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Supply Chain Configuration

Concepts, Solutions, and Applications

Springer

SUPPLY CHAIN CONFIGURATION

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Dedication

To my parents and family
Charu Chandra

To my parents, Jānis and Inta, and my family
Jānis Grabis

Preface

By definition, a configurable (hence also reconfigurable) system can be redesigned and remodeled for specific applications for the new (or changed) environment, and upgraded rather than replaced. With a reconfigurable system, new products and processes can be introduced with considerably less expense and ramp-up time. Reconfiguration efficiency attributed to such systems can be achieved only by means of intelligent decision-making (i.e., use of system synthesis, analysis, and simulation). The supply chain for this system must also be configured, aided, and supported by information systems that enable all supply chain members to learn about these changes expeditiously and adjust their processes accordingly.

Supply chain management deals with complex interactions among supply chain members and decision-making problems. Whether to establish a supply chain configuration or reconfigure an existing supply chain is one of the major decisions to be made. The configuration defines the operating basis of the supply chain. Other managerial decisions are made using the elaborated configuration as input. Therefore, configuration decisions are subjected to particularly comprehensive evaluation, which, in turn, requires utilization of a variety of models and tools. This book aims to cover these models and tools with particular emphasis on model integration and combination.

The supply chain configuration problem in this book is perceived as determining which units (e.g., suppliers, plants) to include in the supply chain, their size and location, and establishing links among the units. In the wider sense, the configuration problem may also include designing and modifying supply chain control structures, information systems, and organizational structures. Such a focused approach allows for thorough coverage of problems, issues, and solutions such as configuration under demand uncertainty, impact of the supply chain power structure, and hybrid modeling.

Explicit focus on the configuration problem, in-depth coverage of configuration models, emphasis on model integration, and application of information modeling techniques in decision-making are distinguishing characteristics of this book.

The primary objectives of this book are to

- Establish a focused scope definition of the supply chain configuration problem
- Develop a supply chain configuration framework supporting development of configuration models for specific cases
- Discuss models and tools available for solving configuration problems
- Emphasize the value of model integration to obtain comprehensive and robust configuration decisions
- Propose solutions for supply chain configuration in the presence of stochastic and dynamic factors
- Illustrate application of the techniques discussed in applied studies

Book Organization

This book is divided into three parts, which are devoted to:

- Defining the supply chain configuration problem and identifying key issues
- Describing solutions to various problems identified
- Discussing applied supply chain configuration problems

The contents of the book are organized in a fifteen chapters format as follows

Chapter 1. Configuration

This chapter describes general nature of configuration. It talks about configurable (reconfigurable) systems, their need, focus, motivation, properties (or characteristics), and general issues and problems faced by configurable systems. Basically, this chapter is intended as an introduction to the "nature of configuration" before delving into the more specific supply chain configuration systems.

Part I Supply Chain Configuration Problem and Issues

Chapter 2. Scope of Supply Chain Configuration Problem

Supply chain configuration is one of the principal supply chain management decisions. It has profound impact on other subsequent managerial decisions. This chapter aims to position supply chain configuration decisions as part of the overall supply chain management decision-making process and to define the scope of the configuration problem. The positioning is described by analyzing the typical sequence of decisions made in the supply chain environment: definition of strategic objectives • product selection • establishing the supply chain • strategic supply chain management • tactical supply chain management • operational supply chain management. The scope definition describes objectives of supply chain configuration, questions being answered, and parameters and costs involved. Alignment of configuration objectives with strategic objectives of enterprises involved in a supply chain, and the supply chain as a whole, is also analyzed.

Chapter 3. Literature Review

The supply chain configuration has been widely studied by both academicians and practitioners. This chapter aims to review these studies and to identify common characteristics of the supply chain configuration problem. The existing research is categorized according to data used in decision-making and several criteria characterizing the decision-making problem and its environment. These criteria include the modeling approach used, application area, problem size, and others. Results of the literature review are used in defining focus areas of remaining chapters in the book.

Chapter 4. Reconfigurable Supply Chains: An Integrated Framework

The purpose of this chapter is to describe "reconfigurable supply chains," their need, and their advantages. Then, we lay out an integrated framework for their implementation that maps problems and issues with suggested methods and techniques (either published in the literature or those laid out in later chapters). Basically, it lays the foundation for methodology in Chapter 5 and solutions described in Part II of the book.

Chapter 5. Methodology for Supply Chain Configuration

Supply chain configuration is a multiple-step process. This chapter identifies methodological steps involved in this process and provides guidelines for accomplishing these steps.

Part II Solutions

Chapter 6. Knowledge Management as Basis of Crosscutting Problem Solving Approaches

The importance of this chapter is to highlight that solutions to supply chain configuration problems must integrate complex modeling and analysis techniques drawn from a host of disciplines, such as Systems Science, Management Science, Decision Sciences, Operations Research, Systems

Engineering, Industrial Engineering, and Information Systems. A proper knowledge management support to decision-making is required to handle such a cross-sectional approach. Taxonomical and ontological approaches to knowledge management are described.

Chapter 7. Information Modeling Approaches

Information modeling is used to gain understating about a decision-making problem, to formalize the decision-making problem, and to prepare input data for quantitative modeling. Process modeling is used to gain understanding of a decision modeling problem by describing entities involved and their interactions. Data modeling is used to describe decision variables, parameters, and constraints. Application of the Unified Modeling Language (UML) and the Supply Chain Operations Reference (SCOR) model for information modeling purposes is described.

Chapter 8. Mathematical Programming Approaches

Mathematical programming is the most prominent tool used in supply chain configuration, specifically for establishing the supply chain network, because of its ability to deal with spatial issues effectively. This chapter presents the generic mixed integer-programming model used in configuration. Application of this model, computational issues, and modifications of the generic model are also discussed. This chapter also briefly discusses non-linear, dynamic, and stochastic programming formulations of the configuration problem.

Chapter 9. Simulation Modeling Approaches

Simulation models are used in evaluating supply chain configuration decisions because of their ability to represent the problem realistically and to capture a wide range of factors. They can also be applied to select the most appropriate configuration from a limited set of alternative configurations. This chapter describes the characteristic features of simulation models used in supply chain configuration. Issues of validation of simulation models in the context of supply chain configuration are raised. An approach for automated model building in the framework of integrated decision-modeling is discussed.

Chapter 10. Hybrid Approaches

Both mathematical programming models and simulation models have their advantages and disadvantages. The hybrid modeling that combines optimization and simulation aims to inherit advantages and to avoid disadvantages. Application of hybrid modeling in supply chain configuration is described. Two important hybrid modeling approaches are described: a) optimization and simulation models are used sequentially, where optimization is used to establish the configuration and simulation used for comprehensive evaluation of this configuration; and b) simulation-based optimization procedures, where the optimization model receives input data from the simulation model at each iteration. An automated approach to building hybrid models on the basis of common data models is presented.

