *Chemical Energy and Exergy: An Introduction to Chemical Thermodynamics for Engineers*, Elsevier Science Publishers.

Sciubba, E. (2003). Extended exergy accounting applied to energy recovery from waste: The concept of total recycling, *Energy* 28(13): 1315–1334.

Silva, M. & Maciel, P. (2005). Modelling and analysis of inventory policy: an approach based on petri nets, *International IEEE Conference on Systems, Man and Cybernetics*, Hawaii.

SimaPRO LCA Software (2010). Website.
URL: *http://www.pre.nl/simapro/*

Simchi-Levi, D., Bramel, J. & Chen, X. (2005). *The logic of logistics: theory, algorithms, and applications for logistics and supply chain management*, Springer Verlag.

Simchi-Levi, D., Kaminsky, P. & Simchi-Levi, E. (2000). *Designing and managing the supply chain: concepts, strategies and case studies*, McGraw-Hill.

Soman, C. A., van Donk, D. P. & Gaalman, G. (2002). Combined make-to-order and make-to-stock in a food production system, *Technical report*, University of Groningen, Research Institute SOM (Systems, Organisations and Management).

Srivastava, S. K. (2007). Green Supply-Chain Management: A State-of-the-Art Literature Review, *International Journal of Management Reviews* 9(1): 53 – 80.

Szargut, J. & Morris, D. R. (1985). Cumulative exergy consumption and cumulative degree of perfection of chemical processes, *Int. Journal of Energy Research* 11(2): 245–261.

Szargut, J., Morris, D. R. & Steward, F. R. (1988). *Exergy Analysis of Thermal, Chemical, and Metallurgical Processes*, Hemisphere Publishing Corporation.

Szargut, J., Valero, A., Stanek, W. & Valero, A. (2005). Towards an international reference environment of chemical exergy, *18th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS)*, pp. 409–417.

Tijms, H. (2003). *A first course in stochastic models*, John Wiley & Sons Inc.

Valmari, A. (1998). The state explosion problem., *LNCS: Lectures on Petri Nets I: Basic Models* 1491: 429–528.

van der Aalst, W. (1992). *Timed coloured Petri nets and their application to logistics*, PhD thesis, Eindhoven University of Technology.

van der Laan, E., Dekker, R., Salomon, M. & Ridder, A. (1996). An (s, Q) inventory model with remanufacturing and disposal, *International Journal of Production Economics* 46-47: 339–350.

van der Laan, E. & Salomon, M. (1997). Production planning and inventory control with remanufacturing and disposal, *European Journal of Operational Research* 102(2): 264–278.

Veleva, V. & Ellenbecker, M. (2001). Indicators of sustainable production: framework and methodology, *Journal of Cleaner Production* 9(6): 519–549.

Viswanadham, N. & Raghavan, N. R. S. (2000). Performance analysis and design of supply chains: a Petri net approach, *Journal of Operations Research Society* pp. 1158–1169.

Zimmermann, A. (2007). *Stochastic Discrete Event Systems*, Springer, Berlin Heidelberg New York.

Zimmermann, A., Knoke, M., Yee, S.-T. & D.Tew, J. (2007). Model-based performance engineering of General Motors' vehicle supply chain, *IEEE Int. Conf. on Systems, Man and Cybernetics (SMC 2007)*, Montreal, Canada, pp. 1415–1420.

9

Analysis of a Supply Chain in Electrical and Electronic Industry

Roberto Ferrauto
Altran Italia S.p.A; Rome, Italy

1. Introduction

This chapter aims to provide a block analysis technique for complex electronic systems. This technique is based on the partitioning of the chain in several functional blocks. Each part of the system is simulated and numerically tested by using the more suitable technique to predict its performance in terms of the analysis of interest. This approach allows an identification of the block responsible for any specification violation and hence a more easy and quick solution of the problem. The simulation techniques can be different and carried out in different domains (time or frequency). The results of each simulation must be then investigated in order to verify if the results are compliant with the passivity and causality check. After the simulation of the complete system is carried out, the parameters of each block are cascaded to get the overall system performances. A flow diagram of the proposed approach is reported in Fig. 1.

This chapter consists in 4 sections. Section 2 describes helpful techniques to predict the frequency content of the input voltage signal. Section 3 describes the different useful ways to numerically characterize the different electronic part. In Section 3.3 the fulfillment of passivity and causality of the port parameters of the results of the simulations is discussed. Section 3.3 describes the evaluation of the DC resistance value of a single block. Finally, in Section 3.4, the computed results can be validated by hardware measurements.

2. Signal spectra

In this section a general overview of the spectral composition of the periodic signals is reported. Pulses described using time are said to be represented in time domain. Most signal integrity work is performed in the time domain, but it's important to understand the way in which the electrical characteristics of the circuit board traces change at different frequencies. The frequency approach is especially useful when studying how losses on transmission lines affect the shape (distortion) and alignment of pulses (intersymbol interference).

Oscilloscope is a common time-domain instrument and the SPICE circuit simulator displays its results in the time domain by default. A vector network analyzer (VNA), which displays the impedance of a component or transmission line at various frequencies, and the spectrum analyzer, a device that simultaneously displays the amplitude across a range of frequencies, is example of frequency-domain instruments.

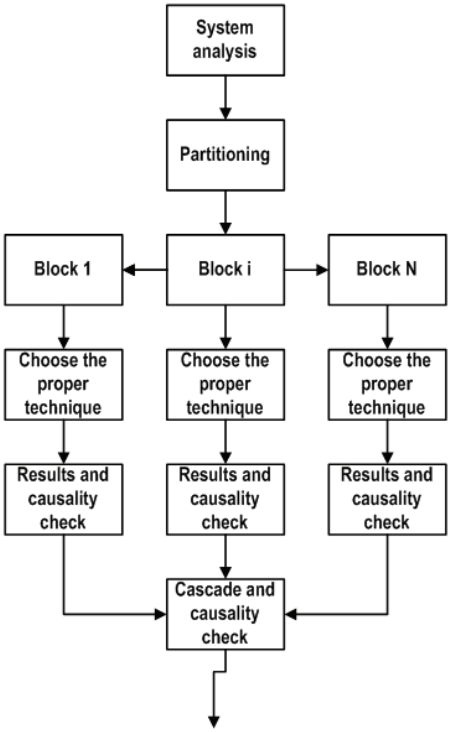


Fig. 1. Flow diagram of the proposed approach

The analysis is concentrated about the signals that are representative of the typical digital products. The waveforms of primary importance in digital circuits are those which represent the clock and the digital data and they are trapezoidal square pulses. These signals are present in the main ICs.

We discuss how time domain factors (rise time, fall time and duty cycle) affect their spectral contents: the spectrum is a function of these parameters.

Taking an infinitive number of harmonics, we could exactly reproduce the signal when we transform back into the time domain. In practice, we don't need to do that; we can show that 15 or 20 harmonics will pretty much guarantee that the signal integrity is preserved. This observation is critical because lossy lines act as low-pass filters and gradually remove higher frequencies. Further, the zero rise time pulses requires more harmonics than an identical pulse having a slower rise time. In the frequency domain this means the zero rise time pulse require more bandwidth than rise time pulses for distortion free transmission. In this section the mathematical model that incorporates the effects of asymmetry between rise and fall edge rates and duty cycle is reported. This model provides bounds of the spectra that will facilitate the analysis of the effects of the signals. Finally some numerical examples are proposed.

2.1 Square pulse spectral analysis

Each square pulse is described by an amplitude A, a pulse width PD τ, a time delay TD and a period T. A rectangular waveform, with parameters A = 1V, TD = 250 ns, PW = 500 ns and P = 1000 ns, is reported in Fig. 2.

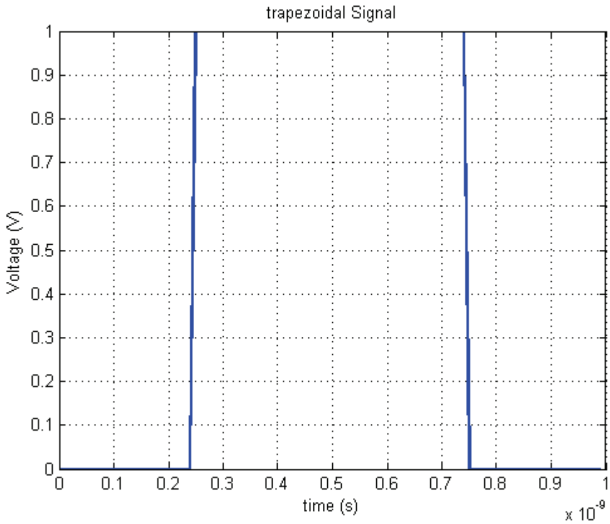


Fig. 2. A = 1 V, TD = 250 ns, T = 1000 ns square pulse

The assessment of the spectral content of this waveform can be carried out using the expansion coefficients of the Fourier series. As a known, a periodic signal x(t), with period T, can be wrote with the series expansion as in (1).

$$x(t) = c_0 + \sum_{n=1}^{\infty} 2|c_n| \cos(n\omega_0 t + \varphi(c_n)) \tag{1}$$

Evaluating the complex-exponential coefficients of the series, c_n, we get the expressions for the amplitude (2) and the phase spectrum (3):

$$|c_n| = \frac{A\tau}{T}\left|\frac{sen(n\pi\tau / T)}{n\pi\tau / T}\right| \tag{2}$$

$$\varphi(c_n) = \pm\frac{n\pi\tau}{T} \tag{3}$$

In Fig. 3 the amplitude spectrum of the square wave we considered as example is reported. The horizontal axes are in terms of cyclic frequency f. The amplitude of the spectral components lie on the envelop that is

$$\frac{A\tau}{T}\left|\frac{sen(\pi f \tau)}{\pi f \tau}\right| \tag{4}$$

This goes to zero where $\pi f\tau = m\pi$ or at multiples of $\frac{1}{\tau}$. This function, denoted as $sen(x)/x$, evaluates the unity for x = 0 and is zero for m = 1,2,3,… . Although the continuous envelope bounds the spectral amplitudes, the spectral components only exist at multiples of the fundamental frequency.

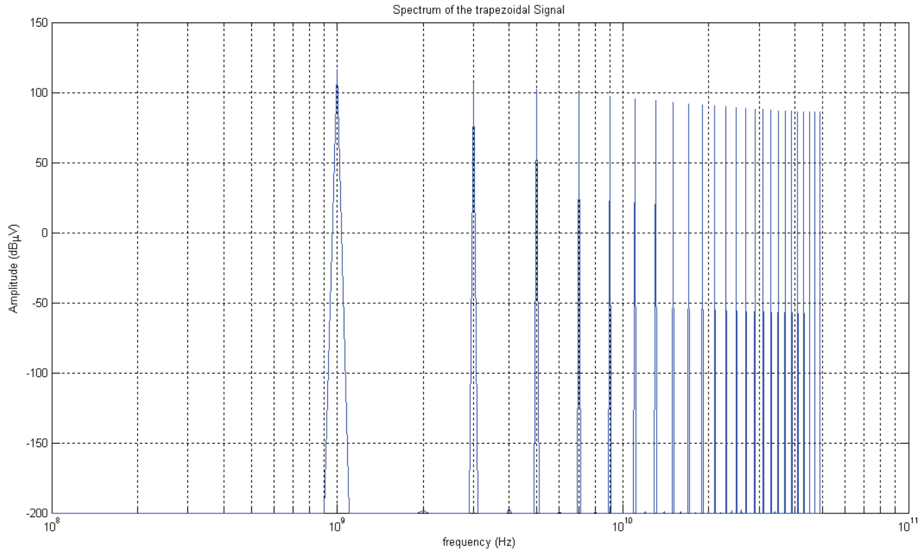


Fig. 3. Amplitude spectrum of the square waveform

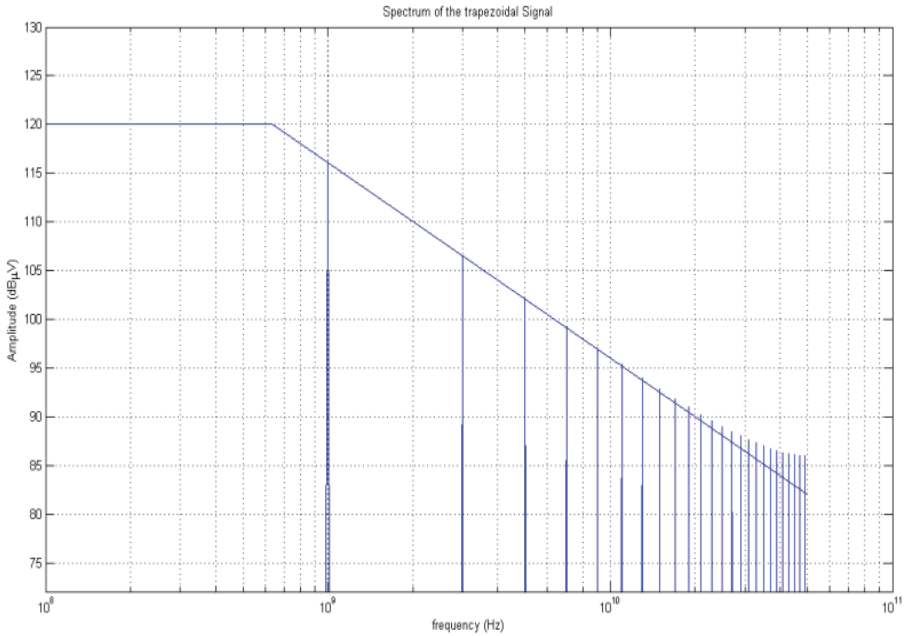


Fig. 4. Bode plot superimposed on FFT of a trapezoidal waveform

Now it's possible to extract more intuitive information from the spectrum expansion coefficients. This allows to generate bounds on the magnitude spectrum. Although these are upper bounds on the spectral components and are approximate, they are very useful in understanding the impact of pulse width on the spectrum of the waveform. In fact, the spectral components follow a form of $sin(\pi f \tau) / \pi f \tau$. The envelope has zeros at $f = m / \tau$ for m = 1, 2, 3, … . The envelope can be bounded by recalling the small-argument expression for sin x, which is that sin $x \cong x$ for x small. This way we get

$$|\sin x/x| \leq \begin{cases} 1 & \textit{for small } x \\ 1/|x| & \textit{for small } x \end{cases} \quad (5)$$

This can be drawn as two asymptotes, as shown in Fig. 4. The first asymptote is unity and has slope on a logarithmic or Bode plot of 0 dB/decade. The second asymptote decrease linearly of -20dB/decade. The two asymptote converge at x = 1. Thus for the square wave the first asymptote has 0 dB/decade slope out to $f = 1/\pi\tau$ and -20 dB/decade slope above that frequency. Applying this to the reference square wave we get the graph reported in Fig. 4 where to the spectrum is added the upper bound.

2.2 Effect of rise/fall time on spectral content.

We can extend these notions to the trapezoidal pulse train. Each pulse is described by an amplitude A, a pulse rise time τr, a pulse fall time τf, a PD, a PW τ and a period T. A trapezoidal waveform, having A = 1V, T = 1 ns, τr = τf = 0.1 ps, τ = 0.4 ps and PD = 200 ps is reported in Fig. 5.

With the assumption that the rise and fall times are equal, $\tau r = \tau f$, the expansion coefficients expression can be put in the form of the products of two $\sin x/x$ expressions. Replacing the discrete spectrum with a continuous envelope by substituting $f = nT$ we get:

$$\text{envelope} = 2A\frac{\tau}{T}\left|\frac{\sin(\pi\tau f)}{\pi\tau f}\right|\left|\frac{\sin(\pi f \tau_r)}{\pi f \tau_r}\right| \quad (6)$$

In order to produce bounds for this spectrum, we calculate the logarithm of this equation, that produces

$$20\log10(\text{envelope}) = 20\log10(2A\,{}^{\tau}\!/_{T}) + 20\log10\left|\frac{\sin(\pi\tau f)}{\pi\tau f}\right| + 20\log10\left|\frac{\sin(\pi\tau_r f)}{\pi\tau_r f}\right| \quad (7)$$

This shows that the composite spectrum is the sum of three pieces:

$$\text{Piece } 1 = 20\log_{10}\left({}^{2A\tau}\!/_{T}\right) \quad (8)$$

$$\text{Piece } 2 = 20\log_{10}\left|{}^{\sin(\pi f \tau)}\!/_{\pi f \tau}\right| \quad (9)$$

$$\text{Piece } 3 = 20\log_{10}\left|{}^{\sin(\pi f \tau_r)}\!/_{\pi f \tau_r}\right| \quad (10)$$

Piece 1, (8), has 0 dB/decade slope and a constant level of 2Aτ/T=2Aτf0. Piece 2, (9), has two asymptotes. The first asymptote has 0 dB/decade slope. The second asymptote has -20 dB/decade slope. The two asymptotes join at $f = 1/\pi\tau$. Piece 3, (10), consists of two asymptotes, one of which has 0 dB/decade slope and unity level (0 dB) and the other has a -

20 dB/decade slope. The asymptotes of the third piece join at $f = 1/\pi\tau_r$. The composite asymptote thus consists of three straight line segments. The first is due to Piece 1 and has a slope of 0 dB/decade and a starting level of $2A\tau/T$. The second segment has a slope of -20 dB/decade and is due to the Piece 2. The third segment has a slope of -40 dB/decade and is due to the sum of Piece 2 and Piece 3. It is evident that the pulse width must be greater than or equal to the pulse rise/fall times. This way the first breakpoint in the spectral bound will be related to Plot 2, whose breakpoint is related to the pulse width and is $1/\pi\tau$. The second breakpoint is due to Piece 3, whose breakpoint is related to the rise/fall time and is $1/\pi\tau_r$. The spectrum of the waveform showed in Fig. 5 is reported in Fig. 6.

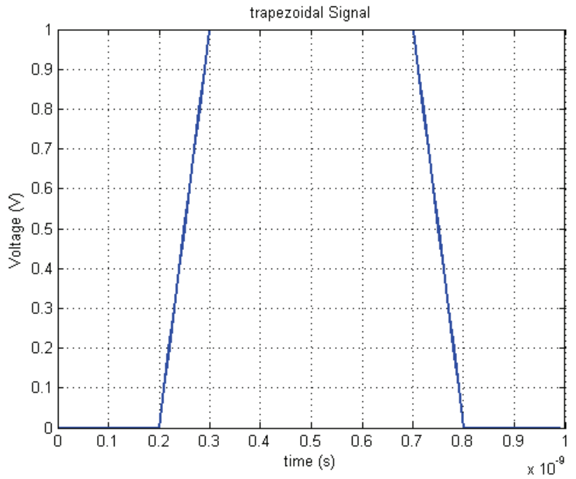


Fig. 5. Trapezoidal square wave

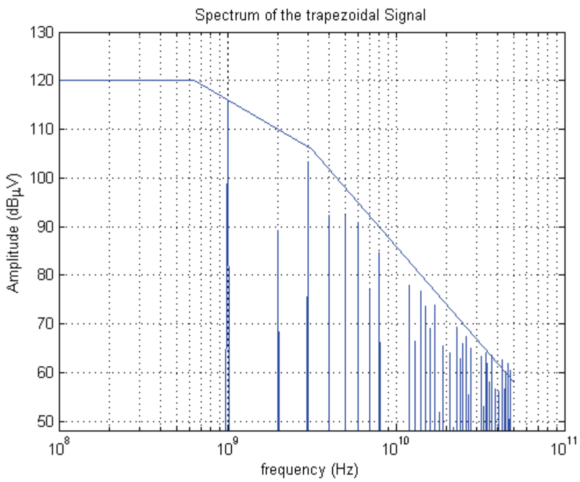


Fig. 6. Spectrum of a trapezoidal waveform having the same rise and fall time

From these spectral bounds it becomes clear that the high-frequency content of a trapezoidal pulse train is primarily due to the rise/fall time of the pulse. Pulses having small rise/fall time will have larger high-frequency spectral content than will pulses having larger rise/fall time. In other words, as rise times increase, the number of significant high order harmonics increase as well. The amplitude of the lower harmonics do not change significantly as rise time increases.

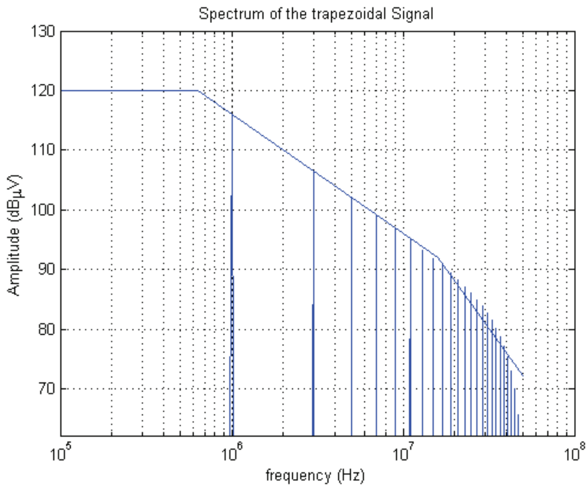


Fig. 7. Spectral bounds for 1 MHz trapezoidal pulse having 20 ns rise/fall time

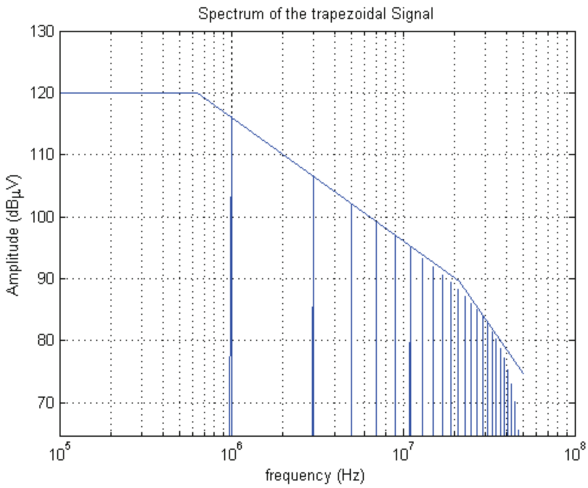


Fig. 8. Spectral bounds for 1 MHz trapezoidal pulse having 15 ns rise/fall time

In order to illustrate this important relationship between pulse rise/fall time and the spectral content of that waveform, we will consider two numerical example.

We will show the spectral bounds for two trapezoidal waveform having:

- A = 1 V, 50% duty cycle, T = 1 μs, $\tau_r = \tau_f$ = 20 ns;
- A = 1 V, 50% duty cycle, T = 1 μs, $\tau_r = \tau_f$ = 15 ns.

The both spectrum are reported in Fig. 7 and Fig. 8.
We can note that the -40 dB/decade bound has moved out from 92 to 89 MHz. The -40 dB/decade breakpoint is commonly used to set the frequency range of analysis where the value of attenuation is enough to neglect the harmonic components at higher frequencies. Anyway, as the spectrogram of a pulse having glitches or plateaus along its edges, or one that overshoots or oscillates about the steady state value, will have more harmonics than the well behaved pulses used here. This leads to take a safe margin of 3-5 times over the -40 dB/decade bandwidth supplied by the numerical analysis.

3. Numerical evaluation

After the frequency range is set, the supply chain, split in several blocks, can be electromagnetically investigated to extract the S-parameters or equivalent circuit. To get a numerically correct response of the chain, the samples of the block are extracted at the same frequency points. Further, a reduction of the interpolation error can be obtained by extracting a large number of samples within the range of analysis. The parameters of each block can be imported in a circuital simulator to get the overall response.
The most important electrical parameters in supply chains analysis are the DC losses and the distortions evaluation of the pulses waveform along the supply chain path.

3.1 Field solver

Electromagnetic field solvers analyze a physical structure such as a circuit board trace or a complex geometry of a connector and produce electrical circuit model. The most common field solvers are those that analyze two dimensional structure (2D solver) while three dimensional structures are analyzed with 3D solvers.