Chapter 11. Information Technology Support for Configuration Problem Solving

Information Technology (IT) has a major impact on supply chain configuration. IT services are used to find the most appropriate supply chain configuration (decision support) as well as to ensure operations of the established configuration (infrastructural support). The decision support side is implemented on the basis of the supply chain configuration data model. Use of data warehousing technologies is explored. Alternative approaches used by major vendors of supply chain configuration tools are also described. Connections between supply chain configuration tools and geographical information systems are discussed. Supply chain management information systems are used to process transactions in the established supply chain. Different architectures of these systems are discussed, including architectures based on monolithic Enterprise Resource Planning (ERP) systems for supply chains, with one dominant member and truly distributed systems that are integrated using middleware technologies for supply chains with independent members. Interactions between configuration decisions and infrastructural support are discussed.

Part III Applications

Chapter 12. Review of Applied Studies

This chapter reviews significant applied studies reported in literature. Issues arising during adoption of configuration decisions in practical situations are discussed.

Chapter 13. Applications in Automotive Industry

The complexity and importance of supply chain configuration are high in the automotive industry. Supplier consolidation, manufacturing flexibility, and modular assembly are major factors influencing configuration decisions. This chapter discusses the impact of these factors on the configuration decision-making process. Specific cases on information modeling, and configuration of flexible supply chains under demand uncertainty are analyzed.

Chapter 14. Application in Retail: Locating a Distribution Center

The retail industry heavily depends upon efficiency of supply chain management. The magnitude of configuration problems and adoption of modern technologies are characteristically common to this industry. A case study of a European retail operation is used as the basis for describing location decisions in a complex supply chain.

Chapter 15. Future Research Directions in Supply Chain Configuration Problem

A concluding chapter, which lays out the agenda of future research directions for the field as seen by the authors, is presented.

Target Audience

The book is targeted to a broad range of professionals involved in supply chain management. It is modularly structured to appeal to audiences seeking a discussion of theoretical and qualitative supply chain configuration problems or a description of more technical quantitative and computational problems, as well as those interested in applied supply chain configuration problems.

The main target group is graduate students in industrial engineering, systems engineering, management science, decision analysis, logistics management, operations management and applied operations research, and practitioners and researchers working in fields of supply chain management and operations management who aim to combine mathematical aspects of problem solving with the use of modern information technology solutions.

Professional/technical readers. This category includes research directors, research associates, and institutions involved in both the design and implementation of logistics systems in manufacturing and service-related projects. Examples will include the National Center for Manufacturing Sciences and the Southwest Research Institute.

Managers, product and process engineers, logistics coordinators, and production planners within the product design, manufacturing, and logistics departments of various companies will also find the book a useful resource.

Academic readers. Professors and research associates within universities and colleges in industrial engineering, manufacturing engineering, mechanical engineering, automotive engineering and engineering management, management science, and production and operations management, will find the book interesting to read.

This book may be used for teaching in graduate and professional development courses. It is also a valuable reference material for research in the area of supply chain management, logistics management, and operations management. The professional societies interested in these areas are:

- Institute of Industrial Engineers (IIE)
- Society of Manufacturing Engineers (SME)
- Institute of Electrical and Electronics Engineers (IEEE)
- INFORMS and Engineering Management Society
- Production and Operation Management Society (POM)
- Decision Sciences Institute (DSI)
- American Production and Inventory Control Society (APICS)

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Contents

Part I Supply Chain Configuration Problem and Issues

1. Configuration

1.1 What is Configuration?

Modern organizations operate in a continuously changing environment influenced by economic, political, and technological developments. These dynamics of change have presented business enterprises with unprecedented opportunities and challenges in their quest for finding new ways to compete. Firms are beginning to move from operating on a regional or national to a global scale. They are increasingly replacing the traditional hierarchical organizational structure with centralized control to a flexible, decentralized set-up with varying degrees of autonomy. They are striving to offer customized products in specialized markets to stay competitive. The ability to quickly adapt to changes, such as with time-to-market products, as well as incorporate institutional reforms will be the key to survival for firms.

In this environment, products are reaching a large consumer population across different market segments with expectations of high quality, low cost, and large product variety. This is resulting in increased complexity in all phases of the product life cycle, as well as rapid turnaround of products. With shorter life cycles than before, the need for product innovation has never been greater. One of the primary means employed by firms to achieve innovation is *configuration*, defined as follows:

> "Configuration is an arrangement of *parts* or elements that gives the *whole* its inherent form."[1]

This definition points to the fact that configuration is achieved through a calibrated perturbation of *system* elements aimed at meeting a revised set of functional requirements and objective(s) for the product, as the core of its existence.

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[1] Merriam-Webster Dictionary and Online Thesaurus.

In this book, we present and explain concepts, solutions, and applications that are important for the effective configuration of the supply chain. The supply chain, which is also referred to as the logistics network, represents an integrated system. It consists of; (a) *entities,* such as suppliers, manufacturers, warehouses, distributors, and retailers, and (b) their *relationships* as they manage the flow of materials in the form of raw materials, work-in-process, and finished goods inventories. To optimize the performance of this system, it is essential to configure it based on the changing dynamics of supply and demand in the market. Before we look into various aspects related to configuration of the supply chain throughout the book, let us first define a configurable system, such as the supply chain and why it is needed, and some of the key issues in managing a configurable system.

1.2 What is a Configurable System?

In defining configuration, the relationship between the whole-part components describes a system in its most basic representation. Because configuration changes the form of the whole, it can be described as a manifestation of a system at any given state relative to its original state at the time of conceptualization. Configuration affects a system's functions, either marginally or completely altering its form. Usually, the basis of configuration is the desire to upgrade or improve the functionality of the system. A system that embodies these dynamic properties is a *configurable* system. We propose a configurable system approach that integrates a system's components from concept to feasible solution. These are

> *System and system design concepts → system of systems → sources of configuration (product-process-resource) → sources of configuration (public policies) → configuration problems → configuration models → configuration solutions*

We describe these elements next.

1.2.1 System and System Design Concepts

A configurable system, as a class of system, follows a general system's main traits but has its own unique features. It is based upon the following three main principles:

- Principle 1 – A configurable system is based upon a *whole-part* relationship
- Principle 2 – A configurable system encapsulates interdisciplinary knowledge
- Principle 3 – The General Systems Theory (GST) influences the design of a configurable system

Whole-Part Relationship.