3.1.1 2D field solver

The use of 2D solvers is for those structures having a shape uniform and easily described in only two dimensions. A group of straight circuit board traces that have a constant width, spacing, height above the ground plane, and thickness is a good example of the type of structure appropriate for 2D analysis.
The field solver calculates the resistances, capacitance, inductance, and conductance of the 2D structure and tabulates them across a user defined frequency range. The frequency range must be carefully selected because, as known, digital pulses contain high-frequency harmonics and losses increase with frequency. Since the shape is uniform, the electrical parameters are specified per unit length. The value for a specific trace is found by multiplying the field solver results by the actual length of the structure. The best solver allow the user to choose the output format from a variety of model types, so a library of the circuit models can be created that are usable by a number of different circuit simulators. At the minimum the field solver should produce both an RLGC output file and S-parameters model, preferably in Touchstone files.

3.1.2 3D field solver

Circuit models for physical structures that are not uniform in shape (such as vias or traces that vary in width or spacing or that bend around objects) are created with a 3D field solver.

As the structure is simulated in three dimensions, setting up the problem space is usually more time-consuming and error-prone than with 2D simulators. As in most of the cases the structures consists in multilayer stack-up, the 3D solver have an intuitive graphical interface in order to make easier the check of the circuit board stack-up and defining the material properties and further verify that the values have been assigned properly and assigned to the correct layer in the stack-up.
The drawing interface should be thoroughly tested to determine the ease in creating and editing complex 3D structures. Although some simulators can directly import the 3D mechanical drawings created by CAD drafting software, it's necessary for the designer to "clean up" the drawing and to crop the regions once it has been imported.
Generally the S-parameters are the default output model type.

3.2 Passivity and causality

The EM characterization of the propagating structures is usually determined in frequency domain using equation-based EM solvers or directly by measurements. Anyway, a transformation techniques is required to obtain time-domain transfer function for such passive structures from their frequency domain response. In this process several source of error can be introduced (numerical approximations due to the meshing techniques, finite precision of the computing implementation and the eventually post-processing of the data).
Passivity simply implies that the structure cannot create energy unless there is an energy source, such as a power supply. For example S parameters generated in EM simulators should theoretically be passive. Passivity is the hardest criterion for algorithms to meet and the most difficult physical constraint to satisfy in the current algorithms. Methods that ensure passivity are only practical for small problems. The problem becomes more difficult for multidimensional S-parameters with many ports. For a large number of ports there is no practical way to ensure passivity, and algorithms rely on reasonable checks that work in most cases.
Causality states that the response cannot be obtained before the excitation, so a reflected signal cannot be generated before the incident wave arrives. In other words the signal cannot show up at the load before it leaves the source. This condition is not difficult to meet, but incidentally, it's easy to violate with traditional circuit models.

3.2.1 Passivity check

Reliable time-domain simulation of high-speed simulation systems requires that each part of the system is modeled with sufficient accuracy. In the contrary case, the parameters extracted, when not passive, can lead to an unstable simulations. The stability problem can be avoided by enforcing passivity. To do this several algorithms are available. Passivity enforcement can be implemented on the Y-parameters models and for S-parameters models.
Most of the commercial simulators offer the passive test as standard. This determines if the frequency dependent S-parameters are passive or not.
One of the criterion we can use to carry out the passivity check takes into account the S parameter of the network.
This one calculates the smallest eigenvalue of the matrix $A = I - S^H S$, where I is the identity matrix, S the scattering matrix and the superscript "H" denotes the Hermitian conjugate. For the S matrix to be passive, the smallest eigenvalue of the matrix A defined above should be non-negative. This calculation is performed at each frequency in the sweep. This passivity

criterion is both necessary and sufficient, while the requirement that the magnitude of Sij should not exceed 1 is just necessary.
The result is a real value that is positive or zero at frequencies where the sub-circuit is passive and negative at the frequencies where it is not-passive. This algorithm can be applied to S parameters produced by networks of any number of port. Due to experimental errors and the errors in EM simulations, small eigenvalue result even for passive structures. As example we can consider the computed S parameters of a microstrip filter, whose picture is reported in Fig. 9.

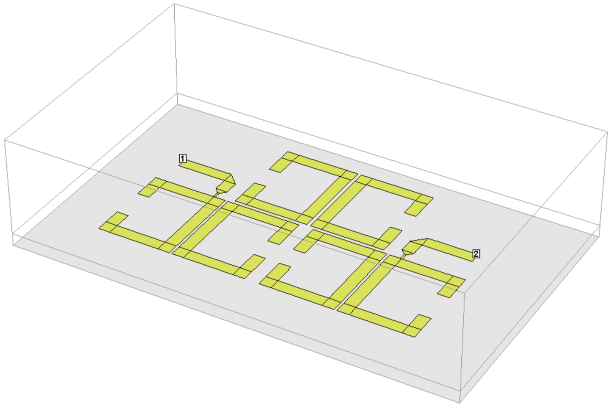


Fig. 9. 11 GHz microstrip filter

The graph of the S parameters is reported in Fig. 10.

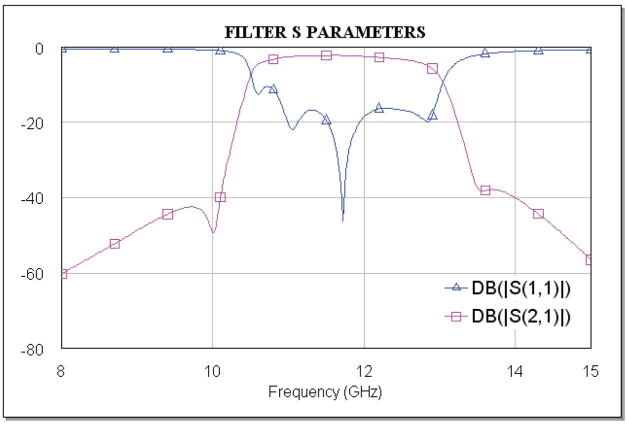


Fig. 10. Achieved 11 GHz microstrip filter S parameters

The result of the passivity check measurement is reported in Fig. 11. This states that the passivity is respected for all the frequency points. Anyway, the passivity can be enforced following the S-parameters calculation. Several iterative algorithms can be implemented to carry out this correction, adding a correction factor, sample by sample.

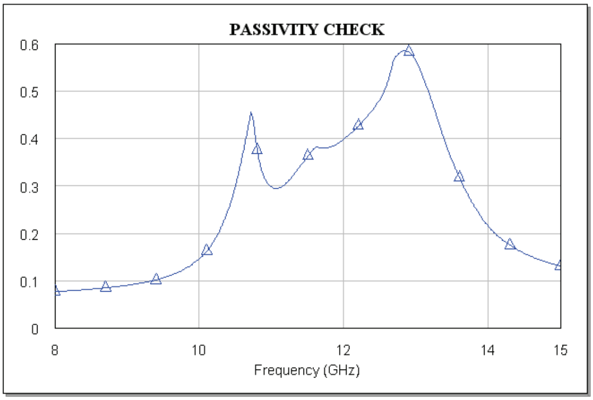


Fig. 11. Graph of 11 GHz filter passivity check result

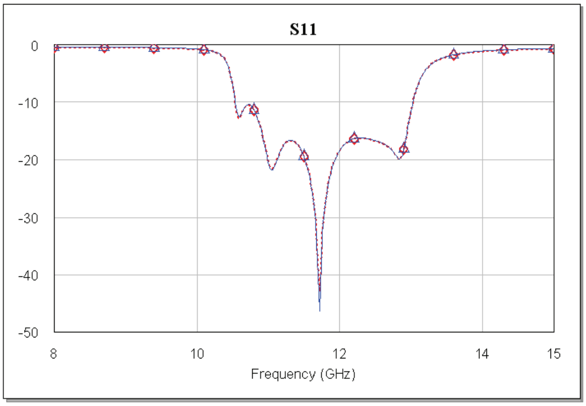


Fig. 12. Computed and passivity enforced S11 curve

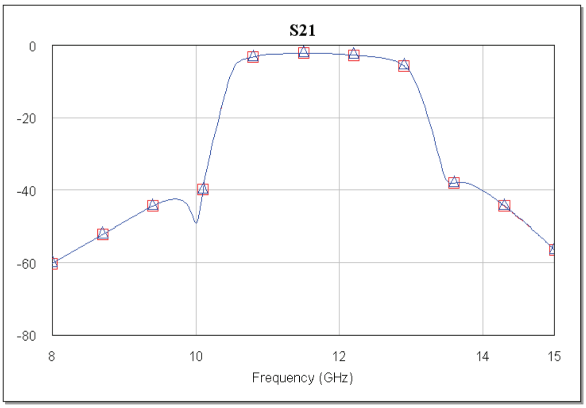


Fig. 13. Computed and passivity enforced S21 curve

Applying the Hamiltonian algorithm to the microstrip filter response, we get the S11 and S21 parameters enforced. In Fig. 12 and Fig. 13 the original and the enforced responses are compared and overlapped. The errors between the two couples of graphs are negligible. In Fig. 14 and Fig. 15 the passivity enforcement errors are reported.

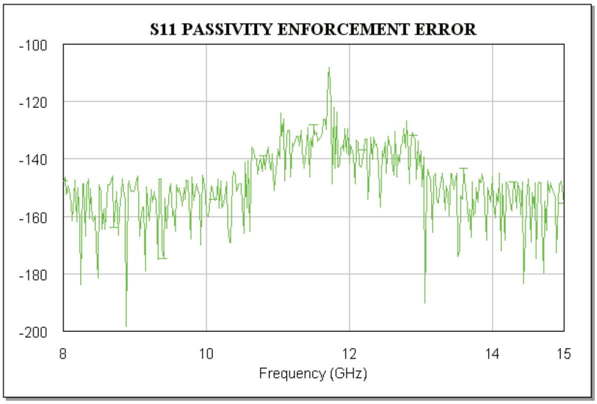


Fig. 14. Error due to the S11 passivity enforcement

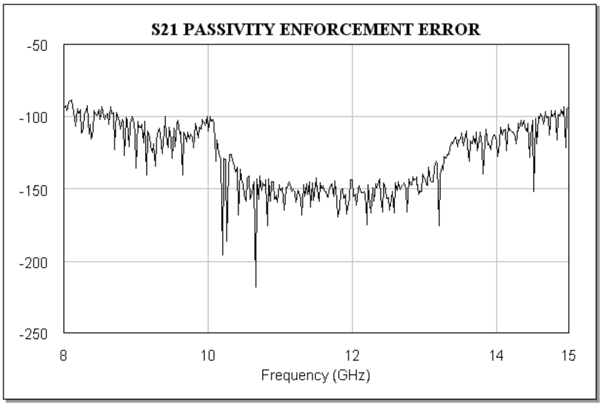


Fig. 15. Error due to the S21 passivity enforcement

3.2.2 Causality check

Before cascading the blocks, each of them must be tested singularly if its multiport frequency dependent characterization matrix (S-parameter, admittance, impedance etc.) fulfils the causality check. In case one or more blocks would not pass this check then they could not be cascaded because their non-causality would render all the system not causal with possible instabilities. The causality check on the extracted S parameters can be performed exciting them with a sinusoidal waveform, within the frequency range of analysis. For each block the physical delay propagation is calculated by evaluating the ratio between the maximum distance and the propagation speed in the block considered.

Comparing the physical delay obtained with that yielded from the simulation, it's possible to conclude if each block is causal or less. We consider a LTCC module, having 1 input port and 3 output ports, Fig. 16.

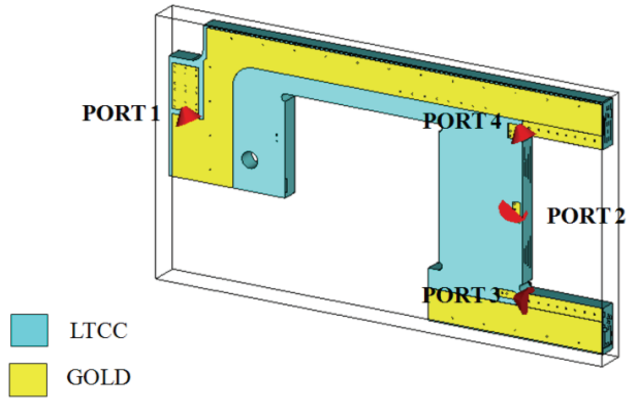


Fig. 16. LTCC module structure

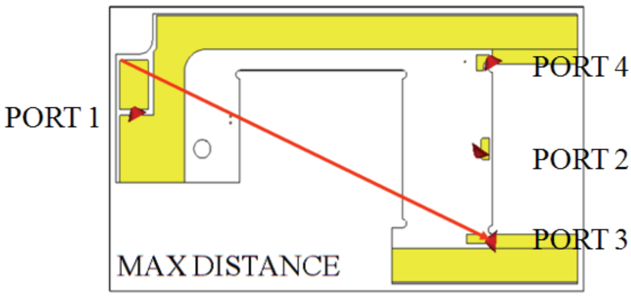


Fig. 17. LTCC module front view with the indication of the maximum distance on the top layer

An EM simulation has been performed to evaluate the S parameters in the range 0-200 MHz. The maximum delay propagation between the input and the output ort is 0.28 ns. Using a circuital simulator, the input port is excited by sinusoidal waveforms in the same range of analysis of the module. If for each frequency, the delay time is higher than the delay time is higher than the delay propagation manually calculated, the model is causal.
In Fig. 18 the schematic of the LTCC model schematic is reported.
In Table 1 the list of the delay propagation manually and schematically evaluated are reported and compared each other. This way we conclude that the LTCC model taken under analysis is causal.
A further test is to import the S parameter of the block under investigation in HSpice schematic. HSpice allows to import only causal models, and if a circuit contains such a model, an error message displays and the circuit is not simulated. If no error is met, it's confirmed that the block also fulfils the causality requirement.

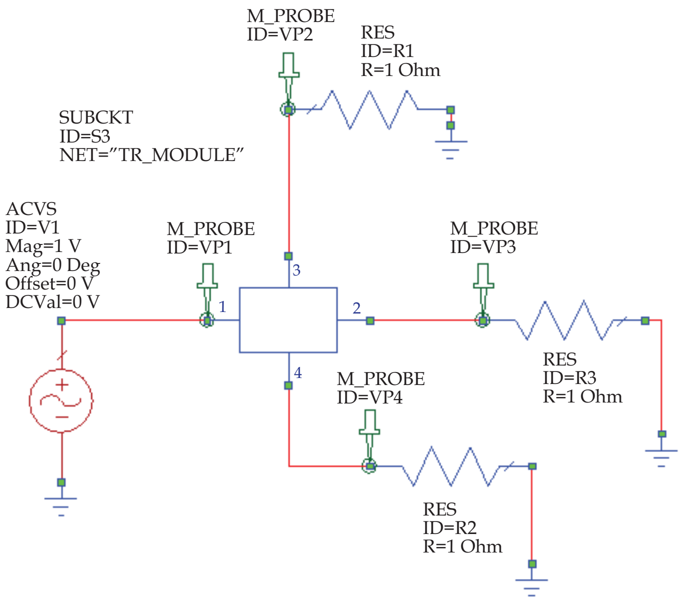


Fig. 18. LTCC module touchstone file in AWR MWO environment

	PHYSICAL DELAY TIME (ns)	DELAY TIME DETECTED VPROBE1 (ns)	DELAY TIME DETECTED VPROBE2 (ns)	DELAY TIME DETECTED VPROBE3 (ns)
@1 MHz	0.28	4.682	4.269	4.153
@5 MHz	0.28	4.598	4.196	4.062
@10 MHz	0.28	4.416	4.021	3.895
@50 MHz	0.28	2.983	2.665	2.563
@100 MHz	0.28	2.043	1.794	1.725
@150 MHz	0.28	1.533	1.345	1.299
@200 MHz	0.28	1.222	1.081	1.050

Table 1. List of the propagation delays manually evaluated compared with the ones evaluated in the schematic

3.2.3 Analytical causality enforcement

The Hilbert transform is used as tool to assess the consistency of measured or numerically computed network transfer functions with respect the causality conditions.

The application of the inverse Fourier integral to the complete frequency response of any physical network should always yield a causal time-domain impulse response. In practice, however, the frequency response information we have is often incomplete (band limited and on a discrete and frequency point grid) and can contain measurements errors. A native application of inverse Fourier integral to such a frequency response almost always yields an incorrect non-causal time-domain model. The Kramers-Kronig relation is very useful in these situation because it allows us to correct the frequency response and built a causal time-domain model.

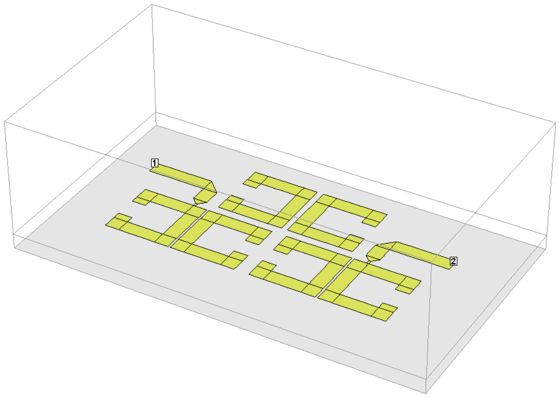


Fig. 19. 20 GHz microstrip filter

Further, these relations give a condition that is both necessary and sufficient, so even before applying an inverse Fourier integral, we can determine whatever a given frequency response will yield a causal or non-causal impulse response. If the real and imaginary part are Hilbert transform of each other, the pulse response is causal, and not otherwise. This fact is very useful because it allows us to test whatever or not a frequency response is causal without ever having to leave the frequency domain.
We apply the causality enforcement to the S parameters of the microstrip filter of Fig. 19. In Fig. 20 and Fig. 21 the computed, red trace, and causality enforced, blue trace, S11 and S21 parameters in the range of analysis are reported.
In both some violation at the borders of the frequency spectrum appear. They are due to the approximation of the numerically computed Hilbert Transform. In Fig. 22 and Fig. 23 the errors produced by the causality enforcements are reported. The levels of causality violations are negligible in the band of operation of the filter.

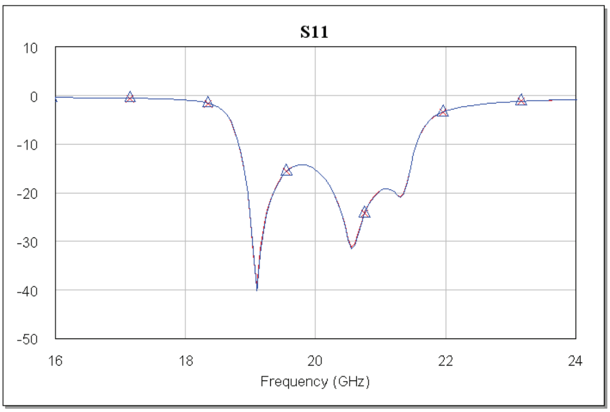


Fig. 20. Computed and causality enforced S11 parameter

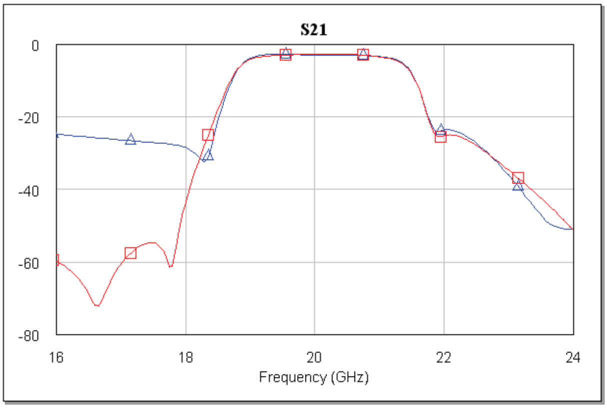


Fig. 21. Computed and causality enforced S21 parameter

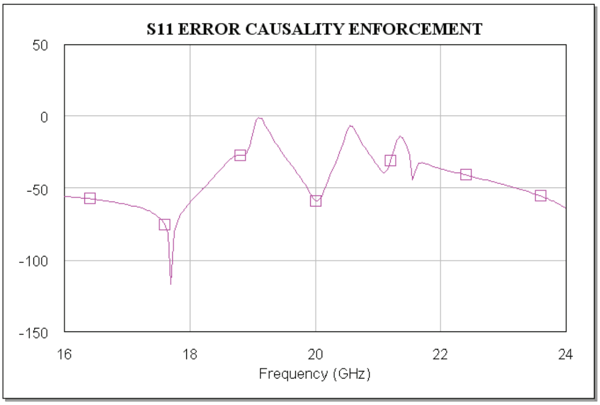


Fig. 22. Error due to the S11 causality enforcement

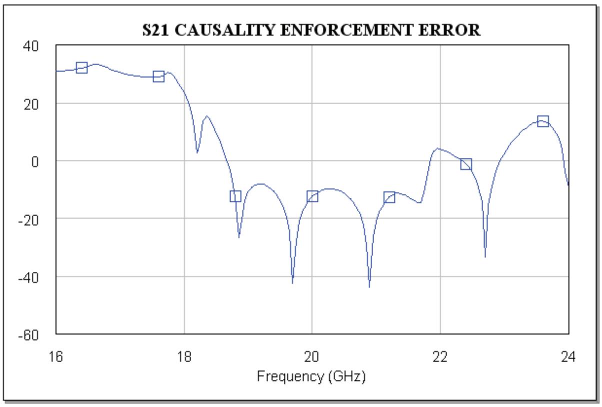


Fig. 23. Error due to the S21 causality enforcement

3.3 DC performance analysis

The last step in this systematic analysis is the evaluation of the DC voltage drop (also known as IR-drop) across each block between their input and output ports. The IR-drop is generally defined as the dc voltage drop across a conductive element due to the dc current flow. The power supply chain in single or multi-layer structure, from the voltage regulator module to the supplied integrated circuits, is affected by the IR drop across each single block planes.
As example we can compute the spatial distribution of the DC electric potential on the conductive parts of a PCB multilayer structure, when a known DC current is injected at their ports.

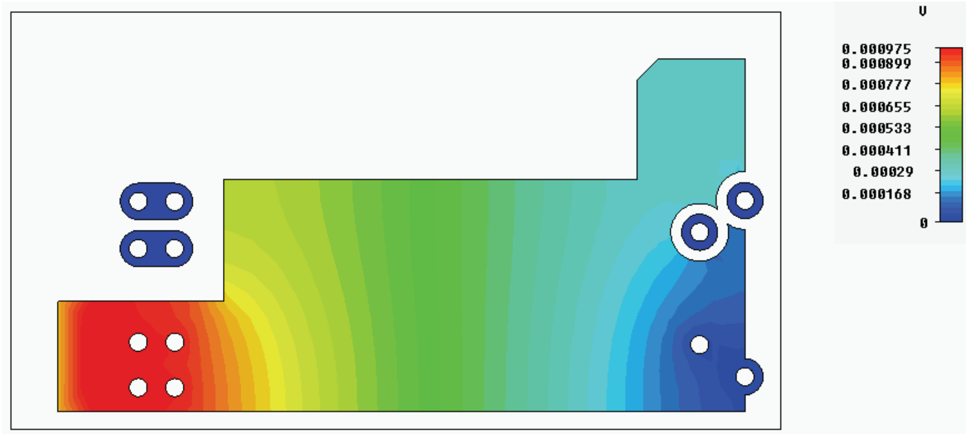


Fig. 24. Spatial distribution of the DC electric potential along the power PCB layer

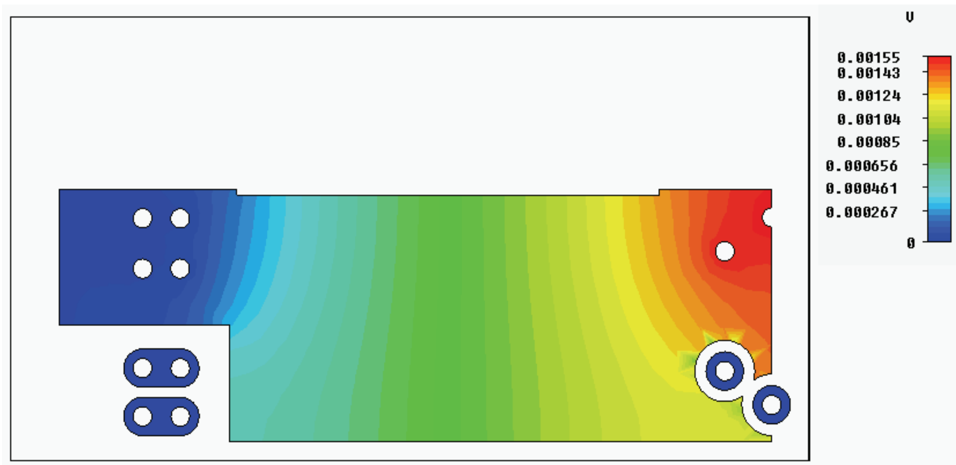


Fig. 25. Spatial distribution of the DC electric potential along the ground PCB plane

For this analysis, due to the complex shapes of the conduction paths, a three dimensional static solver for the current density is used. After having set the ports where the DC current

is injected and drawn, the spatial distribution of the static electric potential between the ports pair is computed. Fig. 24 and Fig. 25 show the voltage distribution for both power and ground layers. From this information it is possible to extract the overall equivalent DC resistance, 2.525 mΩ.
After the DC voltage drop for each block is computed, adding them, the equivalent supply chain DC resistance is known.

3.4 Computed results and measurement validation

All the blocks can be cascaded in order to compute the overall system response. The blocks are imported in a circuital simulator that, using a convolution procedure allows to mix, in the same run, blocks characterized in time domain (as the input voltage source) and blocks characterized in frequency domain.
The voltage pulse is injected at the input port and is evaluated the attenuation and the distortion corresponding at all the output ports. In Fig. 26 the schematic of a supply chain in a circuital simulator environment is reconstructed.

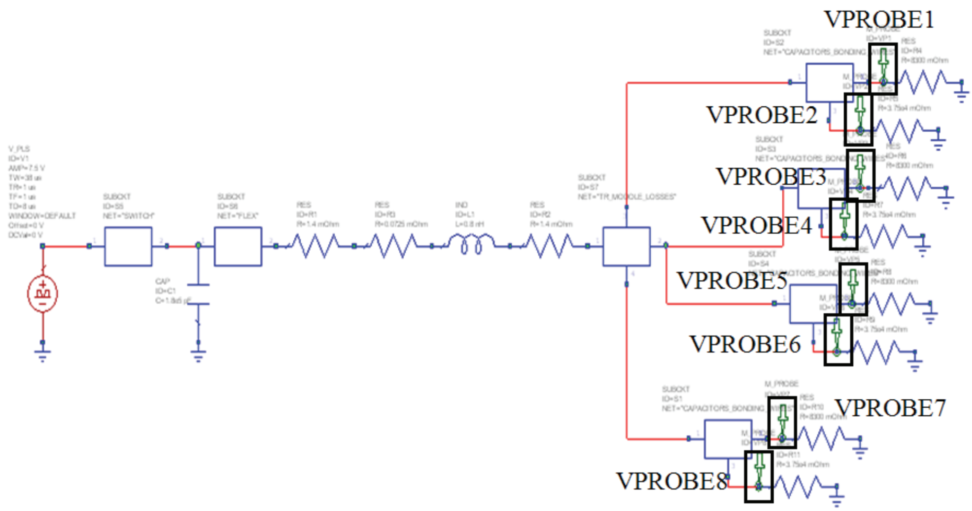


Fig. 26. Schematic of a supply chain

The computed output signals are detected at each output port. In order to validate the developed equivalent model of the supply chain some voltage measurement have to perform on selected nodes and compared with the simulation results. The signals measured at the test points can be compared with the computed ones and the two ones can be overlapped to check the reliability of the proposed approach, Fig. 27 and Fig. 28.

4. Conclusions

This chapter describes a systematic approach for the analysis of the signal integrity of a supply voltage pulse propagating from the input to the output port of a complex supply chain of a devices for spatial and military applications. The use of different approaches and different standard tools makes possible to predict the voltage level and the transient waveform of the propagating pulse in each section of the complex signal path. The instruments to validate the computed and measured parameters are discussed. To validate this analysis approach the measure on the real device has to be performed.

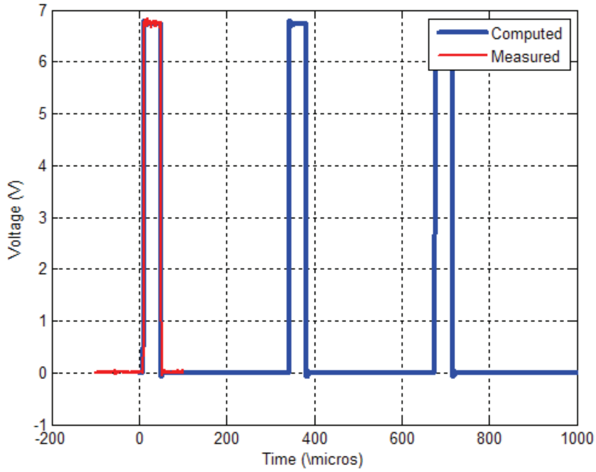


Fig. 27. Comparison between computed and measured transient voltage waveform

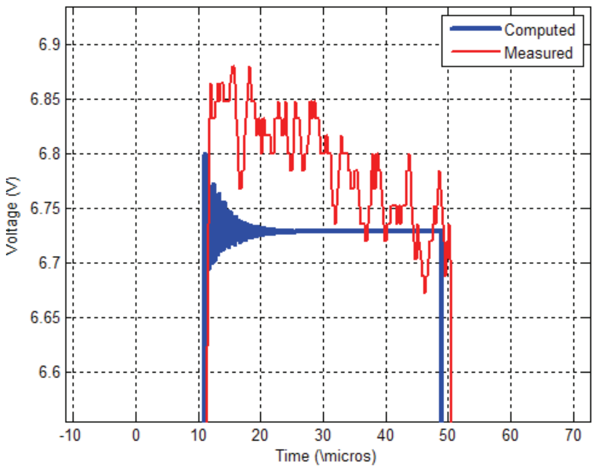


Fig. 28. Comparison between the computed and measured waveform

5. References

A. C. Cangellaris, M. Celik, S. Pasha,, L. Zhao, "Electromagnetic model order reduction for system level modeling, IEEE Trans. Microwave Theory Techn., vol. 47, n. 6, June 1999, pp. 840-850.

Agilent Technologies, Advanced Design Simulator, www.agilent.com, 2010.

AWR, Microwave Office 2009, www.awr.com, 2009.

B. Archambeault, C. Brench, O. Ramahi, EMC/EMI Computational Modeling Handbook, II Edition, Kluwer Academic Publishers, 2001.

C. R. Paul, Introduction to Electromagnetic Compatibility, II Edition, Wiley InterScience Publication, New York, USA, 2009.

Computer Simulation Technology, CST Studio 2010, www.cst.com, 2010.

F. M. Tesche, “On the use of Hilbert transform for processing measured CW data”, IEEE Transactions on Electromagn. Compatibility, vol. 34, n. 3, August 1992, pp. 259-266.

G. Antonini, A. Ciccomancini Scogna, A. Orlandi, “De-Embedding procedure based on computed/measured data set for PCB structure characterization”, IEEE Trans. on Advanced Packaging, vol. 27, n. 4, Nov. 2004, pp. 597-602.

G.Antonini, A.Orlandi, V.Ricchiuti,”Causality Check for SI Data Validation”, in Proc. of 9th IEEE Workshop on Signal Propagation on Interconnects, Garmish-Partenkirchen, Germany, May, 2005.

Hsien-Te Chen; Chieh-Chun Chang; TingTing Hwang, “New spare cell design for IR drop minimization in Engineering Change Order”, in Proc. of 46th Design Automation Conference, San Francisco, CA, USA, 26-31 July 2009 pp. 402 – 407.

H. W. Bode, Network Analysis and Feedback Amplifier Design, Van Nostrand, NJ, USA, 1945.

K. M. Coperich Branch, J. Morsey, A. C. Cangellaris, A. E. Ruehli, “Physically consistent transmission line models for high-speed interconnects in lossy dielectrics”, IEEE Trans. Adv. Packag., vol. 25, n. 2, May 2002, pp.129-135.

R. Ferrauto, F. De Paulis, E. Ippoliti, F. Vasarelli, A. Orlandi, “IR-Drop Simulation using CST STUDIO SUITE”, CST Application Note nr. 71, March 2009.

Robert S. Elliot, Waves and Microwave Circuits, Prentice Hall International, Inc, 1993.

S. L. Hahn, Hilbert Transform in Signal Processing, Artech House Publishers, 2000.

Sonnet Software, Sonnet EM simulator, www.sonnetsoftware.com, 2010.

Synopsis, HSpice, http://www.synopsys.com/Tools/

T. Weiland, “A Discretization Method for the Solution of Maxwell’s Equation for Six Component Fields”, Electronics and Communication, (AEÜ), Vol.31 (1977), p. 116.

10

Research on Measurement and Evolutionary Mechanisms of Supply Chain Flexibility

Li Quanxi, Qi Yibing and Zhao Wanchen
School of Management, Jilin University, Changchun, China

1. Introduction

With the continuously updating of technology and various of customer's requirement, there are various uncertainties in supply chain environment, from market situation, changeable customer's requirement, collaboration of supply chain partnership to various operation management internal supply chain, all of them exist kinds of uncertainties, which add the complexity of supply chain management. Flexibility has been considered as the ability to react uncertainty and a major determinant of competitiveness. In order to guide the supply chain to respond to environmental uncertainty and make accurate decisions for the construction and evolution of supply chain flexibility, fully and accurately measure the level of supply chain flexibility is the key.

The most literatures on the flexibility are concentrated in the context of manufacturing field and enterprise level. With the need of competition and the blurring boundaries of the firm, supply chain flexibility has been receiving increasing attention from both practitioners as well as researchers. Due to the multidimensional concept of flexibility and the complexity of supply chain, the research field of the connotation, basic motive force and generated mechanism of supply chain flexibility are still confusion. In order to response environmental uncertainty, deeply understand flexibility and analysis measurement and evolution of supply chain flexibility in changeable demand environment is a basic goal in supply chain management. Currently, researches on flexibility measurement are still not unified. There are many measuring methods focusing on one aspect of the flexibility elements but few articles comprehensively measuring supply chain flexibility from an overall perspective. Furthermore, almost no researchers draw attention to the issue of supply chain flexibility evolution.

This paper has launched a thorough study of the measurement and evolutionary mechanisms of supply chain flexibility, including building the dimension and measurement index system of supply chain flexibility, presenting integrated measurement method and offering the evolution framework and process, and studied on environmental uncertainty and matching models of supply chain flexibility, proposing a complete theory of supply chain flexibility evolution.

2. Research on content and generation mechanism of supply chain flexibility

2.1 Content and features of supply chain flexibility

In the past decade, driven by the volatile business environment, organizations seek flexibility and quick response to market demand [1]. Modern competition has been changed from competition between enterprises to that between supply chains. Under time-based supply chain competitive environment, supply chain flexibility has become a major topic, which becomes more and more important, discussed by practitioners and scholars [2]. However, because of the multi-dimensional nature of supply chain flexibility concept, today its definition is still not uniform.

Most literatures on the flexibility concentrate in manufacturing field. Vickery et al. (1999) relatively early researched flexibility from the perspective of supply chain, but simply defined flexibility as the reaction to internal and external environmental uncertainty and multifunction of the organization [3]. Gunasekaran et al. (2001) considered that under supply chain environment, supply chain flexibility can meet specific consumer needs through proper products or services, which may be obtained by some techniques [4]. However this understanding is too narrow, relying on technology alone can not build the supply chain flexibility, and in order to get the supply chain flexibility, we must study its formation mechanism in depth and build elements of flexibility.

Therefore the definition of supply chain flexibility is not only necessary to grasp the essence of the concept of flexibility, but also emphasize the characteristics of supply chain, so the concept of supply chain flexibility should accentuate the following:

First supply chain is a function network connecting all node enterprises and overall processes. The function network of supply chain reflects its integrity, which is the essential characteristic of the supply chain. Second, supply chain should be a value added process, which is not a simple sum of node enterprises, but customer demand oriented. Last, the strategic partnership of supply chain is extremely significant to flexibility. So we should focus on changing supply chain partners in case of flexible business environment and reconstruct supply chain system capability and information sharing capacity rapidly and cost-effectively [2].

As can be seen from the above definition, flexibility is an ability that can manage changing. Changing and uncertainty is a prerequisite for the existence of flexibility, therefore the definition flexibility includes several key elements, such as capacity, systems, change, uncertainty, etc. The combination of these elements reveals the essential features of flexibility. At the same time, flexibility is more than a single concept, but in terms of system. It is a feature of system and the flexibility of supply chain system is the object of this paper [5].

Based on the points of view above, consumer-oriented supply chain flexibility is defined, in this article, as the capacity to respond customer-orientedly reasonably and rapidly to internal and external environment and the robustness demonstrated, based on that supply chain is provided with organically integrated core competencies of partners. Supply chain studied in this paper is consumer-oriented supply chain. To facilitate, consumer-oriented supply chain flexibility, in this paper, will be referred to as supply chain flexibility.

(1) Dynamicity

Flexibility is a dynamic concept. Organizations would obtain continuous learning and innovative capacities when they possess flexibility, which can be reflected in the use of

external and internal resources of the organization to make timely response to environmental instability and from the quick adjustment according to projected environmental changes in a proper time [6]. Supply chain is provided with obvious dynamics in the course of its life cycle, including the dynamic cooperation mechanism of supply chain as a result of the formation of partnerships required by business management, the dynamic coordination mechanism and the dynamic contract system, etc. Therefore the dynamic characteristics of supply chain life cycle determine that supply chain flexibility also has dynamics [7].
The flexibility level of supply chain should be a function of environmental uncertainty and relevant to the needs of customers, while flexibility is a relative concept, environmental uncertainty and law of supply and demand cause that the formation and development of supply chain has dynamic characteristics. Consequently the supply chain flexibility should be possessed with dynamic sensitivity to respond to market demand and environmental uncertainty. It is in the state of dynamic equilibrium when the customers' needs and the level of environmental uncertainty are balanced with the level of system flexibility; when the flexibility requirement of customer demand or environmental uncertainty increases, it is necessary to improve flexibility to meet the needs of environmental uncertainty and respond to competition, at which time the original flexibility balance of the system is broken and start to evolve to a new equilibrium [8]. So the law of supply and demand and the degree of environmental uncertainty prompt supply chain to adjust the flexibility continuously and cause dynamic characteristics as a result.

(2) Multidimensional

The multidimensional nature of supply chain flexibility refers to the multi-component ability of supply chain shown when dealing with uncertainty. Precisely because of the multidimensional nature, it makes the research of flexibility various. For instance, many scholars study it from the economic point of view and some others from the perspective of time. There is a mutual constraint among all of these angles, which means a separate one can not fully understand the flexibility and multi-angle investigation must be adopted. An effective and comprehensive definition of supply chain flexibility dimension is of great value to measure the flexibility.

(3) Timeliness

Flexibility is the capacity that system can take fast response when faced with uncertainty. Timeliness of supply chain flexibility is mainly reflected from the quick adjustment of logistics, information flow and network structure of supply chain operations in response to environmental uncertainty and to meet the rapidly changing market demands. Timeliness is the key to effective implementation of supply chain flexibility [8], which requires that supply chain should be realtimely aware of the market changes and environmental uncertainty and take rapid reaction. Meanwhile, environmental changes also makes a certain level of supply chain flexibility effective only in a period of time, which leads that supply chain flexibility has to achieve the required level in a particular term.

(4) Robustness

Supply chain flexibility also has a crucial feature—robustness, which is a fundamental property of the system, an ability to maintain the function of system when facing the variation of internal structure and external environment and a common phenomenon accompanied by uncertainty problem. The core issue of supply chain flexibility is the formation of robust operation and robust strategy [9]. The robustness of the supply chain is the capacity that system is still able to maintain its benefits and continuous operation even being interfered with uncertainties such as internal and external unexpected emergency [9]. It is the flexibility that becomes an embodiment of this ability. Supply chain flexibility is the ability to adapt to changes in market demand, which is usually manifested through the robustness indicated by the relationship between upstream and downstream business under uncertain environment [10].

(5) Scalability

In accordance with the definition that supply chain is a functional network chain to connect all nodes and the overall process of enterprises [11], we can see that this network chain structure of the supply chain has far exceeded the boundaries of a single enterprise and with the development of information technology and the needs of the market, the boundaries between the modern enterprises are becoming increasingly blurred. According to the needs of the business, supply chain can make continued outward extension, which is not only a geographical expansion but also includes the expansion of business scope and production capacity, by means of creating virtual enterprises, dynamic alliances and other forms [11]. This extension of the supply chain is also reflected in its flexibility, which means with the expansion of supply chain and the variation of circumstance, the structure of flexibility is updated correspondingly as a consequence. On the other hand, this has prompted scholars to look upon supply chain flexibility from a systemic perspective and grasp the structural flexibility embodied by supply chain and the evolution of it.

2.2 Elements and driving force of supply chain flexibility

Most current literatures are still focused on the enterprise when investigates the classification of flexibility elements--researching on classification of manufacture flexibility elements, only a few scholars discussed flexibility elements from the perspective of supply chain, but many of them followed the classification of manufacturing. Therefore, based on previous literatures, we define five types of supply chain flexibility from a customer-oriented point of view, which is divided into product flexibility, response flexibility, volume flexibility, new product flexibility and distribution flexibility [3].

Duclos et al (2003) have analyzed the elements of supply chain flexibility, including the flexibility of operation, market, logistics, supply, organization and information [1], and established the conceptual framework of supply chain flexibility [12]. Wang Lu (2008) divided flexibility into short-term and long-term from the perspective of time. Considering it from the short-term point of view, it refers to the capacity to take full advantage of existing resources and facilities aiming at adapting to changes. On the contrary, it reflects the ability that the company adopts new resources, new inventions and new methods and then integrates into the production of current system [6].

The classification of supply chain flexibility above mainly inherited that in firms and manufacture, and the concept was overlapped and the definition was vague among those elements of flexibility, which did not reflect the essential characteristics of supply chain. Therefore, aiming at the scope of this study, we concern about customer needs and adding value for them, focusing on the integration point. We divide the elements of supply chain flexibility into four categories, namely operation flexibility, logistics flexibility, robust network & reconstruction flexibility and information flexibility. The definitions of these four flexibilities are as shown bellow.

1. Information flexibility

In a dynamic changing environment, to make the supply chain flexible, it is essential to realize effective integration among various information systems of different segments of the supply chain in order to transfer information quickly and effectively between member enterprises in it and forming information flexibility consequently. Flexible information mainly consists of two flexibility elements: one is the mechanisms for information exchange with flexibility and the other is information systems with flexibility.

(a) Communication mechanism

The communication mechanism of flexibility is an essential part of supply chain flexibility and it is the general term for information dissemination, information transmission, feedback, information gathering, information processing, etc., collectively, reflecting the efficiency that supply chain deals with information. Furthermore, the capacity that let partner companies know when changing information mainly reflects in the timeliness of the information transmission, which indicates the speed of information processing and sharing. In order to improve the ability of supply chain to respond to changing requirements, we should minimize the policy failures due to the delays made by transmission of information as far as possible, which requires timely transmission of information [13].

(b) Information System flexibility

Information system flexibility, whose main parts are the various types of information systems used by the enterprises in supply chain, refers to the ability of information systems to respond to the internal and external changes of environment and the transmission capacity of information in supply chain [5]. This article defines the information system flexibility as the information transmitting and sharing ability of the cooperative information systems between supply chain nodes neglecting internal processes, which could be measured through the capacity that reusability, reconfigurability and scalability of information system.

2. Logistics flexibility

Flexibility is the capacity that by means of providing technical support and services to receive raw materials cost-effectively and deliver products when organizations supply materials or their customers change requirements [14]. Considering Time-based strategy, logistics flexibility is reflected in customer orientation, which means responding to custom demand rapidly by minimizing the loss of performance in order to ensure the reliability of logistics systems and customer service levels. In this article we define the logistics flexibility as the ability that supply chain in response to environmental uncertainty, adopting appropriate transportation and inventory strategies in a reasonable cost level, adjusting service needs quickly and improving storage space and logistics policies rationally. It can be divided into inventory and delivery flexibility. Effective inventory strategy is a significant way for supply chain to win market and improve performance; hence inventory flexibility can be measured by two indicators that the number of stock policies available and the capacity to adjust inventory level. Delivery flexibility reflects the ability to change the established way of distribution and the capacity to adjust established distribution.

3. Robust network and reconstruction flexibility

Robust network and reconstruction flexibility has two meanings: firstly, the stability and robustness reflected when the existing network structure in response to changes of external environment; the second is the capacity to vary the combination of partnerships and establish flexibility relationships with partners [14]. This article defines the robust network and reconstruction flexibility as the anti-interference ability demonstrated by the existing structure of supply chain and the capacity to make structural adjustments that in accordance with changes in the external environment for the purpose of maintaining high performance, such as the robustness of the existing network structure, fast reconstruction, cultural integration and other capabilities. So the supply chain network must have long-term strategic alliance partnerships to achieve sustained competitiveness, but also offer short-term ability to local adjust in accordance with environmental requirements, which is robust network and reconstruction flexibility.

4. Operation flexibility

Operation flexibility refers to the capacity for each node enterprise of the supply chain to operate and deploy resources rapidly to respond to customer demand on product type, quantity and new products, including the variation and mix of products, yield changes, product innovation and also the ability coping with the changes of product life cycle [14]. This article defines the operation flexibility as the capacity to quickly allocate assets, change manufacturing process and dynamically adjust productivity highlighting the allocation of resources to produce manufactures (including new products) and provide services, which considers customer and market demand from the perspective of operating system. Hence it can be concreted into product flexibility, volume flexibility and resource flexibility. Thereinto, volume flexibility mainly reflects the ability that supply chain can meet customer needs and from a deeper level it indicates manufacturing flexibility of supply chain and the ability to adjust production plans in according with market demand. Beamon(1999) have quantified the volume flexibility, which pointed out that the demand that could be satisfied referred to the number of product D_t for any $D_t \in (D_{min}, D_{max})$that supply chain could provide. D_{min} is the minimum yield to ensure supply chain profit, D_{max} is the maximum number of production achieved by the existing scale of supply chain. Suppose that the customer demand D for any $D \sim N(\mu, \sigma_D^2)$ follows normal distribution, then the calculation formula [15] of volume flexibility G_D is:

$$G_D = P\left(\frac{D_{\min} - \bar{D}}{\sigma_D} \le D \le \frac{D_{\max} - \bar{D}}{\sigma_D}\right) = \Phi\left(\frac{D_{\max} - \bar{D}}{\sigma_D}\right) - \Phi\left(\frac{D_{\min} - \bar{D}}{\sigma_D}\right)$$

5. The driving source of flexibility

Under the dramatic changes in modern business and highly uncertain dynamic environment, supply chain must scan its dynamic circumstance in real-time and identify its degree of uncertainty. only through continuous capture and grasp opportunities and threats that may arise in dynamic environment of opportunities and threats that may arise, can we accurately define and describe the supply chain environment and realize the dynamic environmental monitoring and early warning in order to guide the formation of strategic decision-making of supply chain flexibility and enhance its ability to withstand environmental changes [16]. Jack G.A.J. van der Vorst and A.J.M.B.(2002) have identified the source of the uncertainty generated by supply chain reconstruction strategy and pointed out that uncertainty during decision-making process of supply chain is an important driving factor in the reconstruction of it [17]. As can be seen from some studies, environmental uncertainty is a fundamental driver of supply chain flexibility and it is only the presence of environmental uncertainty that cause flexibility. The gap between the two determines the level of flexibility generation power.