A general system stands for a set of things (or entities) and the relationship among these things. Formally, we had *S = (T, R)*, where *S,T,R* denoted a system *S*, a set of things *T* distinguished within a domain *S*, and relation (or relations) *R* defined on *T*, respectively. Thing (T) consists of seven components: $T = (I, O, E, A, F, M, P)$, which are input, output, environment, agent, function, mechanism, and process, respectively. These components of a generic system are described below in Table 1.1 (Nadler 1970):

Table 1.1 System Components

System Component	Examples
Input	Physical item, information, or service that is necessary to start processes.
Output	Physical item, information, or service that results from processing of input. The output is related to the total accomplishment of the function.
Environment	Physical or sociological factors within which system elements operate. It relates to resource requirements, both physical and human.
Agent	Computational or human resources for carrying process.
Function	Mission, aim, purpose, or primary concern of the system.
Mechanism	Physical or logical facilitators in the generation of an output.
Process	Flows, transformations, conversions, or order of steps that transforms an input into an output.

Formally, the system (whole) may be defined as an assemblage of subsystems (parts), and agents and mechanisms (people, technology, and resources) designed to perform a set of tasks to satisfy specified functional requirements and constraints. In a configurable system, *parts* may define its physical, logical, and virtual systems. For example, these may represent the manufacturing, logistics, and Internet (or eCommerce) systems (or subsystems), respectively. For a configurable system the *whole* gives it form, structure, organization, and arrangement, etc.

Relationships are defined among system components and can be both internal among system elements (identified in Table 1.1) and external with the system's environment. The level of control exerted on the system (i.e., at the strategic, tactical, and operational levels) also defines relationships.

Systems give organization a formal structure, a purpose, a goal (objective), and above all a basis for integration. Such a structure is beneficial for an organization in managing its complexity, integration of its functions, and aligning its product-process-resource structure. System also provides the framework that an organization needs for designing and implementing models, methodologies, tools, and techniques for aligning its business (es) and improving productivity.

In the light of the above explanations, it can be construed that a configurable system is a specialist system, which combines to yield a *system-of-systems* that performs the function of an integrated system for the entire product-life-cycle – i.e., from concept generation to its maturity.

Interdisciplinary Knowledge

Ludwig von Bertalanffy formulated a new discipline, General System Theory (GST) (Von Bertalanffy 1968, 1975), and defined its subject matter as "formulation and derivation of those principles which are valid for systems in general whatever the nature of the component elements and the relations or forces between them." GST enunciated the principle of unification of science, and its essence was inter-disciplinarity. It produced a new type of scientific knowledge – interdisciplinary knowledge. According to Bertalanffy, there is some element of isomorphism (state of similarity) that allows extension of one scientific discipline to other sciences. Thus, in complex systems such as the configurable system, we see the design of knowledge at a high level or generic level, and low level or the domain level. These are, therefore, labeled as general knowledge and domain (specific or expert) knowledge.

Influence of GST on System Design

The biggest influence that GST has had on system design is in its formalization. For example, a system is designed to recognize its whole-part relationship instantiated in its environment (both internal and external).

The concept of isomorphism has facilitated system design by recognizing similarity (or commonness) across entities, relationships, and environmental variables. Similarity implicitly recognizes relationships, thereby improving a system's representation and eventually impacting its performance (quality, reliability, etc.).

Another useful feature of GST in system design is separating information needs (and associated knowledge) at the domain independent (or generic) level from that of domain dependent (or specific/problem) level. Such an approach ensures that the system captures both breadth and depth of knowledge. Because the latter is embedded in the former, the captured knowledge has a larger context, thereby ensuring interactions and thus larger relevance. It also ensures that the knowledge does not become redundant. In Table 1.2, we provide a brief explanation of various design principles that play a part in the overall design of a configurable system.

Table 1.2 Key Design Principles for Configurable System Design

Design Principle	Explanation
Unity	All systems (and their components) are whole (unity) depending on the context in which they are represented.
Commonality	All systems in the universe of systems share common universal characteristics.
Isomorphism	Similarity (and therefore commonality) among system components and associated relationships.
Reuse	Commonality leads to reuse and eventually standardization, conformity, and reliability.
Abstraction	Enables managing complexity by abstracting features of system's components. It also allows representation of relationships, such as whole-part and generalization-specialization.
Polymorphism	Creates classes of systems and reuses them for specialized functions.
Encapsulation	Enables encapsulating knowledge and information-hiding on objects (and classes) to create uniqueness of objects (and classes).
Independence	Domain independent vs. domain dependent knowledge creation.
Inheritance	Enables the avoiding of information redundancy and information-hiding by clustering information representation where they rightfully belong.

1.2.2 Sources of Configuration

As the definition of configuration given in the earlier section suggested, it affects a system's characteristics, such as form, structure, organization, and arrangement. The system's product, process, and resource dimensions mainly represent the sources of these characteristics. We discuss these next.

- *Product-related configuration* is usually implemented as a result of implementation of strategies that make

  - Changes in product characteristics, such as adding more variety due to changes in newer models, colors, additional user-friendly features, etc.
  - Changes in product specifications as a result of either new or enhanced functional requirements due to customer needs, performance standards, process changes, and service criteria
  - Changes in product structure as a result of changes in product design for manufacture, assembly, delivery, new processes, and technology employed for product development
- *Process-related configuration* is implemented as a result of improved or enhanced process technology that enables the enterprise to achieve agility and flexibility in their manufacturing operations, as well as integrate various processes. It enables the achievement of modularity in product development and the acquisition of specialization.
- *Resource-related configuration* is implemented in response to the requirement of specialized, knowledge-intensive resources by the enterprise as it adopts newer advanced technologies to improve its performance.
- *Organization-related configuration* is implemented to meet the need for enhancing organization controls as the decision-making process is carried out in an enterprise. Such a situation arises as decentralized, semiautonomous, or autonomous decision-making is introduced to improve the quality and speed of decision-making.
- *Service-related configuration* is implemented with a view to improving and maintaining both prior- and post- product delivery service in a customer-centric environment.
- *Competitive strategie-related configuration* is implemented as a result of strategy adoption, such as off-shoring, outsourcing, mass customization, time-to-market, and globalization that have the potential of offering a competitive advantage to an enterprise.
- Others
  - *Change in lead-time*. Product development can potentially be highly integrated and, as such, any change in lead-time for any product component will involve reconfiguring the system to account for its impact.
  - *Change in pricing*. This may impact sales contracts and revenue-sharing contracts among the enterprise partners due to a potential change in product sales volume or its market share.
  - *Change in location* on either production or delivery for any component of the product-life-cycle will be cause for re-evaluation, and hence configuration of the system. It will particularly affect

production and logistics activities because these involve movement of goods and associated transportation activities.