In order to facilitate writing, all the uncertainty factors $\{x_{11}(t), x_{12}(t),\ldots,x_{32}(t)\}$ under uncertain environment in supply chain are written in $\{x_1(t), x_2(t),\ldots,x_n(t)\}$. The level perceived by a certain environmental uncertainty factor when supply chain at a certain time *t* is $f(x_i(t))= x_i(t)\times\alpha$, then the momentum generated by supply chain flexibility can be expressed by the following n-dimensional vector: $\vec{F}=[f_1,f_2,\cdots,f_i,\cdots,f_n]$. There into, $f_i=\frac{f(x_i(t))-f(x_i(0))}{f(x_i(0))}$ for any i = 1,2,…,n. Functions $f(x_i(t))$ and $f(x_i(0))$ refer respectively to the level value and the baseline or reference value perceived by *i*th environmental uncertainty factor of supply chain, hence, the momentum generated by supply chain flexibility can be expressed by vector:

$$\vec{F}=[\frac{f(x_1(t))-f(x_1(0))}{f(x_1(0))},\frac{f(x_2(t))-f(x_2(0))}{f(x_2(0))},\cdots,\frac{f(x_n(t))-f(x_n(0))}{f(x_n(0))}].$$

The value of the vector is

$$\left|\vec{F}\right|=\left\{\sum_{i=1}^{n}\left[\frac{f(x_i(t))-f(x_i(0))}{f(x_i(0))}\right]^2\right\}^{1/2}$$

Typically, the higher the value is, the stronger supply chain environmental uncertainty and the greater force generated by the flexibility are.

2.3 Factors and generation mechanism of supply chain flexibility

After analyzing that the environmental uncertainty is the source and impetus of the generation of supply chains, we can see that supply chain flexibility is a capacity which is not constructed without foundation but is subject to the dynamic capability of the core business, supply chain collaboration and other factors to cope with environmental uncertainty. The following will analyze the factors of supply chain flexibility from the aspects of motility and adaptability.

2.3.1 Motility factor analysis

As pointed out earlier, the operation of supply chain is consumer-oriented and core businesses play a key role, consequently they are also significant to the construction of flexibility, which is mainly reflected in their dynamic capability that becomes a motility factor of flexibility as well.

Supply chain is essentially a dynamic enterprise alliance, whose dynamicity determines that supply chain may face dissolving, updating and re-establishing at any time. This uncertainty is due to less competitive supply chain as a whole, profit instability, the distribution of benefits without balance or the incompatibility between a node enterprise and its upstream and downstream enterprises [18]. In a dynamic environment, core competence is definitely important, but if it can not update, then core capabilities will eventually become core rigidities [19], which means that core competencies can not necessarily bring about a sustainable competitive advantage [20]. It is for sake of reconciling the contradiction between competence rigidity and environmental changes that the concept of dynamic capability comes into being [19].

Dynamic capability is not a one-dimensional concept, He Xiaogang(2006) divided the dimension of dynamic capacity by means of empirical research into five areas [20]. Li Xingwang(2006) started with the functional origin of dynamic capacity, which considered that it can be identified from the aspects environment, strategy / tactics, products, resource structure and competitive advantage [21].

After the analysis above, the dynamic capacity is defined as the capacity of resource integration and reconstruction that core business can constantly create new needs and new value which is composed by knowledge, resources, processes and other elements. It can be measured by the following three aspects, namely, environmental insights and customer-oriented value, the configuration and integration capability of value chain and learning ability. Achieving the capture of information in use of learning ability to respond to environmental changes, which is the premise of dynamic capabilities; realizing product/service customization by focusing on customer-oriented value, which is the foundation of dynamic capabilities; Achieving the variation of operational capability through integration and reconstruction ability, which is the means to comply dynamic capabilities [22].

2.3.2 Adaptive factor analysis

Supply chain flexibility is a dynamic supply network in rapid response to environmental changes built around the core business by a number of suppliers, acquirers and other entities. It emphasizes the overall business integration and effective coordination control of each node and its activities to ensure that logistics, information flow and capital flow would run smoothly and all available resources would be utilized and configured sufficiently. Under the competitive circumstance based on time and flexibility, the response rate of end-user's demand is a key factor in the success of the supply chain. In order to obtain flexibility, enterprises must build a seamless supply chain, which makes interoperability play an important role in ensuring the orderly operation of supply chain [23].

As for supply chain flexibility, supply chain collaboration is a crucial factor, coordinating all aspects of its operation and effectively adjusting the level of flexibility to match environmental uncertainty to achieve rapid response to demand. Since the adoption of efficacious collaboration in information flow and logistics can be beneficial to compress the response time of supply chain and enhance overall competitiveness [24], so we see it as an adaptive factor.

Cai Shuqin(2007) divided the collaboration from a practical perspective into management coordination, technical cooperation, and man-machine cooperation. The author thought that supply chain collaboration should be the unity of the three types. Organizations utilize advanced information technology by means of contracts or combination, strengthening mutual coordination and collaboration through rapid and accurate transmission of information to share with each other in order to organize and arrange production and business activities more coordinately within the enterprise and access to the maximum benefit of supply chain under the premise of achieving the common goal [25].

After the analysis above, we consider that supply chain collaboration is mainly reflected in three aspects, the collaboration of management, business and information.

2.3.3 Generating process of supply chain flexibility

The flexible construction of supply chain is a systematic project, improving the level of flexibility from the overall point of view [26]. As for the research target and the characteristics of the flexibility analyzed above, the construction process is mainly divided into four stages, namely, identifying needs and environmental uncertainty for setting goals, determining the value-added process and selecting partners, organizational design and program implementation, performance measurement and dynamic evolution, which is shown in Figure1.

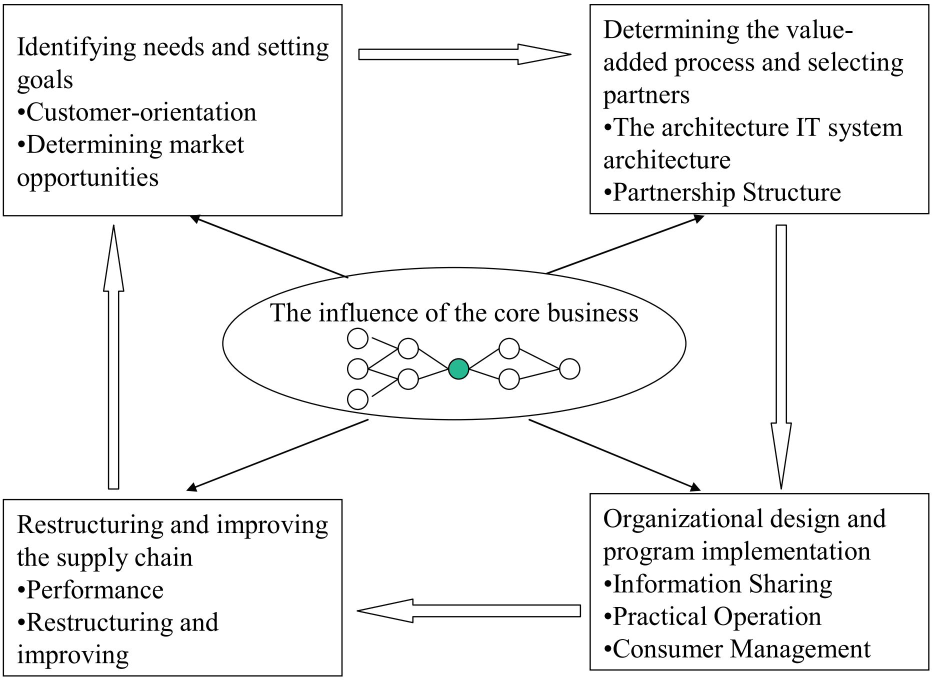


Fig. 1. Construction of demand-driven supply chain

As it is shown in the chart above, in the first stage, core businesses should analyze demand and market opportunity and assess environmental uncertainty. on this basis, they should decide whether to respond to the opportunities and establish strategic goals. The following two aspects must be grasped: (1) to accurately identify and understand the specific needs of consumers, because providing consumers with satisfactory products and services is the purpose to set up the supply chain; (2) to identify and assess the extent and content of environmental uncertainty after understanding consumer needs sufficiently, which is prerequisite for building supply chain flexibility. In the second phase, the core business should firstly identify the value-added term of production according to the objectives established, which is the basis for the formation of supply chain. As the result of determining specific value chain, they can choose the right partner and build a corresponding network structure, so as to reduce non-value-added process more effectively at the same time increase the anti-jamming capability and robustness of supply chain. The following two major aspects must be concentrated at this stage: (1) value chain configuration, which indicates that accurate identification of the value-added process is the foundation to build supply chain and improve operational performance; (2) the construction of robust network, which means to design specific organizational forms for node enterprises and construct robust network based on the value chain model, the participate way of partners, the type of business in supply chain and other factors analyzed by the core business. In the third stage, it is mainly acquired to design the elements of flexibility, including operation flexibility, logistics flexibility and other elements, adopting related techniques, methods and procedures in accordance with the level of environmental uncertainty identified and the network structure built. These are the details in response to environmental uncertainty from a business point of view, but in the specific implementation process of flexibility, whether it is synergistic between systems determines the validity of supply chain, which includes the collaboration of management, information and business. In the fourth stage, it is mainly about measuring supply chain flexibility, analyzing the matching status between the level of flexibility and environmental uncertainty and then adjusting the flexibility to some extent if necessary. By judging the matching level, the core enterprises can understand the evolving direction of supply chain flexibility.

2.3.4 Generation mechanism of supply chain flexibility

The consumer-oriented supply chain flexibility is generated around the core business. Driven by its requirement information, other nodes take capital flow, service flow and logistics as medium through functional division and cooperation, which is in order to obtain the continuously value-added robust network of the entire supply chain [11]. Consequently, the core business plays a significant role in the formation of supply chain.

Based on the analysis above, as it is shown Figure 2, we can understand the effect of core businesses on the formation of consumer-oriented supply chain flexibility. The figure reflected that the supply chain system consisting of the core business, channel enterprises and market is targeted at the customer demand, which means it is closely run around the requirement and focus on variable needs of consumers. The market demand, which is identified by the core enterprise, is the driving source of supply chain. The core enterprise rapidly and effectively integrates the internal and external resources from the perspective of adding value and pass the demand along to the relevant members of the supply chain through valid information sharing, which can meet consumer needs efficiently, rapidly and low-costly.

Consumer-oriented supply chain management is willing to solve the following two problems: firstly, how to accurately identify the real needs of consumers; secondly, how to integrate the internal and external resources quickly and effectively and improve supply chain flexibility to meet individual demand. To illustrate, the effect of the core business on the formation of consumer-oriented supply chain flexibility is mainly reflected in that, first of all, it is identification center of consumer demand. Second, it is the reconstruction center of organizations. The third one is that it is the information exchange center and finally a distribution and dispatch center of logistic.

Therefore, the formation mechanism of supply chain flexibility is the factors that impact the flexibility and the interaction between them. Studying on the formation mechanism of supply chain flexibility will help us to understand the action principle of supply chain so as to find the key flexibility or weakness and improve response capability to customers [27]. Based on the foregoing analysis, we construct the framework of the mechanism of supply chain flexibility, which is shown in Figure 3.

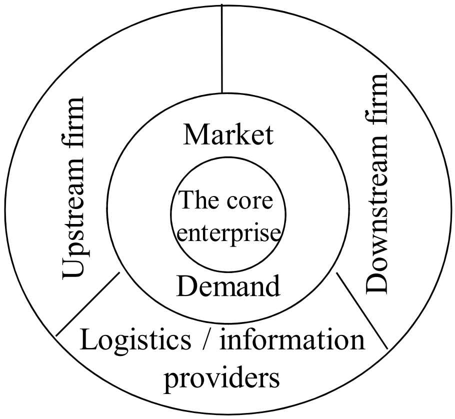


Fig. 2. The position of core enterprises in the consumer-oriented supply chain

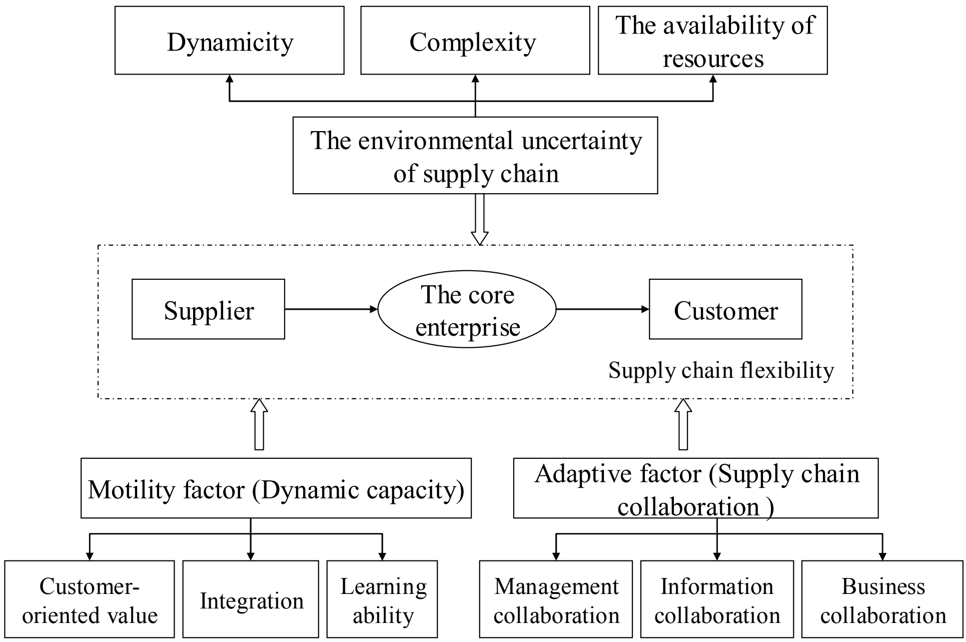


Fig. 3. Generation mechanism diagram of supply chain flexibility

The framework above gives the causes and conditions of the formation and development of supply chain flexibility. Environmental uncertainty provides supply chain flexibility with driving force. It is because of the dynamic, complexity and non-availability of resource that supply chain environment gets uncertainty, which driving enterprises to acquire flexibility in response to changing circumstance. As for the construction of supply chain flexibility, since the supply chain is a complex system, the formation of flexibility is not deliberate, which requires the co-activation of organizations. The important factors include two aspects, one is the motility factor that is helpful for supply chain flexibility to evolve and innovate, namely, the dynamic capability of core enterprises, including environmental insights and customer-oriented value, value chain configuration and integration and learning ability. Another is the adaptive factor to ensure supply chain flexibility to respond effectively and adapt to environmental uncertainty, namely, supply chain collaboration, including the collaboration of management, information and business. Environmental uncertainty is the basis for generating supply chain flexibility and dynamic capability and supply chain collaboration is an important factor to implement and enhance the flexibility, which is targeted at a market-oriented supply chain, in order to provide circumstances and conditions for the generation and evolution of it. Only in the common effect of these three aspects, can supply chain flexibility be rapidly constructed, evolve and adjust appropriately and dynamically according to environmental changes, thereby enhance the performance of supply chain.

3. Environmental uncertainty measurement of supply chain flexibility

Currently, researches on flexibility measurement are still not unified. There are many measuring methods focusing on one aspect of the flexibility elements [10] [28] but few articles comprehensively measuring supply chain flexibility from an overall perspective [29]. Accurately measuring the level of supply chain flexibility is the foundation of the evolution of it, and only on a certain approach to comprehensively investigate the level of supply chain flexibility, can we make corresponding decisions through evolution models.

3.1 Construction of supply chain flexibility dimensions

In order to guide the supply chain to respond to environmental uncertainty and make accurate decisions for the construction and evolution of supply chain flexibility, fully and accurately measure the level of supply chain flexibility is the key. We can analyze the capacity how the existing supply chain responds to environmental uncertainty by an effective measurement, identify the crux of the problem and chart the course of the evolution of supply chain flexibility [8]. The main reason why flexibility is difficult to understand and measure lies in two aspects: On the one hand, flexibility is an inherent expressive ability of the system, not as cost, quality, or other production targets which can be calculated by external manifestations or a certain formula. On the other hand, flexibility is attached to the system; due to the complexity of supply chain it is rather difficult to understand [30]. Therefore, it is necessary to accurately grasp the meaning and development rules of flexibility and construct a reasonable flexibility dimension, and it is the basis of effectively measuring and evaluating the level of supply chain flexibility.

Flexibility is a multidimensional concept [14], flexibility dimension refers to the aspects we can analyze the flexibility of the system from. It is of great significance for understanding and measuring flexibility to anatomize its in depth. Scholars have studied flexibility from different angles. Early researchers [31] [32-35] tended to understand it from three aspects that time, range and cost. Later than that, Upton(1994,1995) described it depending on range, mobility and uniformity [32] [37]. Koste(1999) extended its dimensions to four aspects on that basis, those were range-number, range-heterogeneity, mobility and uniformity [38] [39] [40] [41]. After that, Koste (2004) combined those four dimensions into two, namely range and accessibility [42].

Based on the analysis above, this article would synthesize the features of flexibility and the view of these scholars, and build the supply chain flexibility in two dimensions, namely scope and adaptability. The definition of scope--which reflects the range of available policy options in order to meet the dynamic market demand in supply chain, videlicet, the number of different states and diversity--is consistent with that defined by Slack and Upton. Organizations can increase the range of strategies or through an efficient application of them to achieve greater flexibility, so scope is a necessary dimension of flexibility [43]. The other dimension is adaptability which reflects the resorting capacity of facilities in given scope. The concept of adaptability which is defined as the conversion capability of system that can rapidly, low-costly and efficiently transform from one state into another is more generalized in this article. The dimension of adaptation is more accurate than the concept mobility defined by earlier researchers, because it expresses the conversion capability and difficulty level maintaining a certain level of performance in given scope, and it exercises due caution on cost and efficiency not just the conversion itself [43].

3.2 Construction of supply chain flexibility evaluating index system

Index system as the evaluating standard of supply chain flexibility, how reasonable it designed would affect the evaluation results of supply chain flexibility, so taking the characteristics of supply chain flexibility and the emphasis of this article into account, we should follow these three principles, namely, systematicity, Scientific justification and focus when design it.

To construct the index system scientifically and reasonably, we should take the complexity of supply chain and the multidimensionality of flexibility into consideration, because supply chain is an overall function network chain into which it links suppliers, manufacturers, distributors and end users through logistics, capital flow and information flow driven by consumer demand. Supply chain has independent economic entities which hold their own goals and play different roles with multi-participation in the operation of each other, while it is in a changing external environment, so the supply chain itself is a complex system. The multi-dimensional flexibility and its various properties have increased the difficulty and complexity of supply chain flexibility.

Therefore, in accordance with the construction principles and two kinds of flexibility dimension previously proposed, we analyze four elements of supply chain flexibility--operation flexibility, logistics flexibility, information flexibility and Robust network and reconstruction flexibility respectively from the dimension of scope and adaptation to build the index system. This indicator system is more comprehensive, which integrated reflects the characteristics of flexibility especially the feature under supply chain function network. As it is shown in Table 1, we can understand the detail obviously.

3.3 Comprehensive measurement of supply chain flexibility with series features

Supply chain flexibility is a complex open system, and that complexity is produced by the interaction between the environment and system. At the same time flexibility is a relative concept, so it is necessary to start with the relationship above in order to understand it in depth. For the purpose of measuring the environmental uncertainty and the matching level of supply chain flexibility effectively, accurate quantification of flexibility is the very first thing to do.

	One grade index	Dimensions	Two grade index
Supply Chain Flexibility	Operation flexibility	Scope	The range and number of products available [44]
			The number of application skills of generalist staff [44]
		Adaptability	The capacity to improve existing products [45]
			The ability to change the number of products [44]
	Logistics flexibility	Scope	The number of stock strategy options [44]
			The number of alternative distribution channels [44]
		Adaptability	The ability to adjust inventory quantity [44]
			The capacity to adjust the established shipping method [44]
	Information flexibility	Scope	The frequency of informal information exchange [46]
			The quality and accuracy of information exchange [46]
			The capacity to let partners know quickly in case of changing information [46]
		Adaptability	The ability of reconfiguration or reuse
			Scalable capacity
	Robust network and reconstruction flexibility	Scope	Time to form a stable partnership / selecting time of supplier / time of reconstruction
			Stability and robustness of existing supply chain
			The number of suppliers available
		Adaptability	The ability of cultural integration
			The ability to change suppliers' delivery requirements [44]

Table 1. Index system for measuring supply chain flexibility

As to the measurement of the supply chain flexibility, most existing literatures only discuss one side of a certain element of supply chain flexibility, such as Beamon(1999) who investigated it from the perspective of quantity flexibility, transport flexibility, combination flexibility and new product flexibility [15]. These scholars neglected the network features of supply chain and the flexibility of operation as well as the relationship between supply chain partners [47]. The measuring approaches of existing studies also has limitations, which means most methods concentrate on static analysis, however supply chain flexibility is a dynamic, complex system. Consequently, it is essential to introduce time parameters into measurement models for the sake of quickly and accurately responding to environmental uncertainty. In previous studies, measurement indicators were mainly viewed as constant weights, ignoring the dynamic nature of supply chain flexibility, making a strong one-sidedness of its evaluation. To solve this problem, we introduce the time parameter to measure integrated flexibility level within or at a certain period of time, thus to achieve just in time management and decision-making. For comprehensive measurement, identifying the weight and creating models is the key issue. Previous researchers mostly used AHP to determine weights [48] [49], but the premise of this method is judgment matrix consistency. Psychological experiments show that when the number of elements being compared is more than 9, it would be difficult for the judgment matrix to ensure its consistency [50]. Thus this paper, no consistency test method for determining the weights would be adopted but time parameters would be introduced

Therefore, we build an integrated quantitative model of flexibility with a balanced of 'function' and 'coordination' of all flexibility elements:

$$y = \lambda_1 y^{(1)} + \lambda_2 y^{(2)} = \lambda_1 \sum_{j=1}^{m} w_j^{(1)} x_j + \lambda_2 \prod_{j=1}^{m} x_j^{w_j^{(2)}}$$

Indicators λ_1, $\lambda_2 (\lambda_1 \geq 0, \lambda_2 \geq 0, \lambda_1 + \lambda_2 = 1)$ in the formula above are known scale factors which respectively refer to the percentages the factors 'function' and 'coordination' take in integrated results. Indicators $w_j^{(1)}$, $w_j^{(2)}$ refer to the weights of each flexibility element x_j in 'function' valuation and 'coordination' measurement. When measuring, firstly do the measurement at single index layer, then to measure step by step up, consequently, the measurement of supply chain flexibility would be finished. Concrete steps are as follows:

(1) Dimensionless treatment of index system

We use extreme value approach to Nondimensionalize factors, that is,

$$x_{ij}^* = \frac{x_{ij} - \min_i(x_{ij})}{\max_i(x_{ij}) - \min_i(x_{ij})}, \quad x_{ij}^* \in [0,1].$$

We discuss the flexibility level of several supply chain systems s_i ($i = 1, 2, \cdots, n$) at different times t_k ($k = 1, 2, \cdots, N$), and the supply chain system at each flexibility level has number m valuation indicators $x_1, x_2, \cdots, x_m$, forming time series data $\{x_{ij}(t_k)\}$ as it is shown in Table 2.

	t_1	t_2	…	t_N
	x_1 x_2 … x_m	x_1 x_2 … x_m	…	x_1 x_2 … x_m
S_1	$x_{11}(t_1)$ $x_{12}(t_1)$… $x_{1m}(t_1)$	$x_{11}(t_2)$ $x_{12}(t_2)$ … $x_{1m}(t_2)$	…	$x_{11}(t_N)$ $x_{12}(t_N)$ … $x_{1m}(t_N)$
S_2	$x_{21}(t_1)$ $x_{22}(t_1)$ … $x_{2m}(t_1)$	$x_{21}(t_2)$ $x_{22}(t_2)$ … $x_{2m}(t_2)$	…	$x_{21}(t_N)$ $x_{22}(t_N)$ … $x_{2m}(t_N)$
⋮	…	…	…	…
S_n	$x_{n1}(t_1)$ $x_{n2}(t_1)$ … $x_{nm}(t_1)$	$x_{n1}(t_2)$ $x_{n2}(t_2)$ … $x_{nm}(t_2)$	…	$x_{n1}(t_N)$ $x_{n2}(t_N)$ … $x_{nm}(t_N)$

Table 2. Time series data

(2) Determination of weight $w_j^{(1)}$

Indicator $w_j^{(1)}$ is the weight of each indicator in 'function' valuation. Function valuation primarily concentrates on the contribution of a certain function of the system made by each indicator. Because that adopting addition rules, comprehensive result is so insensitive to index movement, hence the purpose of determining weights is to reflect the distinction between each measured object as a whole as far as possible, namely, the overall difference between systems $s_1, s_2, \cdots, s_n$ and time series data matrix $\{x_{ij}(t_k)\}$. To make the largest overall difference between systems, the total sum of squares of indicator $y_i^{(1)}(t_k) = \sum_{j=1}^{m} w_j^{(1)} x_{ij}(t_k)$, videlicet, indicator $\sigma^2 = \sum_{k=1}^{N}\sum_{i=1}^{n}(y_i(t_k) - \overline{y})^2$ must be the largest, namely,

$$A_k = \begin{bmatrix} x_{11}(t_k) & \cdots & x_{1m}(t_k) \\ \cdots & \cdots & \cdots \\ x_{n1}(t_k) & \cdots & x_{nm}(t_k) \end{bmatrix}, k = 1, 2, \cdots, N .$$

Then calculate each indicator $H_k = A_k^T A_k (k = 1, 2, \cdots, N)$, weight $w^{(1)}(t_k)$ is the priority vector corresponded to the maximized eigenvalue $\lambda_{\max}(H_k)$ of matrix H_k, which means get maximum value of σ^2.