- *Change in supplier selection* either to add or remove a supplier must be accounted for in the product development process. Such a decision may have major impact on product quality, product development, production scheduling, etc.
- *Change in product or process cost* may occur due to changes in the cost of procuring raw materials and other technologies required in the delivery of products.
- *Change in contracts.* Revenue sharing, cost sharing, technology sharing, and resource-sharing arrangements are entered into between enterprise and its business partners.

1.2.3 Impact of Public Policies on Configuration

Many of the social, economic, political, environmental, and technological developments of our times are driving configuration in systems. Public policies enunciated by governmental and non-governmental organizations and industry, which monitor or regulate industrial and business practices, are one of the primary means of implementing suitable changes or reforms. Among some of the significant policy issues with major impact on business practices, and consequently on configuration of systems, are

- *Energy conservation.* Consumption of natural fuel in automobiles, for industrial production, household appliances, and utilities
- *Health care reforms* and their impact on total business costs
- *Social security* entitlements for seniors and their impact on national economy
- *Water and natural resource management*, especially due to increasing consumption by the rising global population
- *Biotechnology* and its impact on problems in business, engineering, and medical sciences
- *Nanotechnology* for unique applications to major problems in engineering, science, and medicine

Public policies are capable of having major impacts at national, regional, and local levels and, as such, solutions designed for these problems must recognize both global and local implications. Accordingly, the factors considered for evaluation in models designed for problem solving are chosen carefully and deliberately.

1.2.4 Configuration Problems

There are two types of problems that are encountered in a configurable system.

At the *macro* level, the whole system is considered and decisions concerning all entities involved are made. Generally, strategic decision-making problems are addressed at this level. Examples of such problems include the following:

- How much to invest in new or existing plants and at what locations?
- Which products to include or exclude in the existing product portfolio?

At the *micro* level, issues concerning implementation of the macro level decisions are addressed. Examples of such problems are

- How much plant capacity should be allocated to a particular product?
- Which product(s) are to be scheduled for production on a given machine?

The problem of coordination and synchronization of activities and resource utilization occurs at all levels of implementation in an enterprise. A common problem encountered is that of *information sharing* among various members/partners in an enterprise. This often leads to either under- or mis-utilization of resources and impacts scarce resources such as capacity and inventory.

1.2.5 Configuration models

Similar to configuration problems, configuration models may also be classified into two types.

Macro model. It describes behavior of the whole system with emphasis on strategic decision-making. Models used are characterized by higher level of abstraction and generality.

Micro model. At this level, the models are designed to investigate behavior of individual entities involved in the system. These models are domain dependent and are designed to solve specific problems.

A third type of model, a *coordination model,* is usually designed to coordinate the interactions between macro- and micro-evel models. This is typically by way of arriving at solutions that meet the objectives of the two types of models.

1.2.6 Configuration Solutions

Configuration solutions designed for solving configuration problems are closely aligned to the configuration models. Examples of some of these solutions are

- *Configuration network optimization* that is aimed at maximizing the revenue flow throughout the network
- *Global optimization* that attempts to optimize both functional and interorganizational objectives
- *System integration* through collaborative planning among various enterprise partners
- *Customer value* for service level maximization through statistical planning and control, and total quality management techniques
- *Information technology and decision support systems*. Implementing enterprise resource planning decision support systems for collaborative planning throughout the enterprise.

These and other solution techniques will be discussed throughout this book.

1.3 Why is a Configurable System Needed?

The motivation for developing configurable systems is the desire to use advanced systems for complex problem solving that can be designed, modeled, and configured according to specifications suitable for specific applications – flexibly and with agility, and upgraded and reconfigured rather than replaced. With a reconfigurable system, new products and processes can supposedly be introduced with considerably less expense and ramp-up time.

The emphasis of configuration is purely on *focused changes* to the system, rather than its total redesign. The changes are caused by many of the sources of configuration and policies described in the previous section. The notion of focused changes is based on incremental or additive design, which implies that a design may not be done from scratch. Instead, an existing design case may be used as the basis with the proviso of refinement/revision for the final designed product.

1.4 Examples and Applications of Configuration

The concept of configuration has been widely applied across many fields and in several different applications. In each case, however, as the definition of configuration given in Section 1.1 suggests, it symbolizes the notion of arrangement of parts (components or sub-systems) forming a whole (system). Implicit in this definition is the idea of integration towards a common purpose or objective. Below, we give examples from various disciplines where the concept of configuration has been applied successfully to improve/upgrade systems.

In *computer systems*, a configuration is deemed as an arrangement of functional units according to their characteristics. Often, configuration refers to the choice of hardware or software, or combination of both. For instance, a configuration for a personal computer consists of 512 megabytes main memory, a floppy drive, a hard disk, a modem, a CD-ROM drive, a LCD monitor, and the operating system, among other components. Many software products require that the computer have a certain minimum configuration. For example, the software may require a graphics display monitor and a video adapter, a specific microprocessor, and a minimum amount of main memory. Similarly, when a new device or program is installed, it sometimes needs to be configured, which means setting up various switches and jumpers (for hardware) and defining values of parameters (for software). For example, the device or program may need to know what type of video adapter is available and what type of printer is connected to the computer.

In the *building construction industry*, configuration refers to the structure and form of the building, such as a dome, apartment building, etc.

In many industrial applications, configuration refers to the change in physical layout. For example,

- *Airfield runway* layout and configuration refers to the maximum possible number of aircraft landing and takeoff due to the layout of the runway
- *Refinery plant and facilities*. Each petroleum refinery is uniquely configured to process specific raw material(s) into a desired line of products
- In *mathematics*, the concept of configuration space is utilized in defining the position of a single point in an *n*-dimensional plane
- In *mechanical engineering*, it is possible to tailor an engine configuration for a certain operation or operations
- In *chemistry*, molecules can be configured according to certain structural arrangements and properties

- In *atomic physics and quantum chemistry*, the electron configuration is the arrangement of electrons in an atom, molecules or other body
- In *logistics systems*, which span a supply chain, configuration refers to the choice of locations for either production or warehousing, or both, and how to organize raw materials and other goods inventory to support various echelons in the supply chain. Obviously, this is the primary topic of this book and a detailed discussion on supply chain configuration follows in the remainder of the chapters

1.5 Key Issues in Configuration

There are key issues encountered in developing configurable systems, and their impact is felt across all levels (i.e., strategic, tactical, and operational) of decision-making in an enterprise.

1.5.1 Coordination and Synchronization

In a configurable system, there is a high level of integration among its parts (or components). This integration is achieved through common strategies and policies, and objectives for the whole (system). In order to achieve it, a high degree of coordination and synchronization of plans and actions among the parts is required.