(3) Determination of weight $w_j^{(2)}$

Indicator $w_j^{(2)}$ is the weight of each indicator in 'coordination' measurement. Researchers used to adopt AHP to determine weight. However, using this method, it is difficult to ensure the consistency of adjustment matrix when dealing with large volume of indicators. Therefore, we adopt order relation approach without consistency test in this article.

Suppose that during a period of time $t \in [t_0, T]$, valuation index $x_1, x_2, \cdots, x_m$ has order relationship $x_1^* \succ x_2^* \succ \cdots \succ x_m^*$ for a certain standard, for which parameter x_1^* refers to i th index after arranging $\{x_j^*\}$ according to the order relationship '$\succ$'. If the length of interval $[t_0, T]$ is relatively lager, it is not stable between indicators $x_1^*, x_2^*, \cdots, x_m^*$. Considering about that, we separate the interval $[t_0, T]$ into number $p(p \geq 2)$ subintervals, and in each of them, order relations between indicators $x_1^*, x_2^*, \cdots, x_m^*$ can be considered stable.

Firstly, identify the ratio $w_{j-1}^*(t_k) / w_j^*(t_k) = d_j(t_k)$ between indicators x_{j-1}^* and x_j^* at a certain time $t = t_k$ for any $j = 2, 3, \cdots, m(w_j^*(t_k) > 0)$, and the assignment of $d_j(t_k)$ can be consulted in Table 3.

$d_j(t_k)$	Demonstration
1.0	x_{j-1} and x_j have the same importance
1.2	x_{j-1} is slightly important than x_j
1.4	x_{j-1} is obviously important than x_j
1.6	x_{j-1} is highly important than x_j
1.8	x_{j-1} is extremely important than x_j

Table 3. Assignment reference of $d_j(t_k)$

So the weights of indicator x_m^* and x_j^* at time t_k is

$$w_m^*(t_k) = (1 + \sum_{r=2}^{m}\prod_{j=r}^{m} d_j(t_k))^{-1} \text{ and } w_{j-1}^*(t_k) = d_j(t_k)w_j^*(t_k),$$

For any $j = 2,\cdots,m-1,m$ and $k = 1,2,\cdots,N$.

4. Comprehensive measurement of supply chain flexibility

According to the index system constructed, collect data for different time points in terms of the table above. Applying the comprehensive measurement model and the method for determining index weight, we could measure the flexibility level of several supply chain systems under the premise of keeping each function of flexibility elements and the coordinated the overall flexibility in mind.

4. Evolution process and matching models of supply chain flexibility under uncertain environment

Context above constructed supply chain flexibility evolution model and comprehensive measurement method from a theoretical point of view, which is the foundation of the evolution of supply chain flexibility. Now, we analyze how the supply chain flexibility evolutes and what the specific processes and methods are from a practical perspective.

4.1 Analysis of supply chain flexibility evolution process under uncertain environment

To make the supply chain adapt to environmental changes, we must monitor environment instantaneously and regulate flexibility appropriately, which involves the evolution of flexibility. According to the foregoing analysis that the fundamental drivers of the development of flexibility, we can see that environmental uncertainty should be the basis for the evolution of flexibility, and we should adjust the flexibility appropriately in light of the requirements of it to environmental uncertainty. So it will involve the matching of supply chain flexibility under uncertain environment.

The matching we talk about mainly refers to whether the level of flexibility that environment uncertainty requires is consistent with the level of reality and potential supply chain flexibility. If not match, it is necessary to accordingly evolve and adjust supply chain flexibility using its dynamic capability and interoperability, which is the basis for decision-making of supply chain flexibility. Therefore, the ultimate goal of flexibility evolution should be to enable the supply chain to adapt to as well as match the environment [51], which also laid a good foundation for supply chain to face changes in future. Figure 4 provides the matching processes of supply chain flexibility under uncertain environment from the practical point of view.

The flow chart in Figure 4 has clearly explained how the supply chain flexibility evolves and matches. Firstly, core business recognizes market demand. Then recognize the main value adding processes and construct supply chain based on whether it responds to demand. After that, analyze the environment uncertainty from the perspective its three dimensions and factors related in order to determine the requirement of supply chain flexibility. Lastly, dissect the reality and potential flexibility of supply chain according to the actual situation and potential resources and decide whether the requirement is appropriately matched with reality flexibility. There are two possibilities: If the reality flexibility is greater than the requirement, the supply chain does not have to take any steps to respond to environmental changes; on the contrary, we should judge how the potential flexibility matches with the requirement. If the potential flexibility is larger than that required by environment, supply chain can adopt strategy combinations or limitedly use external resources without changing the main structure to deal with the problem, which makes supply chain collaboration play an important role. If it is the opposite, it means that the level of supply chain flexibility can not reach that required by environmental uncertainty even under he effect of supply chain collaboration, then the core business should consider building new strategies or reconstructing the supply chain, in the process of which the dynamic capability in the supply chain play a key role.

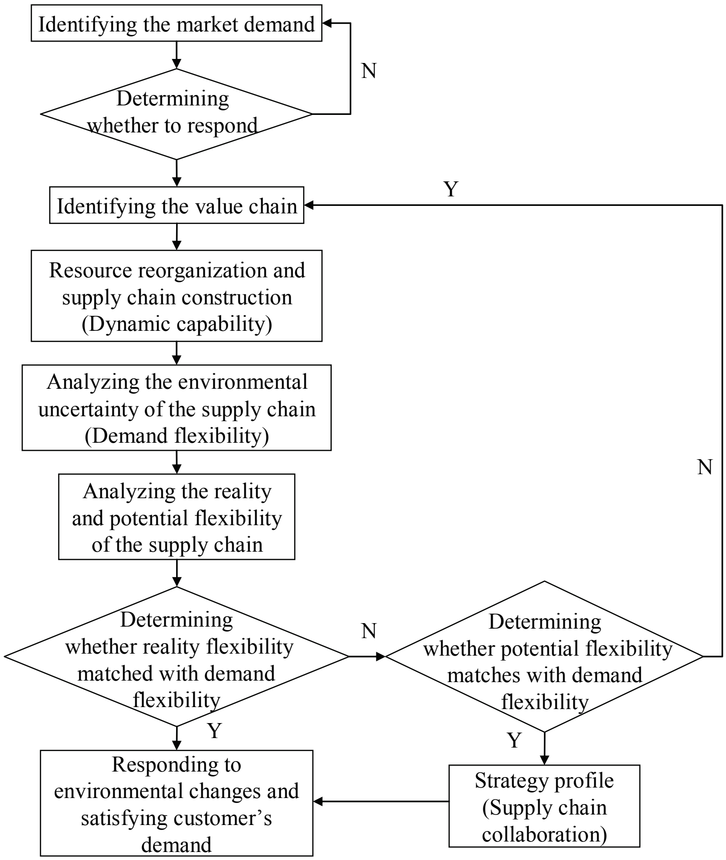


Fig. 4. The matching and evolution flow chart of supply chain flexibility under uncertain environment

There are two main aspects to consider about in the matching problem between supply chain flexibility and environmental uncertainty. Global matching that whether supply chain is able to cope with environmental uncertainty from an overall perspective—the state how reality flexibility matches with the requirement comes the first; Secondly it is component matching, namely the matching situation between each element and environmental uncertainty. Both play a different role. Global matching observes the whole picture, offering the current system flexibility from a integrated perspective, which gives decision-makers an overall awareness. The disadvantage is that we have no idea about the specific circumstances of each element, only after component matching can we determine which one is not flexible to respond to environmental uncertainty. The organic combination of the two can form the supply chain flexible strategies to help managers make decisions, the following will talks about flexibility matching issues.

4.2 Matching models of supply chain demand flexibility and reality flexibility

According to the evolution process, we should firstly match reality flexibility to that required by environmental uncertainty. In order to give a general understanding, we will analyze it from two aspects—global matching and component matching. As the consequence of matching, if reality flexibility is larger than the requirement, it means that the actual state of supply chain is able to cope with uncertain environment and we don't have to take any actions, which reflects the buffering capacity of supply chain flexibility; If it is the opposite, further analysis will be needed to reveal the matching state between demand flexibility and potential flexibility.

4.2.1 Global matching

Reality flexibility refers to the practical level determined by supply chain constructed aiming at a particular consumer demand in the light of actual situation according to each environmental uncertainty factor. Demand flexibility represents the level that each flexibility element should possess under the condition that environmental uncertainty is observed by supply chain. Both of them are filled in Table 4.

Parameter E stands for environmental uncertainty and according to the preceding analysis of its dimensions and factors, we set them to be the rows of the table. Furthermore, we set parameter e_{ij} to stand for individual element of environmental uncertainty and the attention meter of each of them is indicator a_{ij}. In terms of the classification of supply chain flexibility elements, we use letters to represent every element and its corresponding index. To illustrate, letter O stands for operation flexibility and there are four of them--{O_1,O_2,O_3,O_4}; letter L represents logistics flexibility and the four indexes are {L_1,L_2,L_3 ,L_4}; letter I and letter N respectively refers to information flexibility and robust network & reconstruction flexibility, and so forth. At last, determine the actual status of each index depending on individual environmental uncertainty factor with variable x_{ij}^{ij} indicated corresponding to the left in each cell. As for the right, variable $\bar{x}_{ij}^{ij}$ stands for demand flexibility. Thereinto, subscript ij represents the code of flexibility elements corresponded and superscript ij refers to the code of related factors of environmental uncertainty.

We assign the reality flexibility of each element of value $\sum \alpha_{ij} x_{fn}^{ij}$ and the demand flexibility of value $\sum \alpha_{ij} \bar{x}_{fn}^{ij}$. Depending on the comprehensive measurement we discussed above, respectively calculate the level of reality and demand flexibility, namely variable F and E.

Matching function is assumed to be equation $r = \dfrac{F}{E}$.

If $r > 1$, which states $F > E$, it shows that the reality flexibility is larger than the demand one and we set warning coefficient φ_1 here. If inequality $1 < \dfrac{F}{E} < 1 + \varphi_1$ is right, there is no

Environmental uncertainty(E) / Supply chain flexibility (F)		Dynamic (E_1)		Complexity (E_2)		Resource availability(E_3)	
		e_{11}	e_{12}	e_{21}	e_{22}	e_{31}	e_{32}
		α_{11}	α_{12}	α_{21}	α_{22}	α_{31}	α_{32}
Operation flexibility(O)	O_1	x_{O1}^{11} $\bar{x}_{O1}^{11}$	x_{O1}^{12} $\bar{x}_{O1}^{12}$	x_{O1}^{21} $\bar{x}_{O1}^{21}$	x_{O1}^{22} $\bar{x}_{O1}^{22}$	x_{O1}^{31} $\bar{x}_{O1}^{31}$	x_{O1}^{32} $\bar{x}_{O1}^{32}$
	…	…	…	…	…	…	…
	O_4	x_{O4}^{11} $\bar{x}_{O4}^{11}$	x_{O4}^{12} $\bar{x}_{O4}^{12}$	x_{O4}^{21} $\bar{x}_{O4}^{21}$	x_{O4}^{22} $\bar{x}_{O4}^{22}$	x_{O4}^{31} $\bar{x}_{O4}^{31}$	x_{O4}^{32} $\bar{x}_{O4}^{32}$
Logistics flexibility(L)	L_1	x_{L1}^{11} $\bar{x}_{L1}^{11}$	x_{O1}^{12} $\bar{x}_{O1}^{12}$	x_{O1}^{21} $\bar{x}_{O1}^{21}$	x_{O1}^{22} $\bar{x}_{O1}^{22}$	x_{O1}^{31} $\bar{x}_{O1}^{31}$	x_{O1}^{32} $\bar{x}_{O1}^{32}$
	…	…	…	…	…	…	…
	L_4	x_{L4}^{11} $\bar{x}_{L4}^{11}$	x_{L4}^{12} $\bar{x}_{L4}^{12}$	x_{L4}^{21} $\bar{x}_{L4}^{21}$	x_{L4}^{22} $\bar{x}_{L4}^{22}$	x_{L4}^{31} $\bar{x}_{L4}^{31}$	x_{L4}^{32} $\bar{x}_{L4}^{32}$
Information flexibility(I)	I_1	…	…	…	…	…	…
	…	…	…	…	…	…	…
	I_5	…	…	…	…	…	…
Robust network and reconstruction flexibility(N)	N_1	…	…	…	…	…	…
	…	…	…	…	…	…	…
	N_5	x_{N5}^{11} $\bar{x}_{N5}^{11}$	x_{N5}^{12} $\bar{x}_{N5}^{12}$	x_{N5}^{21} $\bar{x}_{N5}^{21}$	x_{N5}^{22} $\bar{x}_{N5}^{22}$	x_{N5}^{31} $\bar{x}_{N5}^{31}$	x_{N5}^{32} $\bar{x}_{N5}^{32}$

Table 4. Data sources of demand flexibility and reality flexibility

necessity for supply chain to take any steps to respond environmental changes. On the contrary, if inequality $\frac{F}{E} > 1 + \varphi_1$ is valid, it means the level of reality flexibility is too high and we can use the existing resources to address environmental uncertainty by the most economical way through appropriate adjustment.

If $r < 1$, which states $F < E$, it shows that the reality flexibility is less than the demand one and we set warning coefficient φ_2 here. If inequality $1 - \varphi_2 < \frac{F}{E} < 1$ is right, it demonstrates that the gap between reality and demand flexibilities is within an acceptable range, and we can adjust it locally through the analysis of the matching status of specific components. On the other hand, if $\frac{F}{E} < 1 - \varphi_2$, it indicates that the gap between demand and reality flexibilities is over acceptable range, which means we need further analysis of the matching states between potential and demand ones.

4.2.2 Component matching

Depending on preceding analysis, each flexibility element has two dimensions, namely range(R) and adaptability (A), which constructs a two-dimensional space, as it is shown in Figure 5. Assuming the reality flexibility of an individual element is f_n, we can obtain its rectangular coordinate $f_n(f_n^R, f_n^A)$ in accordance with the index constructed from two dimensions, by this time the demand flexibility of the element is e_n and its rectangular coordinate is $e_n(e_n^R, e_n^A)$. Transform the rectangular coordinate into polar coordinate, namely $f_n(\rho_f, \theta_f)$, $e_n(\rho_e, \theta_e)$, and component matching function is assumed to be equation $\phi = \frac{\rho_f}{\rho_e}$.

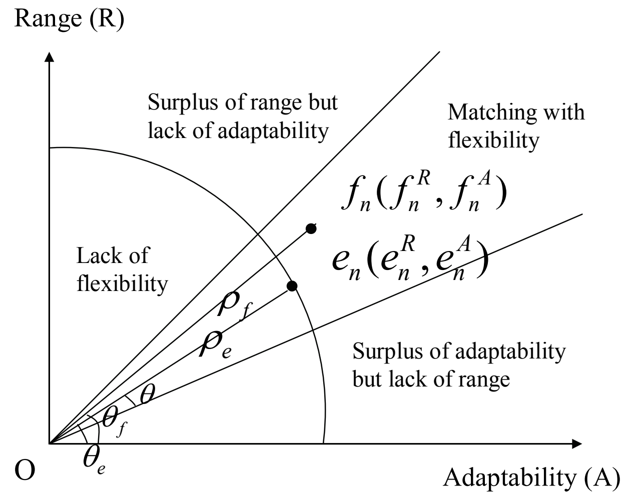


Fig. 5. Reality flexibility elements matching with demand ones

As shown in Figure 5, if $\phi < 1$, which states $\rho_f < \rho_e$, it indicates that the reality flexibility of a certain element is less than the demand one, that is to say the reality flexibility falls within the circle whose origin is O and radius is ρ_e, and it is necessary to be adjusted.

If $\phi > 1$, which states $\rho_f > \rho_e$, it indicates that the reality flexibility of a certain element is larger than the demand one, but it does not mean that the two dimensions of the flexibility are balanced and we need warning coefficient θ here. If $\theta_e - \theta < \theta_f < \theta_e + \theta$, namely reality falls within the area whose center axis is ρ_e and included angle is 2θ, it means the reality flexibility of a certain element is matched with the demand one. If inequality $\theta_f > \theta_e + \theta$ is valid, it indicates a lack of adaptability but an excess of range. However, it is the opposite situation when $\theta_f < \theta_e - \theta$. Both of the two cases above need local adjustment to ensure the most economical way when coping with the changes of environment.

During the feedback evolution process of supply chain flexibility and its dynamic environment, the flexibility continuously adjust itself through its dynamic capabilities and interoperability, hoping to achieve the optimal position in supply chain flexibility space, that is the required flexibility level depending on uncertain environment. Therefore, it is the existence of dynamic circumstance that drives supply chain to construct and continuously evolve flexibility. Based on the anatomize above we can see that the matching between reality and demand flexibility is a process which starts with the overall situation, grasps the details, adjusts locally and balances dimensions, aiming at allocating resources through the most reasonable way to address environmental uncertainty. Moreover, when the matching result indicates that there is gap or deviation between the reality flexibility and the demand one, we should construct and adjust the supply chain appropriately and here we can define the momentum function of its flexibility evolution as $\gamma = \sqrt{(r-1)^2 + \sum_{i=1}^{4}(\phi_i - 1)^2}$, thereinto, variables r and ϕ_i are the consequences of global and component matching respectively, variable i for any $i \in [1,4]$ refers to the supply chain flexibility elements. The larger value variable γ is, the greater momentum of supply chain flexibility evolution and the stronger tendency are.

4.3 Matching models of supply chain demand flexibility and potential flexibility

After the comparison of the demand flexibility required by environmental uncertainty and the reality one, if the former is greater than the later, it is necessary to further contrast the potential flexibility with the demand one, which determines the choice of supply chain flexibility strategy, that is, if the demand flexibility is less than the potential one, supply chain can finitely capture the boundary elements according to its own situation without shifting its main structure to choose or mix strategies in order to address environmental changes. Supply chain collaboration at this time plays an important role. If the demand flexibility is greater than the potential one, then the supply chain must reorganize the resources or reconstruct the structure through its dynamic ability to respond to environmental changes.

Strategies \ Indicators		Levels of flexibility elements			
		O_1	O_2	…	N_5
Potential flexibility	1	$x_{1,O1}$	$x_{1,O2}$	…	$x_{1,N5}$
	2	$x_{2,O1}$	$x_{2,O2}$	…	$x_{2,N5}$
	…	…	…	…	…
	m	$x_{m,O1}$	$x_{m,O1}$	…	$x_{m,N5}$
Demand flexibility	Optimal values	$x_{e,O1}$	$x_{e,O1}$	…	$x_{e,N5}$

Table 5. Flexibility levels and optimal values of each supply chain flexibility element under m kinds of strategies

The demand flexibility here is defined as before, that is the flexibility level of supply chain depending on the degree of environmental uncertainty. The potential flexibility refers to the capacity that supply chain maximally uses of available resources under the existing main structure to form strategy combinations. We can use m kinds of strategies to represent their potential flexibility. Demand flexibility can be considered to be the optimal status of flexibility that supply chain should have under the condition that each element observes the level of environmental uncertainty. Specific data is shown in Table 5.

All indicators of the four elements of supply chain $\{O_1, O_2, \ldots, N_5\}$ can form *m* kinds of strategies according to different levels of environmental uncertainty during a period of time. The index values corresponded by all policies have formed the potential flexibility of the supply chain. We use variable F_H to represent it and $F_H=\{F_{H1}, F_{H2}, \ldots, F_{Hm}\}$. Thereinto, variable $F_{Hi}=\{x_{i,O1}, x_{i,O2}, \ldots, x_{i,N5}\}$, which means the whole index value of ith strategy. The optimal flexibility values that each indicator identified in the light of environmental uncertainty should have during a certain period form demand flexibility which is represented by F_E, and $F_E=\{x_{e,O1}, x_{e,O2}, \ldots, x_{e,N5}\}$. Based on all of these, we define matching function as

$$\varphi_i = \frac{1}{n}\sum_{j=O_1}^{N_5}\frac{\delta_{\min}+\tau\cdot\delta_{\max}}{\delta_{ij}+\tau\cdot\delta_{\max}}\,.$$

Thereinto, variable n refers to the number of indicators and variable τ for any $0<\tau<1$ is a parameter of the model. As to equation $\delta_{ij}=\left|x_{i,j}-x_{e,j}\right|$, it stands for the deviation between the ith strategy under the jth index and the value of demand flexibility for any i = 1, 2, …, m and j = O_1, O_2, …, N_5. We define $\delta_{\max}=\max\{\delta_{ij}\}$ as the maximum value for δ_{ij} and

$\delta_{\min} = \min\{\delta_{ij}\}$ as the minimum value for δ_{ij}. So the matching function is also can be written as:

$$\varphi_i = \frac{1}{n}\sum_{j=O_1}^{N_5} \frac{\delta_{\min} + \tau \cdot \delta_{\max}}{\delta_{ij} + \tau \cdot \delta_{\max}} = \frac{1}{n}\sum_{j=O_1}^{N_5} \frac{\min\{|x_{i,j} - x_{e,j}|\} + \tau \cdot \max\{|x_{i,j} - x_{e,j}|\}}{\{|x_{i,j} - x_{e,j}|\} + \tau \cdot \max\{|x_{i,j} - x_{e,j}|\}}.$$

Matching function φ_i for any $\varphi_i \in [0,1]$ represents the level how close potential flexibility possessed by ith strategy and demand flexibility of the supply chain to each other, which reflects the resilience of supply chain to respond to variable resources in the environment. The closer φ_i is to 1, the stronger resilience between the potential flexibility and the demand one. Therefore, when analyzing matching status, we should choose the strategy corresponded by the maximum value of matching function φ_i among all the strategies in acceptable range. We can assume warning coefficient $\psi \in (0,1)$, and if $\varphi_i \geq \psi$, it means that the potential flexibility is matched with the demand one, that is, the supply chain can deal with environmental uncertainty by means of strategy combinations or a selection of a set of strategies without changing the main structure of it, during which process the coordination among organizations in supply chain plays the key role--through the effective collaboration between enterprises in supply chain, limited use of certain resources can form a suitable strategy to respond to environmental changes. On the other hand, if $\varphi_i < \psi$, it indicates that the potential flexibility is not matched with the demand one, which means it can not cope with environmental changes. Then it is essential to use the dynamic ability of supply chain to reconstruct itself or reorganize resources for the sake of forming innovative flexibility to respond to environmental changes.

To synthesize the analysis above, we can select strategies and make decisions by means of judging the matching status between the level how uncertain the environment is and the potential and demand flexibilities, providing a theoretical basis of rationally allocating flexibility of supply chain.

5. Conclusion and recommendation

This article targeted at increasing environmental uncertainty faced with modern supply chain, which discussed about the characteristics of supply chain flexibility, evolution mechanisms, matching models and some other topics in this area. It is mainly shown as the following two aspects.

First, based on the analyzed content and characteristics of supply chain flexibility, we researched on the fundamental drivers and the essence of environmental uncertainty and then constructed its dimensions, namely, complexity, dynamicity and resource availability. On that basis, we analyzed the factors of supply chain environmental uncertainty which is the fundamental driven source of its flexibility. Furthermore, we investigated the impact of flexibility factors from two perspectives, motility and adaptability, in accordance with the characteristics of flexibility, which is the foundation of supply chain flexibility's generation and evolution. As to the formation mechanisms of supply chain flexibility, using previous studies for reference, we divided the various elements of supply chain flexibility into operation flexibility, information flexibility, logistics flexibility and robust network and reconstruction flexibility. Besides, we comprehensively analyzed the formation process of supply chain flexibility and the function and generation mechanism of core enterprises.

Secondly, in accordance with the characteristics of flexibility dynamicity, we made further exploration of the measurement and evolution of supply chain flexibility based on its generation mechanism. In this paper, we analyzed the evolution theory of supply chain flexibility from the point of view of theoretical framework, measurement methods and practical process. First of all, we constructed the dimension and comprehensive index system of it according to previous studies. Then on this basis, we made further investigation of its evolution mechanism, which discussed the principles and strategies of the evolution process and gave the evolutionary framework from the theoretical perspective. In the end, based on the theories and methods, we provided the specific process and matching models of supply chain flexibility under uncertain environment. With the help of matching models and judgment criteria, managers can make the appropriate adjustment, which can contribute to supply chain decisions.

Summing up the above, there are some recommendations in order to construct supply chain flexibility and improve performance:

1. To identify environmental uncertainty accurately
2. To enhance the communication and cooperation between enterprises in supply chain
3. To enhance the adaptability and coordination of supply chain resources
4. Raise awareness of flexibility

6. Reference

[1] Adrian E. Coronado M., A.C.L., Evaluating opeartions flexibility in industrial supply chains to support build-to-order initiatives[J]. Business Process Management, 2007. 13(4): 572-587.

[2] Duclos L., V.R., Lummus R., A conceptual model of supply chain flexibility[J]. Industrial Management & Data Systems, 2003. 103(6): 446-456.

[3] Vickery S., C.R., Droge C., Supply chain flexibility: an empirical study[J]. The Journal of Supply Chain Management, 1999. 35(3): 16-24.

[4] Gunasekaran A., P.C., Tirtiroglu E., Performance measures and metrics in a supply chain environment[J]. International Journal of Operations & Production Management, 2001. 21(1/2): 71-87.

[5] Li Guangming, Research on the Flexibility of Supply Chain Information System[D]. Tongji University, 2008: 64-70.

[6] Wang Lu, Li Penglin, Flexible Strategy of Enterprise Management[J]. Technology and Innovation Management, 2008. 29(4): 355-358.

[7] Zhang Yunbo, Wu Zhenye, Yang Chenglian, Integrated System Model for Flexible Supply Chain[J]. Southwest Jiaotong University, Journal of Southwest Jiaotong University, 2004. 39(2): 244-247.

[8] Gai Jun, The Study of Supply Chain Management Optimization Based on Demand-driven [D]. Xian: Xidian University, 2008.

[9] Huang Xiaoyuan, Yan Nina, Research Progress on Supply Chain Robustness [J]. Chinese Journal of Management, 2007. 4(4): 521-528.

[10] Das S., A.-M.L., Modelling the flexibility of order quantities and lead-times in supply chains[J]. International Journal of Production Economics, 2003. 85: 171-181.

[11] Ma Shihua, Lin Yong, Supply Chain Management[M]. Beijing: Machinery Industry Press, 2005.

[12] Leslie K. Duclos, R.J.V., Rhonda R. Lummus, A conceptual model of supply chain flexibility[J]. Industrial Management & Data Systems, 2003. 106(6): 446-456.
[13] Wang Damiao, Song Yan, Agile Supply Chain Performance Evaluation Index System [J]. Science-technology and Management, 2005(3): 95-99.
[14] Zhang Yibin, Chen Jin, Review for strategic perspectives of flexibility in environmental uncertainty [J]. Application Research of Computers, 2008. 25(4): 970-985.
[15] Beamon, B.M., Measuring supply chain performance[J]. International Journal of Operations & Production Management, 1999. 19(3): 275-292.
[16] Zhang Shoufeng, Research on Flexible Strategy of Enterprises Based on the Hyper-competitive Environment [D]. Wuhan: Wuhan University of Technology, 2005.
[17] Jack G.A.J. van der Vorst, A.J.M.B., Identifying sources of uncertainty to generate supply chain redesign srategies[J]. International Journal of Physical Distribution & Logistics Management, 2002. 32(6): 409-430.
[18] Lu Yaobin, Yang Guangming, Yang Mincai, the Source, Performance and Coping Strategies of Supply Chain Uncertainty [J]. Science & Technology Progress and Policy, 2004. 21(4): 87-89.
[19] Guo Lixin, The State-variables and the Influence Factors of Enterprise Dynamic Capabilities System s Evolution [J]. Science of Science and Management of S.& T., 2008. 29(6): 142-147.
[20] He Xiaogang, Li Xinchun, Fang Haiying, Measuring and Efficiency of Dynamic Capabilities: An Empirical Study in China [J]. Management World, 2006(3): 94-171.
[21] Li Xingwang, Wang Yingjun, Dynamic Capabilities Theory and Its Prospect [J]. Contemporary Finance & Economics, 2004(10): 103-106.
[22] Jiao Hao, Cui Yu, Dynamic Capabilities in the Enterprise: Integrated Framework of Theory and Re-positioning [J]. Journal of Tsinghua University(Philosophy and Social Sciences), 2008. 23(S2): 46-53.
[23] Diao Li, Liu Xilin, Chen Hongjie, Study on Coordination Degree Model of Agile Supply Chain System [J]. Soft Science, 2007. 21(2): 16-19.
[24] Dong Fengna, Review on Information Flow Study of SC [J]. Logistics Technology, 2005(5): 49-53.
[25] Cai Shuqin, Liang Jing, The Relation between Information Sharing and Supply Chain Coordination [J]. Chinese Journal of Management, 2007. 4(2): 157-162.
[26] Zhang Yunbo, Supply Chain Flexibility Management for Agile Manufacturing[J]. Reform of Economic System, 2003(3): 55-58.
[27] Zhang Guangming, Supply Chain Flexibility and its Mechanism [C]. Modern Industrial Engineering and Management Seminar（MIEM'06）Collected Papers, 2006: 210-213.
[28] Graves S.C., T.B.T., Process flexibility in supply chains[J]. Management Science, 2003. 49(7): 907-919.
[29] Wu Bing, Liu Yili, Zhao Lindu, Measurement of Supply Chain Flexibility [J]. Industrial Engineering Journal, 2008. 11(3): 68-72.
[30] Liu Yingzi, Three-dimensional Measurement of Flexibility Index [J]. Journal of Huazhong University of Science and Technology Edition of Social Sciences, 1998. 3: 94-96.
[31] N., S., Flexibility as a manufacturing objective [J]. International Journal of Operations & Production Management, 1983. 3(3): 4-13.
[32] Fernando F. Suarez, M.A.C., Charles H. Fine, An empirical study of flexibility in manufacturing[J]. Sloan Management Review, 1995. 37(1): 25-32.

[33] Wang Delu, Zhang Mier, Optimization Model of Enterprise Strategic Flexibility during Industry Conversion[J]. Journal of Industrial Engineering and Engineering Management, 2008. 22(3): 126-129.
[34] Stuart, E.J., Strategic flexibility for high technology maneuvers: a conceptual framework[J]. Journal of Management Studies, 1991. 281: 69-89.
[35] P., G.W.P., Towars a definition of flexibility: In search of the holy grail? [J]. OMEGA, 2000. 28(4): 373-384.
[36] Upton, D.M., Flexibility as process mobility: the management of plant capabilities for quick response manufacturing[J]. Journal of Operations Management, 1995. 12: 205-224.
[37] D.M., U., The management of manufacturing flexibility. California Management Review, 1994. 36(2): 72-89.
[38] Chen Junhua, Wu Jingyan, Facing Uncertainty:Enterprise Flexibility on the Basement of Intension of Agents [J]. Science & Technology Progress and Policy, 2009. 26(9): 102-105.
[39] Lori L. Koste, M.K.M., A theoretical framework for analyzing the dimensions of manufacturing flexibility[J]. Journal of Operations Management, 1999. 18: 75-93.
[40] Zhu Aimin, Yu Lijuan, Rigidity and Flexibility of Core Competence and the Balance Between Them [J]. Science of Science and Management of S.& T.(monthly), 2006. 27(2): 144-149.
[41] Wan Lunlai, Da Yingli, Nature of flexibility about enterprises and the strategy for constructing the flexibility of enterprises [J]. Journal of Management Sciences in China, 2003. 6(2): 89-94.
[42] Lori L. Koste, M.K.M., Subhash Sharma, Measuring dimensions of manufacturing flexibility[J]. Journal of Operations Management, 2004. 22: 171-196.
[43] Swafford, P.M., Theoretical development and empirical investigation of supply chain agility[J]. Doctor of Philosoph Paper in the DuPree College of Management, 2003.
[44] Patricia M. Swafford, S.G., Nagesh Mruthy, The antecedents of supply chain agility of a firm: scale development and model testing [J]. Journal of Operations Management, 2006. 24: 170-188.
[45] Chang S.C., Y.C.L., Cheng H.C., Sheu C., Manufacturing flexibility and business strategy: an empirical study of small and medium sized firms [J]. International Journal of Production Economics, 2003. 83: 13-26.
[46] Brian Fynes, S.d.B., Donna Marshall, Environmental uncertainty, supply chain relationship quality and performance[J]. Journal of Purchaing and Supply Management, 2004. 10: 179-190.
[47] Meng Jun, Zhang Ruoyun, Supply Chain Flexibility Comprehensive Assessment System[J]. China Management Informationization, 2007. 10(9): 56-59.
[48] Mao Xuting, the AHP-based Flexibility Evaluation of Enterprise Management System [J]. Business Economy, 2006(6): 74-76.
[49] Famg Yinghua, Du Dong, the AHP-based Flexibility Evaluation of Enterprise Production System [J]. Science and Technology Management Research, 2005(9): 191-196.
[50] Guo Yajun, the Theory and Methods of Comprehensive Evaluation [M]. Science Press, 2002.
[51] Zhou Haijun, Yang Zhong, the Motives and Direction of Organization Flexibility management: the case of Yangzi Petrochemical [J]. Modern Management Science, 2009. 6: 14-16.

Part 4

Risk Managements in Supply Chain

11

A Feedback Model of Control Chart for Supplier Risk Management

Jing Sun[1] and Masayuki Matsui[2]
[1]*Graduate School of Engineering, Nagoya Institute of Technology,*
[2]*Department of Informatics, Graduate School of Informatics and Engineering, The University of Electro-Communications, Japan*

1. Introduction

This chapter proposes a control chart model for supplier risk management. In these days, to improve the customer satisfaction of supplier, there has been an increased interest in IT (information technology) control charts which are used to monitor online production processes.

In the supply chain system shown in Figure 1, prompt response of the supplier to the feedback trouble information from the maker is important, not only has become a key point of the supplier competitive edge, but also useful for the improvement of the bottleneck of the whole supply network. In the setting of the due time of the treatment to the various assignable cause, because idle and delay risks are the trade-off relation, setting the optimal due date becomes a problem of great interest to the supplier. The trade-off problem of this research is shown in Figure 2, which will be explained in detail in §2.1.

Since Duncan's pioneering work [1], many studies have been developed to serve different purposes for the economic model of control charts. From the viewpoint of the production run, Gibra [2], Ladany and Bedi [3], Jones and Chase [4], Saniga [5] have considered the economic statistical model of the $\bar{x}$ control chart for the infinite-length horizon; Crowder [6], Del Castillo and Montgomery [7] have considered models of the control chart for short run cases. However, the feedback model stating from out-of-control state was not considered explicitly.

Sun, Tsubaki and Matsui [8] [9] have defined and considered the CAPD models of the $\bar{x}$ control chart based on a feedback case. Sun, Tsubaki and Matsui [10] developed the CAPD model of control chart in which tardiness penalty was considered. However, the penalty of idle cost was not considered in those works.

In this paper, a feedback model of control chart considered not only the delay penalty but also the idle penalty is proposed for supplier. First the cost elements of the feedback case are analyzed and the mathematical formulations which correspond to the case are shown. Then, to give clearer understanding about the trade-off relation in this feedback model, the behaviors of idle cost and delay cost are studied by numerical experiments. Finally, to find out the optimal due time, the relations between the due time and the total expectation cost by the change of action time are discussed.

2. The feedback model

2.1 Explanation of the feedback model

Figure 2 shows some of the time variables used in the feedback model with the idle and delay penalties. In this paper, the feedback model starts from the out-of-control state (at point *E*) by an assignable cause. But the cause is not understood until the process is searched for when the plotted point is beyond the control limits. At point *F*, let the assignable cause be detected for the first time by the $\bar{x}$ control chart. During *F* to *J*, the action is done. Therefore, from point *J*, the process comes back to in-control state. The random variables *D* and *A* represent the interval from *E* to *F* and the interval from *F* to *J*, respectively. *T* is the due time.

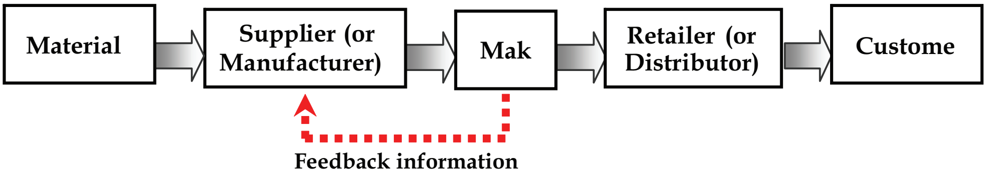


Fig. 1. The supply chain system with feedback information

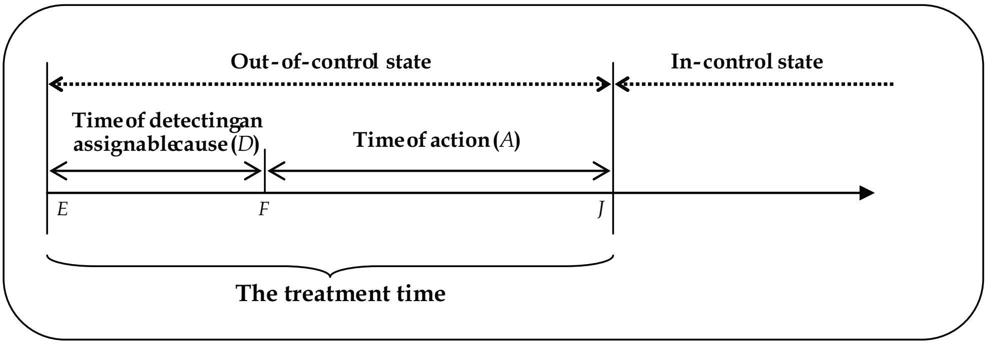


Fig. 2. Some of the time variables used in the feedback model

From Figure 2, it can be noted that when $T<(D+A)$, the delay penalty occurs, and when $T>(D+A)$, the idle penalty occurs.

In this chapter, the assumptions of the design in this research are as follows:

i. The due time *T* is short, and the process is repetitive.

ii. The quality shift occurs in the middle of an interval between samples [11]

2.2 Explanation of the costs and mathematical formulations

In this paper, the evaluation function is the expected total cost as follows:

$$C_t = E[cost\ per\ cycle] = C_C + C_A + C_I + C_D. \tag{1}$$

In the feedback model, the check cost, action cost, idle cost and delay cost are considered, respectively, as follows:

(i) The check cost (C_C)

It is the cost for sampling and plotting on the $\bar{x}$ control chart every interval v for monitoring the process. Therefore the expected check cost is calculated as follows:

$$C_C = \{[(c_0 + c_1 n) / v]E[cycle] \tag{2}$$

(ii) The action cost (C_A)

It is the cost for acting the assignable cause and preventive measure. Therefore the expected action cost is calculated as follows:

$$C_A = c_a E[(T-D)^+ - (T-D-A)^+] \tag{3}$$

(iii) The idle cost (C_I)

It is the cost for the idle penalty. Therefore the expected idle cost is calculated as follows:

$$C_I = c_i E[\max(T-D-A, 0)] \tag{4}$$

(iv) The delay cost (C_D)

It is the cost for the delay penalty. Therefore the expected delay cost is calculated as follows:

$$C_D = c_d E[\max(D+A-T, 0)] \tag{5}$$

Where

$$E[cycle] = E[\min(D+A, T)] \tag{6}$$

In this paper, we use assumption of [11] that the shift occurs in the middle of an interval between samples, therefore, $\mu^{-1}{}_2$ is set as follows:

$${\mu_2}^{-1} = v(1/P_a - 1) + v/2 = v(1/P_a - 1/2) \tag{7}$$

α (the type I error probability) and Pa (power) of the $\bar{x}$ control chart are given by [7],

$$P_a = \int_{-\infty}^{-k-\delta\sqrt{n}} \Phi(Z)dZ + \int_{k-\delta\sqrt{n}}^{\infty} \Phi(Z)dZ \tag{8}$$

$$\alpha = 2\int_{k}^{\infty} \Phi(Z)dZ. \tag{9}$$

If it is assumed that both the random variable D and A are independent and exponentially distributed with mean $\mu^{-1}{}_1$ and $\mu^{-1}{}_2$, then combining equations (1)-(5), the expected costs of check, action, idle and delay are shown as follows:

$$C_C = [(c_0 + c_1 n)/v] \frac{1}{\mu_1 - \mu_2}\{\frac{\mu_2}{\mu_1}(e^{-\mu_1 T} - 1) - \frac{\mu_1}{\mu_2}(e^{-\mu_2 T} - 1)\} \tag{10}$$

$$C_A = c_a\{\frac{1}{\mu_2} + \frac{1}{\mu_1 - \mu_2}(-\frac{\mu_1}{\mu_2}e^{-\mu_2 T} + e^{-\mu_1 T})\} \quad (11)$$

$$C_I = c_i\{T + \frac{1}{\mu_1 - \mu_2}(\frac{\mu_1}{\mu_2}(e^{-\mu_2 T} - 1) - \frac{\mu_2}{\mu_1}(e^{-\mu_1 T} - 1)\} \quad (12)$$

$$C_D = c_d\{-\frac{1}{\mu_1 - \mu_2}(\frac{\mu_2}{\mu_1}e^{-\mu_1 T} - \frac{\mu_1}{\mu_2}e^{-\mu_2 T})\} \quad (13)$$

From (12) and (13), it can be obtained $\partial C_I / \partial T > 0$ and $\partial C_D / \partial T < 0$. Therefore, it can be understand that the expected idle cost (*CI*) increases with the increase of the due time (*T*), the expected delay cost (*CD*)decreases with the increase of the due time (*T*). Therefore, it also can be understand that the two risks (*CI* and *CD*) have a trade-off problem.

3. Numerical experiments

In this section, first we study the behaviors of idle cost and delay cost to give a clearer understanding about the trade-off relation in the feedback model by numerical experiments. Then, to find out the optimal due time of this feedback case for supplier, the relations between the due time and the total expectation cost by the change of action time are studied. The parameters used in this paper are from a company, which are based on a real situation. Where $c_0 = 0.05$, $c_1 = 0.04$, $c_a = 96$, $c_i = 96$, $c_d = 1000$, $v = 1$, $\delta = 2$, $k = 3.0$.

3.1 The trade-off relation of idlec and delay cost

From Figure 3, it can be noted that the expected idle cost *(CI)* increases with the increase of due time *(T)*. This is because that the idle penalty increases by the increase of due time.
Also it can be noted that the expected idle cost *(CI)* increases with the decrease of action time *(a)*. This is because that the idle penalty of worker or machine increases by the decrease of action time, when *T* is set.

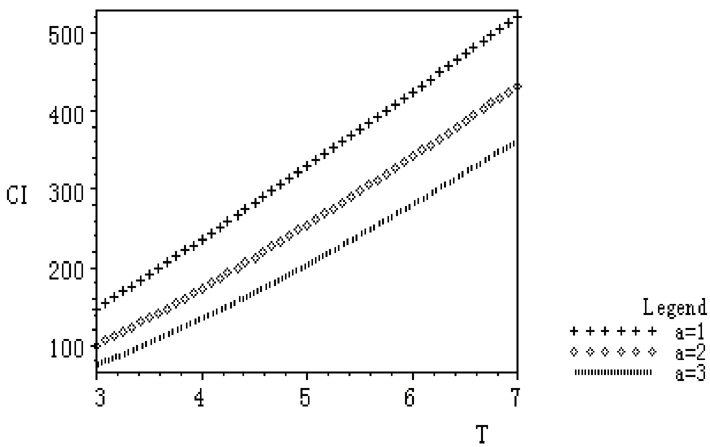


Fig. 3. The behaviors of idle cost (*a*=1, *a*=2 and *a*=3)

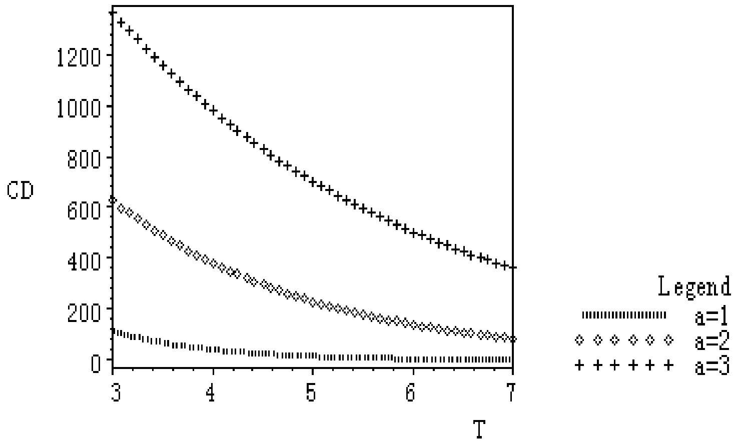


Fig. 4. The behaviors of delay cost (*a*=1, *a*=2 and *a*=3)

From Figure 4, it can be noted that the expected delay cost *(CD)* decreases with the increase of due time *(T)*. This is because that the penalties for delaying the due time decreases by the increase of due time.

Also it can be noted that the expected delay cost *(CD)* decreases with the decrease of action time *(a)*. This is because that the delay penalty decreases by the decrease of action time, when *T* is set.

3.2 The relation between the due time, action time and total expected cost

To understand the relation between the due time and the total expectation cost, Figure 5 shows you the behaviors of all of the cost elements (check, action, idle and delay costs) by the change of due time.

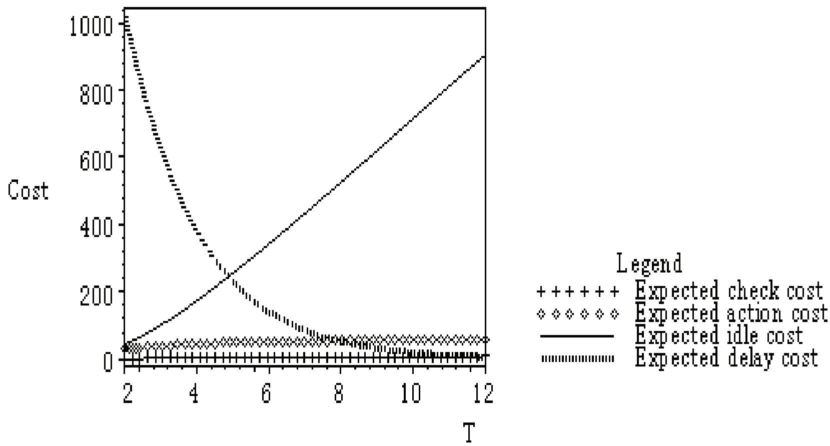


Fig. 5. The behaviors of check, act, idle and delay costs

To clarify it, the behaviors of check and act costs of Figure 5 case is shown by Figure 6.