1.5.2 Conflicting Objectives

Various parts (components) that together define the whole (system) have their own objectives. As we configure them together, invariably these objectives become in conflict or work against each other. For example, the objective of minimizing costs in one sub-system may be at odds with maximizing product variety in another sub-system. It becomes quite important, therefore, to find a compromise between these conflicting objectives.

1.5.3 Complex Network

The structure and functioning of a configurable system may become highly complex, especially when the sub-systems (plants or facilities) are co-located and there is a high-level of interlinking among them (e.g., flow of materials or inventories occurs within the-plant or facility). Obviously, the question arises on the makeup of the structure so it will meet the stated objectives (of both parts and whole), which in this case may be shortest lead-time or least cost.

1.5.4 System Variation Over Time

A configurable system is a self adapting, dynamic system. As described earlier, this could happen due to changes in any of the system's components or controls exercised via various strategies or policies reflecting changes in the environment. For example, if the demand input to a production system is based on the point-of-sale data captured through various order entry outlets, the configured system would naturally integrate inputs and outputs from all related subsystems (i.e., forecasting, order management, inventory management, production planning, and shipping and warehousing).

1.5.5 Push-Pull Strategies

One of the ways business enterprises have remained competitive is by pushing change through turnover of products and their inventories so that when the consumer demands shifts, the system is nimble and agile enough to respond to changing circumstances. By adopting an approach to work on a push-pull strategy, they are able to postpone adoption of emerging changes to products and associated processes and / or resources in the product life cycle, as late as possible without adversely affecting the business. This is achieved by pushing the product in the product-life-cycle until such phase or time, that it could be easily pulled away, in order to reflect evolving changes resulting in a new product configuration.

1.5.6 Direct-to-Consumer

With the advent of the Internet and its creative uses in all aspects of the product-life-cycle, it is quite natural for enterprise systems to be configured to shorten the time required for a product to reach the ultimate consumer. This implies the elimination of echelon(s) throughout the product life cycle. Some noteworthy examples are through application of eCommerce techniques, the role of traditional middleman (such as a travel agent in the airlines industry, teller in the banking sector, order taker in consumer and mail-order catalog industries) is either being eliminated or becoming irrelevant and, therefore, unnecessary. The end result is that manufacturers or suppliers are reaching the end-consumer directly, thereby realizing savings in time and cost.

1.5.7 Strategic Alliance

As products are being designed to offer enhanced features, it is becoming apparent to firms that they do not have the capability to go it alone. They are, therefore, seeking strategic alliances by partnering with other firms who add value to the product, and help meet the targeted objectives. However, the resulting arrangement raises more questions, primarily related to synchronizing the plans, strategies, and objectives of alliance partners, as well as sharing the common benefits among them.

1.5.8 Mass Customization

One of the ways firms have attempted to differentiate their products to consumers is by offering customized products. This has been achieved by designing products that meet conflicting objectives of low cost, high quality and customer value, large variety, and shorter lead times. The challenge lies in how to, (a) configure various systems that support product life cycle to absorb variations in consumer demands, and (b) the resulting activities to support their fulfillment without causing a major disruption in the enterprise system.

1.5.9 Outsourcing and Procurement Strategies

As firms find innovative ways to compete, they have resorted to strategies that would bring down product costs and/or lead times. Outsourcing of components, business functions, and services are increasingly being used as a means to achieving these strategies. Such activities, however, lead to a major problem in coordination of ordering and receiving so that the product may be assembled or produced according to schedule.

1.5.10 Information Technology and Decision Support Systems

These have played an important role as enablers of various functions, as well as decision-making tools in the product life cycle. This is particularly true in the case of enterprise resource planning systems that firms have been using successfully to integrate actions and policies across functions and entities in an enterprise. The problem, however, arises whenever newer functions are introduced into the enterprise, especially when various parts or entities of the system are either not ready or incapable of integration due to various reasons, primarily lack of technological capabilities.

1.5.11 Customer Value

This should be measured in tangible or intangible terms. Intangible value can be measured by customer perception of the product in terms of usefulness, appeal, etc. Tangible value can be measured by price, after sales service, warranty, etc.

In the rest of the book, we describe various solution approaches and techniques to many of the above issues. These utilize models and algorithms drawn from operations research, statistics, simulation, and information sciences disciplines among others.

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2. Scope of Supply Chain Configuration Problem

2.1 Introduction

As firms position themselves to stay competitive, they face the challenge of transforming their operations from a static to a dynamic business environment. An obvious choice for transformation are supply chain operations because of their potential impact on almost every aspect of the business encompassing the extended enterprise. This is a complex undertaking because supply chain management entails managing the following under the umbrella of a common framework:

- Entity relationships, such as product, process, resource, organization, supplier, retailer, customer, etc.
- Flow of goods, services, cash, and information
- Objectives, strategies, and policies

Further, the framework is developed to account for risk and uncertainty caused by factors internal and external to the enterprise. Obviously, this requires reconfiguring the supply chain in order to keep pace with the changing environment.

In this chapter, we focus on studying the nature of the supply chain and its configuration in a dynamic business environment. We develop an understanding of the basis for a supply chain configuration problem, its classifications, and its various dimensions.

2.2 Supply Chain and Supply Chain Management

The management of a supply chain is a complex undertaking. It involves considering its unique system structure, dynamic design, hierarchical modeling needs, multi objectives, and the need for coordination of interactions among its entities. We discuss below how these elements can be brought together to make supply chain management effective.

2.2.1 A Systems Perspective on Supply Chains

Supply chain is a special class of system. Accordingly, it inherits all the general properties of a system. In addition, it has its own characteristics due to the special network structure. Next, we present a system perspective on supply chain.

Supply chain, and Supply Chain System

A supply chain is a network of suppliers, manufacturers, warehouses, distributors, and retailers who, through coordinated plans and activities, develop products by converting raw materials to finished goods inventory. In the process, they share materials, financials, and information flows between their facilities. In this arrangement, the supply chain network performs as a unit (whole) with various business entities (supplier, manufacturer, warehouse, distributor, and retailer) playing the role of its members (parts). The coordinated plans and activities define the relationships among these members according to which flows are shared based on a common objective. This definition leads to the observation that a supply chain is a *system*, as also explained in Sections 1.1 and 1.2 of the book.

We also assert that a supply chain is a *complex* system, as well as a system-of-systems, because it embeds other systems representing product, process, and organizational structures of an enterprise. In this regard, three system facets applied to the supply chain are depicted in Fig. 2.1, and elaborated below.