From Figure 6, it can be noted that the expected check cost (*Cc*) and action cost (*CA*) increase with the increase of due time.
From Figures 5 and 6, it has been understood that determining the optimum value of due time that minimizes the expected total cost is based on the balance of the size of the inclination of *Cc*, *CA*, *CI* and *CD*. As the result, the relation between the expected total cost and due time of the feedback model is shown by Figure 7.
From Figure 7, it can be note that the optimal value of due time to minimize the expected total cost exists. Also, from Figure 7, it can be note that the optimal value of due time increases with the increase of action time. Therefore, it can be understand that a longer due time should be set when the action time is longer from an economic aspect.

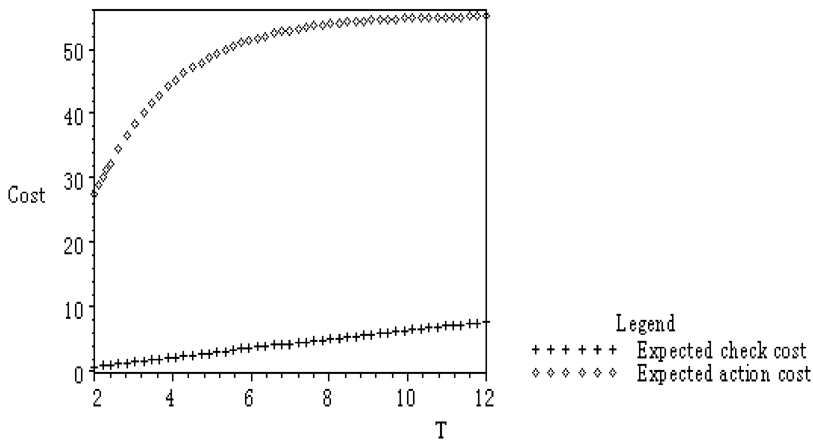


Fig. 6. The behaviors of check and act costs

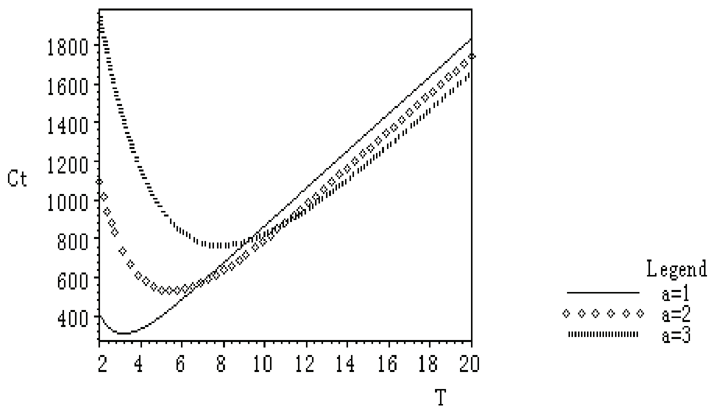


Fig. 7. The relation between *T*, *a* and *Ct*

Tables 1 show the relation between the due time, action time and total expectation cost of the above case. From Table 1, supplier could find out the optimal due time corresponding to the various action time. For instance, in Table 1, we can note that when action time is 2, the minimum *Ct* is 537.0, and the optimal due time would be set at 6.

a	T														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.50	378.6	220.6	256.6	340.2	433.9	529.7	625.9	722.2	818.4	914.7	1011.0	1107.2	1203.5	1299.8	1396.0
0.75	559.2	290.9	267.0	327.4	413.5	507.0	602.6	698.7	795.0	891.3	987.6	1084.0	1180.3	1276.6	1373.0
1.00	765.2	404.4	311.0	333.7	402.3	488.4	581.0	676.0	771.8	868.1	964.4	1060.7	1157.1	1253.5	1349.9
1.25	984.9	549.6	387.7	364.6	406.8	478.8	564.2	655.7	749.9	845.4	941.4	1037.6	1134.0	1230.4	1326.9
1.50	1212.9	717.3	492.3	420.7	430.4	482.3	555.8	640.6	731.0	824.5	919.4	1015.1	1111.2	1207.5	1303.9
1.75	1446.3	901.4	619.8	500.1	474.1	501.4	558.8	633.3	717.4	807.0	899.6	993.9	1089.2	1185.1	1281.2
2.00	1683.2	1097.4	765.7	600.1	537.2	537.0	575.0	636.0	711.1	794.6	883.3	975.1	1068.9	1163.7	1259.3
2.25	1922.7	1302.6	926.5	717.7	618.2	589.0	605.1	650.0	713.6	789.0	872.1	960.1	1051.2	1144.3	1238.7
2.50	2164.1	1514.8	1099.2	850.5	715.3	656.6	649.2	676.1	726.0	791.4	867.2	949.9	1037.2	1127.6	1220.2
2.75	2406.8	1732.5	1281.9	996.2	826.9	738.7	706.9	714.3	749.0	802.7	869.5	945.5	1027.8	1114.6	1204.4
3.00	2650.7	1954.6	1472.7	1153.0	951.2	834.0	777.6	764.6	782.8	823.3	879.8	947.8	1024.0	1106.0	1192.3
3.25	2895.4	2180.2	1670.2	1319.3	1086.8	941.5	860.4	826.5	827.3	853.6	898.6	957.4	1026.3	1102.6	1184.4
3.50	3140.9	2408.8	1873.5	1493.8	1232.3	1059.9	954.6	899.5	882.3	893.5	926.0	974.6	1035.2	1104.9	1181.4
3.75	3386.9	2639.8	2081.6	1675.3	1386.6	1188.3	1059.1	983.0	947.4	942.9	962.2	999.7	1051.2	1113.3	1183.7
4.00	3633.3	2872.9	2293.9	1863.0	1548.8	1325.6	1173.3	1076.2	1022.2	1001.6	1007.0	1032.8	1074.4	1128.2	1191.7

Table 1. The relation between due time *(T)*, action time *(a)* and expected total cost *(Ct)*

Also, from Table 1, it can be noted that a longer due time should be set when the action time is longer.

4. Conclusions

In this chapter, we proposed a feedback model of the $\bar{x}$ control chart in which idle and delay risks are considered in order to improve customer satisfaction of supplier. Because of competition in supplier markets, prompt responding to the feedback trouble from the maker is more important.

In the setting of the due time of the treatment to the various assignable cause, because idle cost and delay cost are the trade-off relation, setting the optimal due date becomes a problem of great interest to the supplier.

To resolve this problem, we proposed a feedback model of control chart for supplier and showed their mathematical formulations. Then, to give clearer understanding about the trade-off relation in this feedback case, the behaviors of idle and delay costs are studied by numerical experiments. Moreover, to find out the optimal due time, the relations between the due time and the total expectation cost by the change of action time are discussed. The results obtained in this paper are useful for the setting the optimal due time of the feedback case to supplier.

5. Nomenclature

The notation used is as follows:

n the sample size per each sampling

v the sampling interval

T due time

c_0 fixed sampling cost
c_1 variable sampling cost
c_a action cost of per unit time
c_i idle cost of per unit time
c_d delay cost of per unit time
δ size of the quality shift in the mean
A time of action
D time of detecting the assignable cause
$\mu^{-1}{}_1$ mean of the D
$\mu^{-1}{}_2$ mean of the A
k control limits width

6. Acknowledgment

This research was partially supported by Japan Society for the Promotion of Science, a Grant-in-Aid for Research Activity Start-up, 22810011 in 2010.

7. References

[1] A. J. Duncan, "The economic design of charts used to maintain current control of a process," Journal of the American Statistical Association, vol. 51, pp. 228-242, 1956.
[2] I. N. Gibra, "Economically Optimal Determination of the Parameters of $\bar{x}$ Control Charts," *Management Science*, vol. 17, pp.635-647, 1971.
[3] D. S. Bai, M. K. Lee, "An economic design of variable sampling interval $\bar{x}$ control charts," *International Journal of Production Economics*, vol. 54, pp. 57-64, 1998.
[4] L. L. Jones, and K.E. Case, "Economic design of a joint $\bar{x}$ and R Chart," *IIE Transactions*, vol. 13, pp. 182-195, 1981.
[5] E. M Sanige, "The Economic statistical Design of control Charts with an application to $\bar{x}$ and R Chart," *Technometrics*, vol. 28, pp. 3-10, 1986.
[6] S. V Crowder, "An SPC models for short production run: minimizing expected cost," *Technometrics*, vol. 34, pp.64-73, 1992.
[7] E. D. Castillo, and D. C. Montgomery, "A General Model for the Optimal Economic Design of $\bar{x}$ Charts Used to Control Short or Long Run Processes," *IIE Transactions*, vol. 28, pp.193-201, 1996.
[8] J. Sun, M. Tsubaki and M. Matsui, "Economically Optimal Sampling Interval v in PDCA and CAPD Quality Control Model of $\bar{x}$ Control Charts", Hawaii International Conference on Statistics, Mathematics and Related Fields, pp.1009-1016, 2004.
[9] J. Sun, Michiko Tsubaki, Masayuki Matsui, "the CAPD model of $\bar{x}$ chart with tardiness penalty for improving supplier quality", The Proceedings of the 3rd IEEE International Conference on Management of Innovation and Technology, pp.802-806, 2006.
[10] J. Sun, M. Tsubaki and M. Matsui, "Economic Models of $\bar{x}$ Chart with Tardiness Penalty in Finite Due Time Processes," *Journal of Japan Industrial management Association*, (in Japanese), vol. 57, no.5, pp.374-387, 2006.
[11] S. P. Ladany and D. N.Bedi, "Selection of the Optimal Setup Policy," *Naval research Logistics Quarterly*, vol. 23, pp.219-233, 1976.

12

Supply Chain Modeling Based on Restructuring Activities

Lucian Hancu
"Babeş-Bolyai" University and SoftProEuro s.r.l.
Romania

1. Introduction

The restructuring activities of the type Mergers and Acquisitions (M&A) constitute a real challenge for the companies competing with the ones involved in M&A processes, as such a restructuring process usually improves the resulting company's position on the market by creating or consolidating a competitive advantage. The competitive advantages take the form of reducing overall costs by economies of scale, access to new markets, access to new products or technologies.

From the perspective of Supply Chain Management, the Mergers and Acquisitions can induce changes in the supply chain, which affect the life of business entities, especially the small ones, which remain unable to quickly adapt to these changes; thus struggling to survive in the turbulent business environment.

Current Supply Chain Management techniques mostly rely on the barcodes and Radio Frequency Identification (RFID) technologies in order to keep track of the product from its assembly line to the final customer. A noted example of large-scale RFID usage is Wal-Mart's request that its top one hundred supplier introduce RFID tags for better tracking their products, distribute these products more efficiently and eliminate abnormal costs from the shipment and distribution to Wal-Mart (Sliwa, 2004), cited in (Fuld, 2006) and (Hancu, 2008b).

Although there are clear advantages of introducing such technologies in the product's lifecycle, small entities might encounter difficulties (for instance, lack of financing) in implementing such technologies on a larger scale, which limits the applicability of the mentioned technologies in revealing the changes in the supply chains due to the Mergers and Acquisitions activities.

On the other part, accessing data regarding product tracking from the assembly line to the customer constitutes a real challenge. Such data remains private to the companies involved in the supply chains and is accessible only through authentication interfaces or private tracking identification numbers (as in the case of Web-based package tracking systems provided by most courier companies).

In this chapter, we describe a different approach in studying the changes in the supply chains due to mergers and acquisitions activities, based on constructing a set of Virtualized Supply Chains (VSCs) and applying the mergers-induced changes to these Virtualized

Supply Chains. Our aim is to reduce the risks in the supply chain by highlighting which one of the three investigated mergers alternatives (*upstream vertical merger*, *downstream vertical merger* and *conglomerate merger*) is better suited for diminishing the risks in the supply chains sets.
In order to quantify the implications of the three types of mergers to the supply chain, we first generate a list of Virtualized Supply Chains and then we compute the risks associated with each supply chain and the risks corresponding to each business class that appears as a member of the Virtualized Supply Chain. We apply the selected mergers strategies, compute the risks associated with the new Virtualized Supply Chains; then compare the initial risks with the ones highlighted after introducing the mergers shifts in the supply chain.
The chapter is structured as follows. In the next section, we provide a survey on the research literature correlated to the Supply Chain Management (SCM) field the measuring and the managing of risks in the SCM. The third section introduces the terminology that we later employ during our research, which regards the virtual modeling of the Supply Chains: *business class*, *business dependency*, *bounded* and *unbounded Virtualized Supply Chain*, *risk of a business class* and *global risk of the Virtualized Supply Chain Set*.
The subsequent section describes our method of modeling Virtualized Supply Chains by applying the three restructuring strategies: *upwards vertical merger*, *downwards vertical merger* and *conglomerate merger*. The fifth section of the chapter presents the results of our modeling, while the subsequent section highlights our final conclusions.

2. Related work

Studying the impact of the mergers activities on the supply chains is a noted subject of academic research, as mergers usually consist in integrating the operations of the involved companies, from the step of introducing an order, purchasing raw materials, processing operations, the financial aspects of both orders to suppliers and requests from clients, warehouse operations when required and final shipment of the products to the clients (DePamphilis, 2009).
Vertical mergers are combinations of entities along the supply chains with a great chance of improving economic efficiency by cutting intermediaries and reducing overhead (Harrigan, 1985), cited by (Bruner, 2004). An example of vertical merger would be the merger between an aluminium smelter and a bauxite miner (*upstream vertical merger*) or between the same aluminium smelter and an airplane producer (*downstream vertical merger*). As mentioned in (Bruner, 2004), supply chain disruptions are listed among the classic concerns of operating managers, based on the fact that a merger or alliance between two companies has great impact among both clients and suppliers. This was also the case with the recent alliance between two IT distributors from Romania (Preda, 2009), which conducted to the appearance of a larger competitor in the IT distribution market. Even if a full integration and merger is far from being completed, involving anti-trust laws, competitors tend to be seriously affected by such a merger or strategic alliance.
Various forms of collaborations in the Supply Chains are enlisted in (Meca et. al., 2008). The research is conducted on the principle of multi-firm analysis that has become the subject of research in the operations management field, due to the market globalization and a more intense competition among business entities. The article distinguishes between horizontal (cooperation between peers, in the form of inventory cooperation) and vertical cooperation through the supply chain. The vertical coordination is divided into the coordination of

actions and a full merger, in the first case the two actors act independently, while in the case of the mergers the parties are under centralized control and give up their independence as now constitute a single business entity. According to the authors, there is a limited research studying cooperative game theory as the base for vertical cooperation in the Supply Chain.

In our opinion, the distinction between vertical coordination as two independent companies and full merger cooperation should not be treated separately, from the Supply Chain perspective. We have seen in practice that a full integration is realized after a long process of integration of the two business entities, as it was the case of the two IT distributors, described in (Preda, 2009).

A framework for ranging business entities through the Supply Chain is proposed by (Huo, 2009). According to the performance of the suppliers, the business entities would be classified into *partners*, *key suppliers, qualified suppliers* and *in questioned suppliers*. The *partners* qualification is given to the top performance suppliers, *key suppliers* to the ones that have reached the minimum threshold performance and are going to the top class, *qualified suppliers* for the ones that have reached the minimum requirements but no improved action has been observed, while the *in question suppliers* are the ones that have never reached the minimum requirements and are expected to be rejected from being suppliers. A system for evaluation of the suppliers is also given in the article, each supplier being inspected in terms of Quality, Delivery, Technical support, Collaboration and Cost. The Partner certification is given to suppliers obtaining a score between 92%-100%, Key suppliers to the ones ranging between 80%-91%, Qualified supplier: 70%-79% and In questioned suppliers 70%.

Our approach in managing risks through the supply chain is based on a similar principle that the one highlighted in (Huo, 2009), with the difference that we categorize classes of business entities instead of single business entities. That is, we would rank as high risk a whole business class instead of a single company. The reason for applying such approach is that the same risk category can be assigned to the whole business class, as there would be a higher probability that prices would increase in that business class, which would induce a risk in the supply chain by altering the costs of that business class's primer consumers, then propagating such risk through the supply chain. We highlight our approach of classifying business classes according to the risk measures in the next and fourth section of the chapter.

A thorough analysis of supply chain risks is provided in (Kiser et al., 2006). According to the authors, external risks can be revealed by facts that appear either upstream or downstream through the supply chain. These risks are:

- *Demand risks* – the customer demand is unpredictable or misunderstood.
- *Supply flow risks* – interruptions than might appear in the flow of the product.
- *Environment risks* – shocks that appear outside of the supply chain, but significantly influence the supply chain (e.g. the rising of oil prices due to the starting of an army conflict in one of the oil export countries).
- *Business (or Financial) risks* which express the financial or managerial stability of the supplier
- *Physical risks* which correspond to a change in the conditions of the physical facilities of the supplier.

In contrast, internal risks are fired by the events that occur within the company:

- *Manufacturing risk* caused by changes in the internal processes or operations
- *Business risks* – when modifications are made in key personnel, management personnel or the reporting departments.

- *Planning and control risks* – ineffective management or a planning process that is not appropriate
- *Mitigation and contingencies* – not putting contingencies in place.

The authors (Huo et al., 2006) propose a 6 step process of risk management within the supply chain, the steps involved being:

- *Supplier base*: identifying each row material that is needed in producing the desired result, identifying the strategic materials and understanding suppliers' organization.
- *Vulnerability*: the business entity should reveal the scenarios that are likely to happen, identify the causes that would imply them to appear, and the measure in which the company is more or less able to cope with these scenarios.
- *Implications*: use simulations in order to quantify the impact of each risk when appeared
- *Mitigation*: when an unexpected event occurs, how the company should act in order to get back to a normal situation and continue its activity in a natural way.
- *Costs and benefits*: costs in mitigation actions are accompanied by a benefit from reducing risks and lowering costs when a risky event appears.
- *Measures and actions*: identifying roles and responsibilities within the organization for partnering with suppliers in order to secure the supply chain. The idea is similar with the one expressed in (Hancu, 2011), in which a mechanism of replacing an abnormal unavailability of a supplier by one of its peers is proposed.

Analyzing risks from a company's perspective conducts to a more thorough analysis compared with the case of analyzing classes of business entities. Despite this lower-accuracy inconvenient of analyzing classes of business entities, the business classes approach has the advantage of scale, as its conclusions are applicable to a larger number of business entities than in the case of a single analysis. With the aiming of a higher impact advantage, we present a method of reducing risks in virtually constructed Supply Chains based on restructuring activities of various mergers types. The following section introduces the main definitions employed in our research, which we shall later use during our methodology description.

3. Definitions

In this section, we describe the terminology that we later apply in our research. Instead of tracking products by one of the techniques that the research literature highlights, we generate a set of Virtualized Supply Chains, which are computed by linking two classes of business entities that come in a direct dependency relation.

The Virtualized Supply Chains link various direct-dependent business classes, thus dealing with a greater diversity of Supply Chains examples than in the case of tracking products via Radio Frequency Identification (RFID) or barcode scanning. The later Supply Chain tracking technique would be limited to the business entities that use barcodes or RFID, usually formed by courier companies or large super markets like Wal-Mart.

3.1 The class of a business entity

The *class of a business entity* denotes its main activity code according to a standard classification scheme. In our research, we use the Romanian Classification of the Economic Activities (CAEN), which complies with the European Standard of Classification of the Economies (NACE).

3.2 Business dependency

We denote that two business classes $Class_A$ and $Class_B$ come in a *Business Dependency* relation, when two or more Business entities (one having its main activity code $Class_A$ and the other – $Class_B$) establish relationships of the type supplier-client. By gathering all the business dependencies from the Business classes of the analyzed entities, a Business Dependency Map can be computed, which is later employed in the construction of the Supply Chains.

The Business Dependency Map establishes relationships between classes of business entities and the probabilities that various business classes depend on other business classes. We have previously constructed the Business Dependency Map from the online search logs of our Web-based search application for business entities, by considering a dependency between the first searched entity's business class and the following searched entities' business classes coming from the same Web session (Hancu, 2008a).

3.3 Bounded and unbounded virtualized supply chains

A *Virtualized Supply Chain* (*VSC)* is a list of business classes that come in a direct dependency relation. The Virtualized Supply Chains are constructed as follows. Instead of considering as parts of the supply chain a specified producer, its suppliers and clients, we construct a Virtualized Supply Chain by linking classes of business entities (for instance: *Restaurants* and *Production of bread*) that come in a direct dependency relation according to the Business Dependency Map.

The Virtualized Supply Chains can be either *unbounded*, as introduced in (Hancu, 2008b), or *bounded*. An *unbounded* VSC denotes a supply chain which is constructed by linking direct-dependent business classes until no more business classes can be added at the end of the last business class, as there is no other business class available for the insertion (i.e. no class which depends on the last-added Business Class and which has not already been added to the VSC).

In this chapter, we introduce the notion of Bounded Virtualized Supply Chain, which denotes a Virtualized Supply Chain that has the length *n*, i.e. it links exactly *n* direct-dependent business classes. The introduction of Bounded Virtualized Supply Chains comes as a step forward in the study of Virtualized Supply Chains and it enhances the studies from our previous work (Hancu, 2008b).

Considering that the Business Classes *Restaurants* and *Production of bread* are in a dependency relation (which means that a business entity from the *Restaurants* business class can have a client or supplier an entity of the *Production of bread* business class), we can construct a Virtualized Supply Chain that starts with either the two business classes, then are followed by other business classes that come in a direct dependency relation with the last business class from the supply chain.

The *bounded* Virtualized Supply Chains are the supply chains that are of a specified size (for instance, the *5-Bounded* Virtualized Supply Chains are the VSCs that are formed of five business classes that are each one dependent with the previous business class according to the Business Dependency Map).

The *unbounded* Virtualized Supply Chains are the supply chains constructed from a starting business class that have no possibility of expanding, i.e. no other business class can be added at the end of the Virtualized Supply Chain that comes in a direct dependency with the last-added business class of the Virtualized Supply Chain (as the last-inserted business class has no direct dependants, or its direct dependant business classes were previously added to the Virtualized Supply Chain).

3.4 Risk of a business class, global risk of the virtualized supply chain set

By considering the computed set of both bounded and unbounded Virtualized Supply Chains, we calculate the risk of each business class by *flooding* each Virtualized Supply Chain with a starting risk of 10 units (which means that the company from that business class can increase prices by 10% or can lower its production by 10%).

We propagate the risk through the Virtualized Supply Chain and sum up all the risks associated with each business class, then classify the business classes as *High-risk business classes*, *Medium-risk business classes* and *Low-risk business classes*.

The *Risk of a Business Class* sums all the risks associated with that business class, after the flooding of the risks in the set of Virtualized Supply Chains. Instead, the Global Risk associated to the Virtual Supply Chain Set sums all the risks from all the Business Classes. The goal of our research is to reduce the Global Risk by applying merger strategies. The methodology is further discussed in the next section of this chapter.

4. Research method

The construction of the Business Dependency Map explained in (Hancu, 2008a) yields to the derivation of a list of probabilities between pairs of business classes, that we can employ in the construction of Virtualized Supply Chains, both bounded and unbounded, as explained in the previous section. For the initial set of Virtualized Supply Chains, we compute the global risk by flooding each VSC with an initial risk of 10 units, than adding to the current risk the previously computed supply chain risk. The current risk is formed by the probability that the current business class depends on the previous business class in the VSC.

Our previous approach highlighted in (Hancu, 2008b) employed products instead of sums in the computation of the current risk. The current risk was calculated as a product between the past risk and the probability that the current business class depends on the previous business class. In a thorough analysis of our past approach, we have realized that the current risk becomes insignificant, as the probability of correlated business classes is usually less than 10%, in some cases being even much smaller.

While the past approach made the assumption that the risk *decreases* with the browsing of the Virtualized Supply Chain (see Figure 1 for an example of such a 5-bounded Virtualized Supply Chain), we now assume that such risk *increases* while we navigate through the Virtualized Supply Chain.

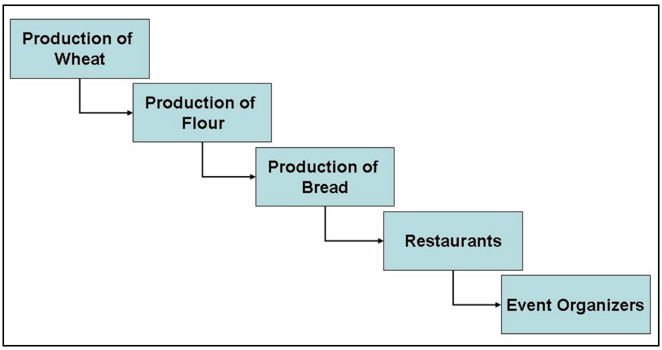


Fig. 1. Example of a virtualized supply chain

With the purpose of reducing the risks of the supply chains, we compare the results of applying three merger strategies to the Virtualized Supply Chains: *upstream vertical merger* (an example is depicted in Figure 2), *downstream vertical merger* (see Figure 3 for an illustrated example) and *conglomerate merger* (highlighted in Figure 4).

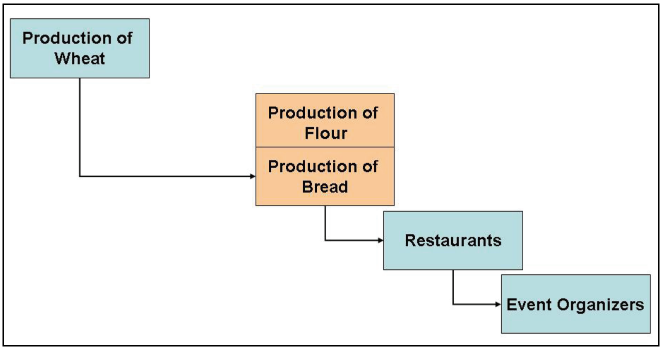


Fig. 2. Example of an upstream vertical merger

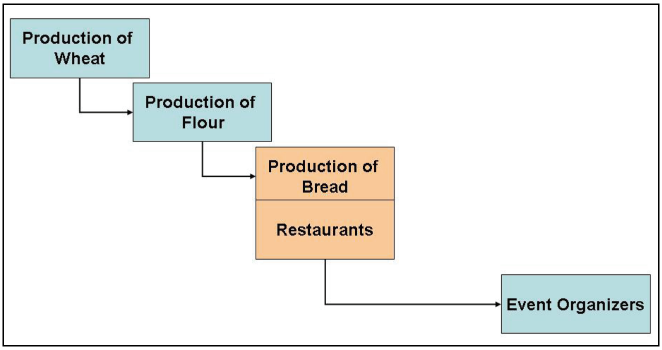


Fig. 3. Example of a downstream vertical merger

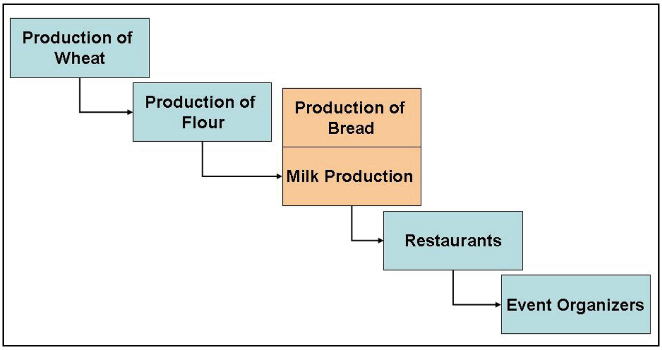


Fig. 4. Example of a conglomerate merger

The three mergers strategies and their induced changes to the supply chains are highlighted in the above-mentioned figures together with the initial unaltered Virtualized Supply Chain. The upstream vertical merger proposes a merger between the *Production of flour* and *Production of bread* business classes (we would suggest that a company whose business activity code is *Production of flour* should merge with a company whose activity code is *Production of bread*); the downstream vertical merger suggests a strategic action between the *Production of Bread* and *Restaurants* business classes, while the conglomerate merger strategy would suggest a merger between two different business classes that are neither upstream nor downstream vertical mergers (they are not closely related in the supply chain).

In contrast with our previous studies, in which we have applied only a risk-reduction technique similar to the conglomerate merger one (that consisted in replacing the high-risk business classes with medium-risk business classes, then replacing high- and medium-risk business classes with low-risk business classes), we now apply three different risk reduction strategies. The three strategies (upstream vertical mergers, downstream vertical mergers and conglomerate mergers) consist in replacing the business classes from the high-risk business classes with its upstream (respectively, downstream) lower business classes from the supply chain, together with replacing high-risk business classes with unrelated business classes (that are neither upstream, nor downstream close in the Virtualized Supply Chain – in the case of *conglomerate mergers*) which exhibit lower risks. In the next section of the chapter, we highlight the results of our experiments together with our findings regarding the risk reduction strategies in the Virtualized Supply Chains by applying the three different types of mergers as restructuring activities.

Although the risk reduction technique is similar with the one presented in (Hancu, 2008b), there are some differences in our current approach with respect to the one of our previous studies. The first and foremost difference relies from the computation of the risk associated with each Virtualized Supply Chain, thus having a significant impact on the final computation of the Global Risk of the VSC set.

We pointed out that in our previous approach we have used products for linking the previous risk of the business class with the current risk of the business class in the VSC. This conducts to the diminishing of the current risks of the business classes, as we navigate through the Supply Chain. As the algorithm of the unbounded VSC construction yields to longer Virtualized Supply Chains (formed by up to 251 business classes), and the dependencies probabilities less than 0.10, the risk soon becomes insignificant. Summing insignificant risks yields to the computation of a lower global risk, which was the case of our results from our past researches.

On the other part, the risk reduction algorithm functioned on a set of Virtualized Supply Chains which were almost zero, in the case of our previous approach. This implied that the risk reductions were made at the beginning of the Virtualized Supply Chain, where the risks were higher, thus contributing to a lowering of the overall Global Risk associated with the Virtualized Supply Chains set. In the subsequent section, we depict the results from our research and discuss our findings.

5. Applying restructuring strategies to supply chains

Our experiments are generated as follows. We compute the set of the Virtualized Supply Chains and then calculate the global risk of the VSC, which conducts to the computation of the list of High Business Class, Medium Business Class and Lower Business class. We later apply the conglomerate merger strategy by replacing high-risk business classes with medium and low risk business classes. In the subsequent step, we apply both strategies for Upstream and Downstream Vertical merger in the same time.

The upstream and downstream vertical mergers occur as follows: first, we identify a business class A and consider the classes $Prev_A$ and $Next_A$ (as the previous and next classes in the supply chain). If the risk of the business class $Prev_A$ is high and there is a dependency probability between the previous class (the Upstream Business class) of $Prev_A$ and A, we can apply the *Upstream Vertical Merger* to $Prev_A$ and A. If the risk of the business class $Next_A$ is high and there is a dependency probability between the A and the subsequent class (the Downstream Business class) of $Next_A$, then we can apply the *Downstream Vertical Merger* to $Prev_A$ and A. In the case we can apply both Upstream and Downstream Vertical mergers at the same business class *A*, we construct the two new supply chains, for each of the applied strategies.

The reason for applying both upstream and downstream vertical mergers during the same experiments is the following: a downstream vertical merger at the *n*-th step in the VSC would be equivalent with an upstream vertical merger at the *n+1*-th step. Processing *Upstream* and *Downstream* experiments in two different steps would imply that some of the *upstream* mergers in the first experiment would be equivalent to the *downstream* mergers in the second experiment.

We repeat the same mergers-based risk reduction strategies for both unbounded Virtualized Supply Chains and Bounded Virtualized Supply Chain with threshold above or equal to 5. The Unbounded Virtualized Supply Chain construction computes the maximal length of a VSC as 255.

The results are highlighted in the following figures. In the Figure 5, we depict the whole experiments: no risk management strategy, conglomerate merger, upstream (upward) vertical merger and downstream (downward) vertical merger. We notice a different trend of the Conglomerate risk management strategy with respect with the other management strategies, which follow the same pattern.

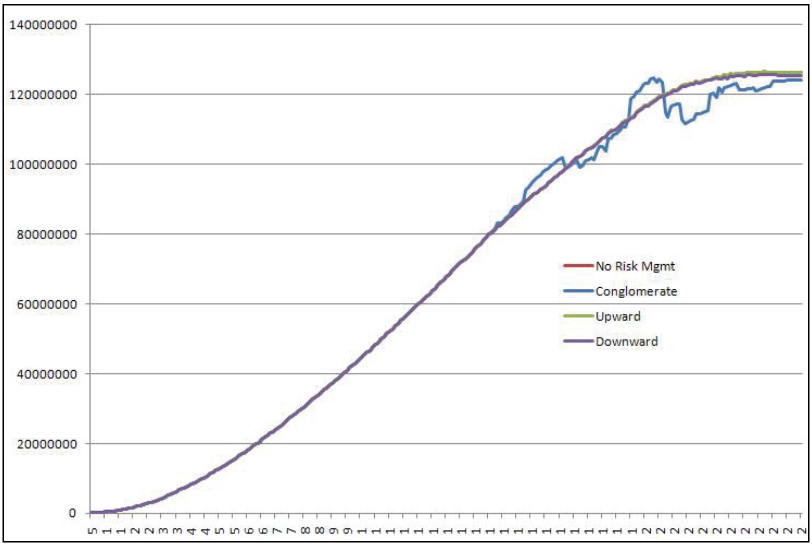


Fig. 5. Risks for 5-bounded VSCs to unbounded VSCs

In the Figure 6 and Figure 7 we depict the experiments from the bounded Virtualized Supply Chains, with the aim of revealing the differences between the risk management strategies. The shapes reveal that there is not a significant difference between the *no risk management* and upward vertical merger, while Conglomerate merger is the best risk management strategy for VSC starting the 207 threshold.

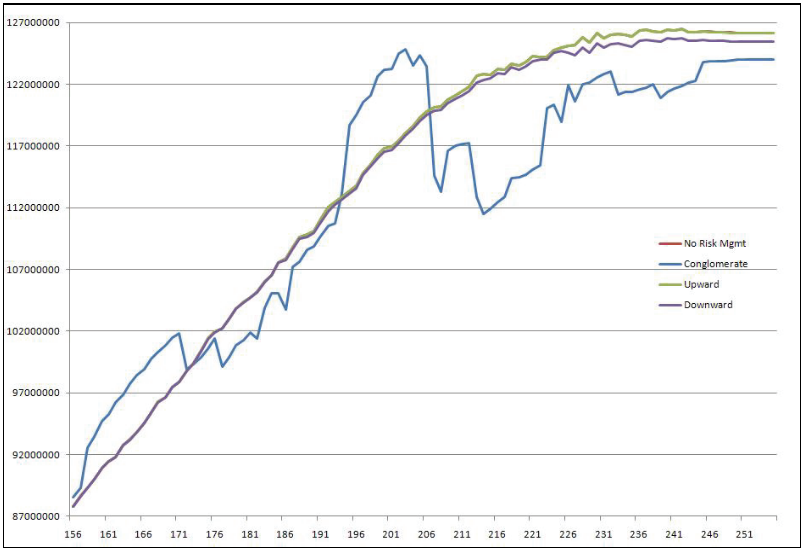


Fig. 6. Risks for 156-bounded VSCs to unbounded VSCs

Fig. 7. Risks for 227-bounded VSCs to unbounded VSCs

A more thorough analysis is done in the Figure 8 and Figure 9, where we depict the difference between *Conglomerate* and *Downwards Vertical* merger and between *No risk management* and *Upwards Vertical* merger. The analysis points out that the upwards risk management is better than applying no risk management, while conglomerate mergers are better suited for reducing risks than downstream vertical mergers.

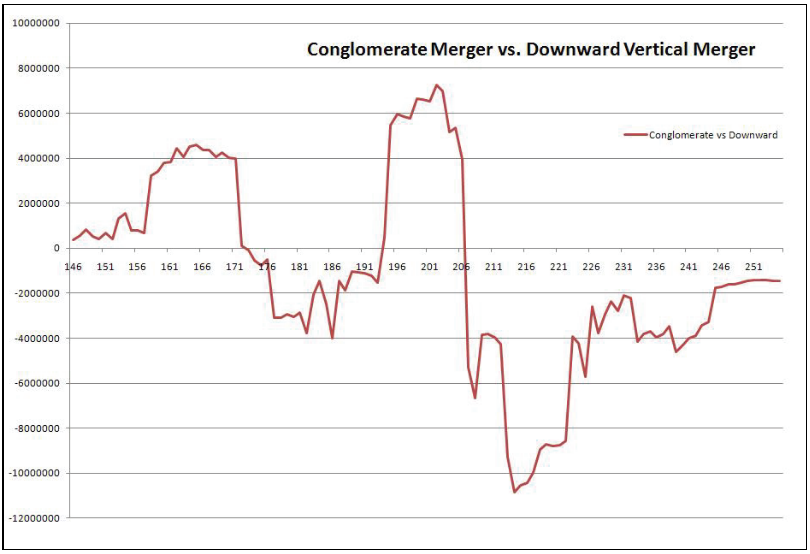


Fig. 8. Conglomerate compared to downward vertical merger risks

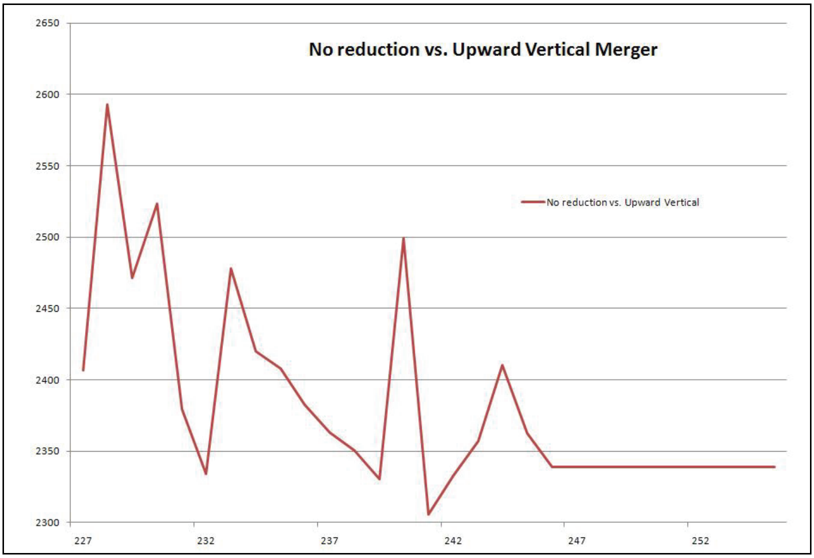


Fig. 9. No reductions compared to upward vertical merger risks

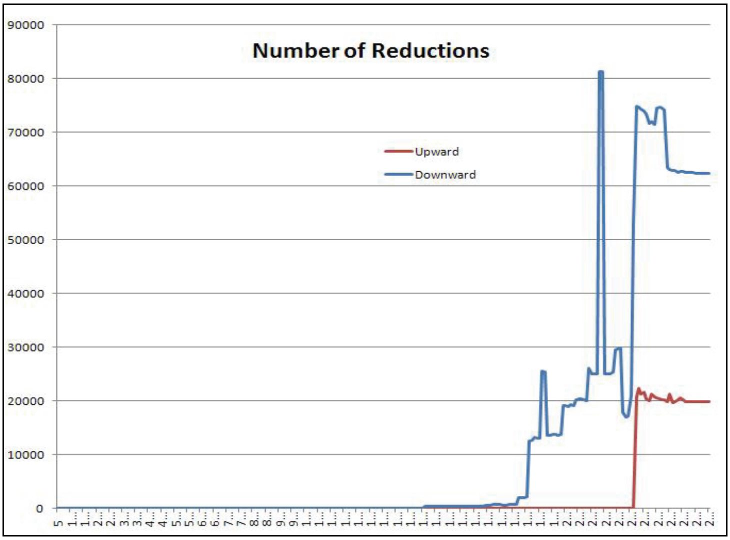


Fig. 10. Number of reductions for upward and downward vertical mergers

In the Figure 10, we have depicted the number of reductions from Upward and Downward vertical mergers, with the sole detail that the number of upwards vertical mergers reductions is multiplied by 100, as to appear in the Figure. The figure highlights that there is a threshold above which the risk reductions appear. We denote as risk reduction a replacement of a higher-risk business class by a lower-risk business class, by one of the strategies pointed out above. The threshold is lower for Downward business classes with comparison with the upwards business classes and the number of risk reduction is also significantly higher. This conducts to the fact that the downstream vertical merger is better suited for risk management than the upstream vertical merger. Obtaining more risk reductions for *downstream vertical mergers* and a lower threshold for the beginning of risk reductions are the causes for which downstream vertical mergers are less risky than the other ones, according to our risk computation algorithm.

As highlighted in the Figure 10, there are VSC for which there are no reductions, which yields to the computation of the same global risk of the VSC set in the case of no-risk-reduction, upwards and downwards vertical mergers.

An interesting fact appears as we compute the global risks for the conglomerate mergers risk reduction strategy. The Figures 5, 6, and 8 reveal that there are VSC sets for which the global risk is higher in the case of applying the conglomerate strategies than in the other strategies, while for VSCs starting the 207 threshold, the conglomerate merger is best suited for reducing risks (see also the excerpts depicted in the Table 1).

The results from our approach significantly differ from the ones depicted during our past researches, as we have introduced a slightly different method in the computation of the global risk of the VSC set and the risks of all of its associated business classes. Instead of multiplying the current dependency probability with the previous risk, we sum the current dependency probability with the previous risk. This yields to higher global risks associated with the business classes, while the reductions of the risks is lower, as compared with the results from our previous experiments highlighted in (Hancu, 2008b).

Threshold	No risk mgmt	Conglomerate	Upstream	Downstream
207	120126931,1	114579004	120126931,1	119865803,9
208	120224021,6	113318490,3	120224021,6	119964766,8
209	120784228,6	116613522,8	120784228,6	120462697,3
210	121135881,3	117000408,7	121135881,3	120829932,6
211	121432329,5	117164522,5	121432329,5	121125697,1
212	121771115,3	117206781,3	121771115,3	121464914,7
213	122679136,7	112904153,1	122679136,7	122171811,2
214	122836452,1	111465331,5	122836452,1	122327477,7
215	122778063,5	111939860,8	122778063,5	122468845,7
216	123229506,3	112486049,9	123229506,3	122919765

Table 1. Global Risk score (excerpts)

The insights derived from our research reveal that the downward vertical mergers are less risky than the upward vertical ones, and conglomerate mergers are the less risky approach in the Virtualized Supply Chains that are above the 207 threshold. We explain our findings as follows: merging with a distributor is less risky than merging with a supplier. While the supplier might increase its prices and alter our profitability by unexpectedly increasing production costs, the distributor's pressure (or power of negotiation) should be significantly lower. In addition, the supplier could have an increased position on the market, which could limit our options of substituting him with one of its competitors. In contrast, the distributor's powers should be lower, as we could always choose an increased number of smaller distributors instead of a larger one, thus this larger distributor would not obtain a significant negotiation power.

On the other part, a conglomerate merger should increase product diversification and that would imply lower risks. For instance, a conglomerate between an aluminium smelter and a steel producer would not be as affected by the increase of the bauxite price as a sole aluminium smelter alone. There are also cases in which the risk associated with the conglomerate merger is greater than the one in the case of no-risk management strategy or the vertical mergers cases. In the Figure 8, we depict the situations in which the global risk is greater in the case of conglomerate mergers compared to the case of downstream vertical ones. In fact, conglomerate mergers would have a greater difficulty of integration, which would increase the risks of mergers failure (as studied in Cartwright).

6. Conclusion

The technique described in the chapter serves at highlighting the strategic action better suited for reducing the risks in the supply chains. Studying the implications of the supply chain modeling based on the strategic actions like the ones of mergers and acquisitions can improve the quality of mergers suggestions, by highlighting the positive aspects (such as cost reduction as a result of economies of scale) but also the negative aspects (a possible increase in the supply chain's risk) of such a suggested merger.

The results from our studies can be further developed by varying on the construction of the Virtualized Supply Chains set, which should reveal interesting facts on the proposed risk management strategies by applying restructuring activities. The current approach starts with the construction of the VSC from a given business class and it appends business classes

to the end of the Virtualized Supply Chain until no more supply chains can be appended. In the case of the bounded supply chain, the process stops when the length of the supply chain reaches the threshold. This approach conducts to the computation of the same number of Virtualized Supply Chains in the case of the *unbounded* VSC experiments and *bounded* VSC experiments, as the *bounded* VSCs are sub-Virtualized Supply Chains of the *unbounded* VSC. A different approach would consists in dividing an *n*-bounded supply chain of the form $Class_1$, $Class_2$, …, $Class_{n-1}$, $Class_n$ in two *n-1*-bounded VSCs: $Class_1$, $Class_2$, …, $Class_{n-1}$ and $Class_2$, …, $Class_{n-1}$, $Class_n$.
Examining which merger strategy is better suited for reducing the risks in the Virtualized Supply Chains set constitutes an intermediary step in further developing more advanced techniques for suggesting mergers between two or more business entities.

7. Acknowledgment

This work has been supported by CNCSIS-UEFISCSU, under the Project no. 397/2010 "Collaborative Methods for Improving Merger Decisions Support (MECIDEF)".

8. References

Bruner, R. F., (2004), Applied Mergers and Acquisitions, *John Wiley and Sons*, pg. 141.

Cartwright, S., Why Mergers Fail and How To Prevent it, *QFinance*, http://www.qfinance.com/mergers-and-acquisitions-best-practice/why-mergers-fail-and-how-to-prevent-it?full, accessed on 25/03/2011.

DePamphilis, D., (2009), Mergers, Acquisitions and Other Restructuring Activities, *Academic Press*, pp. 224-225.

Fuld, L. M., (2006), The Secret Language of Competitive Intelligence, *Crown Business*, pp. 226-227.

Hancu, L., (2008a). Data-Mining Techniques for Supporting Merging Decisions, *International Journal of Computers, Communications and Control*, Volume:3, Supplementary Issue: ICCCC 2008, pp. 322-326, Oradea, Romania.

Hancu, L., (2008b), Supply Chain Risk Management by Mining Business Dependencies, *Proceedings of the International Conference SYNASC*, September 2008, Timisoara, Romania.

Hancu, L., (2011), Creating Virtual Communities by Means of Swarm Intelligence, Broad Research in Artificial Intelligence and Neuroscience, Vol. 2, Number 1, pp. 38-43.

Harrigan, K.R., Vertical Integration and Corporate Strategy, *Academy of Management Journal*, Vol. 28, No. 2, pp. 397-425.

Huo, Y., Jiang., X., Jia, F., and Li, B. (2009), A Framework and Key Techniques for Supply Chain Integration, in Supply Chain – The Way to Flat Organization, Edited by Yanfang Huo and Fu Jia, *I-Tech Publishing*, Vienna, Austria.

Kiser, J., Cantrell, G., Six Steps to Managing Risk, *Supply Chain Management Review*, 10(3), pp. 12-17.

Meca, A., Timmer, J., (2008), Supply Chain Collaboration, in Supply Chain – Theory and Applications, Edited by Vedran Kordic, *I-Tech Education and Publishing*, Croatia, pp. 1-18.

Preda, G., (2009), Tornado: Merger with RHS brings us back on retail, *Business Standard*, July 24.

Sliwa, C., (2004), Wal-Mart Takes 'Tough Love' Approach with RFID Directive, *Computerworld*, January 19, 2004.