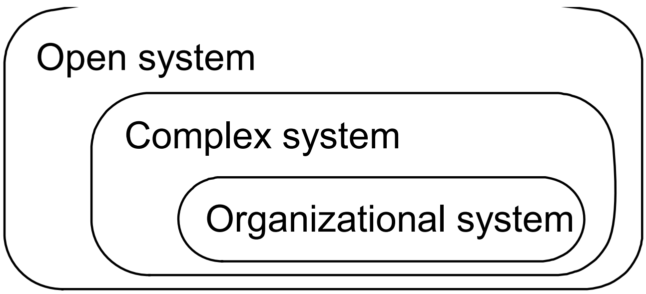

Fig. 2.1 General system facets applied to a supply chain.

From the system management perspective, a supply chain is viewed as an organizational system (Kast and Rosenzeig 1972), because a supply chain has managerial issues that can be classified into three levels − strategic, tactical, and operational (Simchi-Levi et al. 2003). As described in Table 2.1, long-range supply chain management issues need to be planned at the strategic level, in order to accommodate the varieties of policies and objectives across the supply chain network. At the tactical level, mid-range supply chain activities need to be planned and synchronized. At the operational level, day-to-day tasks and operations in the supply chain must be managed.

Table 2.1 Decision-Making Levels in Supply Chains

Decision-Making Level	Timeline	Type of Decision Made
Strategic	3 to 10 years	Investment on plants and capacities. Introduction of new products. Creation of a logistics network.
Tactical	3 months to 2 years	Inventory policies to use. Procurement policies to be implemented. Transportation strategies to be adopted.
Operational	Day-to-Day	Scheduling of resources. Routing of raw materials and finished products. Solicitation of bids and quotations.

A supply chain can also be characterized as a complex system (Agostinho and Teixeira 2003), which is defined as an organization of a large number of simple, mutually interacting parts (such as a supply chain's individual members) capable of sharing information among themselves, as well as with its environment, and adapting its internal structure as a consequence of such interactions. From the perspective of interaction with its environment, a supply chain can be considered an open system. To survive, a supply chain maintains steady state by continuous inflow and outflow from and to its environment, like biological organisms. Steady state implies that its system requirements are fixed for a specific period of time to make the system manageable.

As firms debate the adoption of the supply chain concept to manage their business operations in the extended enterprise, an obvious question arises as to what alternative forms of supply chain to implement − i.e., should it be product focused, or should customer focus be important? The answer lies in the fact that the type of supply chain to be implemented should be a function of both product characteristics and customer expectations. This is quite true, because adopting a supply chain that does not conform to the needs of the product and its customer is not justified (Fisher, 1997). We describe below two types of supply chains that meet this criteria (Vonderembse et al. 2006).

Lean Supply Chain

According to Vonderembse et al. (2006), "a lean supply chain employs continuous improvement efforts that focus on eliminating waste or non-value steps along the chain. It is supported by the reduction of setup times to allow for the economic production of small quantities; thereby achieving cost reduction, flexibility and internal responsiveness. It does not have the ability to mass customize and be adaptable easily to future market requirements." This type of supply chain is essentially based on the lean principles, which advocate the reengineering of business processes to remove all non-value added activity, generally ascribed as the source of waste in the system. Another significant feature of the lean technique applied in the lean supply chain is integration across functions of the enterprise. The accrued benefits are a high capacity utilization rate, shorter lead times, and minimization of total supply chain costs.

Agile Supply Chain

According to Vonderembse et al. (2006), "an agile supply chain profits by responding to rapidly changing, continually fragmenting global markets by being dynamic and context specific, aggressively changing, and growth oriented. They are driven by customer designed products and services." This type of supply chain is based on the principles of agility, which nurtures a production environment where products are adaptable to future changes in volume, variety, and lead times. In this environment, a high level of synchronization is desired with the result that members of the extended enterprise, such as the suppliers, also implement agility principles in their business operations.

Supply Chain Management

Supply Chain Management (SCM) involves various approaches utilized to effectively integrate suppliers, manufacturers, and distributors in performing the functions of procurement of materials, transformation of these materials into intermediate and finished products, and distribution of these products to customers in the right quantities, to the right locations, and at the right time to meet the required service level with minimal cost.

Supply chain management also involves managing a connected series of activities that is concerned with planning, coordinating, and controlling movement of materials, parts, and finished goods from the supplier to the customer. For this to occur, material, financial, and information flows are managed as decisions are made at strategic, tactical, and operational levels throughout the supply chain. Supply chain management issues span a large spectrum of a firm's activities at these levels (Simchi-Levi et al. 2003). Table 2.1 summarizes decisions made at these levels.

2.2.2 The Supply Chain as a Configurable System

A configurable supply chain is a system that efficiently adapts to its environment, offered in the form of supply and demand issues for the product(s) to be manufactured. A configurable supply chain is needed to manage logistics in a configurable system. This is because the adopted policies for product, process, and resource components of a configurable system have to be integrated with both inbound and outbound logistics decisions to realize benefits of flexible strategies. Some of the key triggers for designing and implementing a configurable supply chain are as follows:

- Introduction of new product(s), or upgrade for existing product(s)
- Introduction of new, or improvement in existing, process(es)
- Allocation of new, or re-allocation of existing, resource(s)
- Selection of new supplier(s), or deselection of existing ones
- Changes in demand patterns for product(s) manufactured
- Changes in lead times for product and/or process life cycles
- Changes in commitments within or between supply chain members

A configurable supply chain can help in assessing the impacts of one or more of the following factors / activities in a configurable system:

- Flows due to materials, inventory, information, and cash
- Throughput due to movement of products
- Capacity utilization
- Costs at various stages of the product development life cycle
- Lead time in product development
- Batch and lot sizing
- Process redesign
- Product development strategies
- Procurement and/or allocation of resources
- Strategic, tactical, and operational policies for the supply chain

Analysis of these factors / activities involves dealing with a wide range of managerial problems and spans across all tiers of the supply chain. Problem-solving approaches need to consider both interactions among factors and activities, and supply chain members.

2.2.3 Supply Chain Management Process

Supply chain configuration is one of the principal supply chain management decisions. It has profound impact on other subsequent managerial decisions. The decision-making process involved in configuring the supply chain analyzes the entire spectrum of system capabilities ranging from deterministic to stochastic systems. This is primarily due to the hybrid environment encountered in a supply chain where key factors in the decision-making process such as product demand, materials inventory, and available capacity may undergo rapid variations due to uncertainties caused by various control mechanisms, such as inventory and procurement policies, supply and revenue contracts, and so on. We propose supply chain configuration as an integral part of the overall supply chain management process.

Supply chain management is carried out as a step-by-step process. This process moves from a macro to a micro perspective that, in effect, aligns objectives to problems and their solutions. We briefly describe these steps.

1. *Definition of strategic objectives*. These high-level objectives are aimed at steering the supply chain on a specific course. These may have significant impact on the performance or operations of the supply chain. These are primarily related to the allocation of resources, positioning of the product, and implementation of key strategies. For example, where to locate plants, investment in manufacturing capacities, decisions on outsourcing or off-shoring of manufacturing or other activities, introducing the product to newer and / or emerging markets, and so on.
2. *Product selection*. A candidate product or products, whose supply chain is to be managed, are selected. Ideally, this would be an established (or matured) product whose product and process life cycles are well established and in which supply chain partners are already collaborating to offer the product to consumers. One could also select a new product whose supply chain has been clearly identified and potential partners are firmly on board. In this case, however, closer attention is warranted in monitoring implementation of various strategies and measuring objectives put in place at the time the supply chain is designed.
3. *Establishing the supply chain*. This is a process requiring a high level of collaboration, coordination, and synchronization among various activities and operations spread over a potentially large and varied number of supply chain partners. It starts with the selection of suppliers of raw materials and components. It may be prudent to have both primary and secondary suppliers. Next, manufacturing and production operations must be clearly identified. This involves

decisions regarding (a) identifying the manufacturing processes (through the process design activity), (b) location of facilities where these processes will be carried out, (c) allocation of resources to processes, and (d) production schedules. Following this step, decisions on product-related logistics must be made, which involves inbound and outbound logistics, such as procurement of raw materials, transportation and warehousing of inventory, and distribution of inventory to retailers. Finally, operations related to marketing the product to the consumer must be defined. In all of these activities, various policies related to forecasting demand, managing inventory, product planning, and so on must be clearly identified.

4. *Classifying the problems*. As described earlier, the supply chain has a complex structure with entities that have the role of a whole (supply chain) and its parts (supply chain members). The interaction of these entities with each other and with the environment creates problems at both the higher (global or macro) and lower (local or micro) levels. Accordingly, the nature of these problems in terms of their complexity and impact on the enterprise performance is different. For example, macro-level problems may have potential impact on the enterprise, while micro-level problems are more focused and may only impact a function or unit of the supply chain. A more detailed discussion of problem classification appears in Section 2.3. Due to the complexity of the supply chain structure, it is prudent to decompose the problem at macro and micro levels to design, model, and solve these problems efficiently and effectively.
5. *Strategic, tactical, and operational level supply chain management.* As a complex and integrated business enterprise, the impact of decision-making on the performance of the supply chain is felt at all levels, such as strategic, tactical, and operational. Table 2.1 summarizes the types of decisions and the frequency with which these are made at various levels. The challenge in designing and modeling the decision-making tools is to incorporate integration of input in the form of shared information and other variables across various decision-making levels.
6. *Classify problem-solving models and solutions.* Similar to classification of problems described above, problem-solving models and solutions for the supply chain are also classified at the macro and micro levels. In fact, these models are designed to solve macro- and micro-level problems, respectively. In addition, an integration model is designed to essentially integrate solutions provided by macro and micro models, and in most cases iteratively, thereby ensuring that an optimal, and more than likely a sub-optimal solution, is obtained. We

provide extensive coverage on various problem-solving models and solutions throughout the rest of the book.

2.3 Supply Chain Management Problem Domain

Supply chain management involves dealing with multiple managerial and technical problems (Cooper et al. 1997; Mentzer et al. 2001). These problems highlight several common issues that must be addressed for a supply chain to function effectively and efficiently. We discuss below some of these issues and how they have been addressed in the published literature.

Distribution Network Configuration

This issue deals with the selection of warehouse locations and capacities, determining the production level for each product at each plant, and finalizing transportation flows between plants and warehouses so as to maximize production, transportation, and inventory costs. This issue relates to information sharing: (a) inter-firm between marketing, production planning, inventory planning, and receiving and warehousing functions, and (b) intra-firm between manufacturer, suppliers, distributors / retailers, and transporters. It is a complex optimization problem dealing with network flows and capacity utilizations (Ballou 2001; Beamon and Fernandes 2004; Bozarth and McDermott 1998; Cakravastia et al. 2002; Cochran and Marquez 2005; Duray et al. 2000; Ernst and Kamrad 2004; Garavelli 2003; Salvador et al. 2004; and Schmidt and Wilhelm 2000).

Inventory Management

This issue deals with stocking levels at various echelons in the supply chain. Demands from echelon-to-echelon are considered in making this decision. This is a decision problem solution which involves using forecasting, inventory management, and simulation and optimization algorithms. Retailers, suppliers, and manufacturers deal with this issue in a supply chain by sharing information on customer demand, inventory levels, and replenishment schedules (Childerhouse et al. 2002; Sheffi 1985).

Supply Contracts

This issue deals with setting up relationships between suppliers and buyers in the supply chain through establishment of supply contracts that specify mutually agreed-to prices, discounts, rebates, delivery lead times, quality standards, and return policies. This approach differs from traditional approaches because its central focus is on minimizing the impact of decisions made at not just one echelon in the supply chain, but on all its players. A retailer sets up these contracts with a distributor or directly with a manufacturer. To manage this issue, it is incumbent upon various supply chain players to share information related to product price, cost, profit margins, warranty, and so on. This is a decision problem solution that could range from a simple linear programming problem to a complex game theory algorithm (Cachon 2002; Cachon and Lariviere 2000; Fisher et al. 1997).

Distribution Strategies

This issue deals with decisions pertaining to the movement of goods in the supply chain. Among the strategies available are direct shipments, cross-docking involving trans-shipments, and load consolidation. The objective is to minimize warehousing (storage) and transportation costs. A manufacturer makes decisions about warehousing or direct shipment to the points of usage of various products, utilizing information shared among manufacturers, suppliers, distributors, and retailers in the supply chain. Solutions to this problem involve network algorithm utilizing linear, and nonlinear programming techniques in deterministic and stochastic environments (Frohlich and Westbrook 2001; Lee 2003).

Supply Chain Integration and Strategic Partnering

One of the key issues in managing supply chains is integration (Bramham and McCarthy 2004). Information sharing and joint (or collaborative) operational planning are basic ingredients for solving this issue. Implementation of Collaborative Planning, Forecasting and Replenishment (CPFR) (Aviv 2001; Ng and Vechapikul 2002; Caridi et al. 2005; Fliedner 2003), as carried out by Wal-Mart retail stores in their supply chain aided by information sharing through common software platforms such as Enterprise Resource Planning (ERP) are viable strategies (Akkermans et al. 2003). In a manufacturing supply chain, it would mean CPFR among the retailer, supplier, and the manufacturer of products. The main idea of this technique is to avoid carrying excess inventory through accurate forecasting, and utilizing commonly agreed to demand data, information about which is shared among various supply chain partners (Anonymous 2000).

Outsourcing and Procurement Strategies

An important issue to consider is what to manufacture internally and what to buy from external sources. One of the problems to be dealt within making these decisions is identifying risks associated with these decisions and minimizing them. Another issue to consider is the impact of the Internet on procurement strategies and what channels to utilize (public or private portals) when dealing with trading partners. In arriving at the decision of whether to outsource or buy, various optimization models may be utilized to balance risk and payoffs. Once this decision has been made, use of appropriate information technology components, such as Internet portals and procurement software, plays a key role in these decisions. An example of this issue in a manufacturing supply chain may be the decision to outsource a component assembly rather than making it in-house. Information sharing for outsourcing and other procurement issues is accomplished in the supply chain and its extended enterprise, for intra-firm and inter-firm, via Intranet, Extranet, and Internet portals (Chen et al. 2004).

Information Technology and Decision Support Systems

One of the major issues in supply chain management is the lack of information for decision-making. Information technology plays a vital role in enabling decision-making via information sharing throughout the supply chain. Some of the key ingredients of information technology in the supply chain are use of Internet and Web-based service portals, integrated information/knowledge within ERP software, and decision support systems that utilize proven algorithms for various strategic, tactical, and planning problems in specific industry domains (Fiala 2005). Significant progress has been achieved in enabling physical supply chain integration. Lau and Lee (2000) use the distributed objects approach to elaborate on an infrastructure of integrated component-based supply chain information systems. Kobayashi et al. (2003) conceptually discuss workflow-based integration of planning and transaction processing applications, which allows for effective integrated deployment of heterogeneous systems. Verwijmeren (2004) develops the architecture of component-based supply chain information systems. The author identifies key components and their role throughout the supply network. Themistocleous et al. (2004) describe the application of enterprise application integration technologies to achieve physical integration of supply chain information systems. However, approaches and technologies for logical integration at the decision-modeling level, where common understanding of managerial problems is required, are developed insufficiently (Delen and Benjamin 2003).

Customer Value

The supply chain must be measured by its ability to deliver value to the end customer, or the consumer. This may be in the form of price, quality, service levels, or perceived value. Solutions based on statistics and operations research can be employed to measure the quality of a product, and the reduction of lead-time to enhance service rates. Input for this purpose is acquired via information sharing among various supply chain members (Baiman et al. 2001; Beamon and Chen 2001; Bullinger et al. 2002).

Challenges for Information Sharing in the Supply Chain

In light of various decision-making levels and issues facing effective management of the supply chain, it becomes imperative to find globally optimal integrated solutions. However, it is difficult to achieve depending on whether the problem-solving models designed for the purpose achieve local (or sequential) or global optimization of the supply chain network. Depending on which approach is adopted, the requirement for information sharing will be starkly different. For example, in the case of sequential supply chain optimization, the objective of its individual partners is optimized without regard to the overall supply chain network objective. Accordingly, the need for information sharing is limited and/or closed, sometimes nonexistent and usually offline. For global supply chain optimization, however, the objective for the overall supply chain takes precedence over each partner's objective. For this scenario, information sharing is extensive, open, and online (Beamon 1998; Fiala 2005; Simchi-Levi et al. 2003).

Based on the above review of issues, we summarize the key supply chain problems and their proposed problem-solving approaches in Table 2.2.

2.3.1 Overall Supply Chain Management Problems

From Table 2.2, it can be gleaned that supply chain management issues pose complex problems. The supply chain problem domain can be analyzed at various levels of decomposition. At the first level, the overall problem of supply chain management consists of multiple sub-problems such as product design, network design, logistics management, customer service, and others. For purposes of further discussion, we define these problems as *general* and *specific*. Specific problems occur at the vertical direction of problem decomposition and deal with one particular issue, for instance, inventory management. General problems cross multiple specific problems horizontally. Dealing with these problems requires solving multiple specific problems, for instance, ensuring customer service involves solving problems from logistics and sales areas. The list of problems presented below is composed primarily on the basis of the published literature and experiences of authors.

The problem of coordination and synchronization of activities and resource utilization occurs at all levels of implementation in an enterprise. A common problem encountered is that of “information sharing” among various members/partners in an enterprise. This often leads to misallocation of resources and impacts scarce resources such as capacity and inventory.

Table 2.2 Supply Chain Management Problems and Suggested Problem-Solving Approaches

Supply Chain Issue and Related Problem	Problem-Solving Approach
Distribution Network Configuration	Network Flow Optimization
Inventory Control	Forecasting and Inventory Management
Supply Contracts	Global Optimization
Distribution Strategies	Warehousing and Transportation Costs Management
Supply Chain Integration and Strategic Partnering	Collaborative Planning, Forecasting and Replenishment (CPFR)
Outsourcing and Procurement Strategies	Managing risk, payoff tradeoffs with Outsourcing vs. Buying
Information Technology and Decision Support Systems	Implementing Enterprise Resource Planning Decision Support Systems
Customer Value	Statistical Process Control, Total Quality Management, Service Level Maximization

General Problems

The main general supply chain management problems are:

Competitiveness. The house of supply chain management (Stadtler 2005) considers solving this problem as the ultimate goal of supply chain management. To maintain competitiveness, a supply chain must outperform competing supply chains in at least some aspects such as prices, quality, or delivery responsiveness.

Customer service. It characterizes the ability of supply chains to meet customer requirements. Approaches to addressing this problem are as diverse as the customer requirements representing such aspects as cost, quality, and responsiveness.

Coordination. Coordination of decisions by each supply chain member are made with regard to the impact these decisions will have on the performance of other supply chain members.

Collaboration. Joint activities performed by supply chain members to achieve common goals (Kliger and Reuter 2005) include product design and planning. In the case of collaborative product design, manufacturers, suppliers, and potential customers work together to design product that best suits market requirements and the capabilities of parties involved.

Integration. Addressing the *integration* problem enables customer service improvements, coordination, and collaboration. Information sharing is an important integration sub-problem.

Robustness. Supply chains operate in uncertain environments. Operations need to be planned and executed with respect to this uncertainty.

Flexibility and agility. Customer requirements and operating environments are dynamically changing. Addressing flexibility and agility issues implies the ability of reactive and proactive response to change.

Risk/benefit sharing. Implemented supply chain decisions have different impacts on supply chain members. Some of the units may assume larger risks and incur additional costs in the name of overall supply chain benefit. Risk and benefit sharing is essential for building trust and enforcing commitment among supply chain members.

Globalization. This presents both opportunities and challenges. Cost reduction and expansion in new markets have become possible. On the other hand, increasing competition, local regulations, and cultural adjustments cause additional difficulties.

Outsourcing. Firms focus on their core competencies to achieve a high level of competitiveness in specific areas while allocating supporting functions to partners.

Mass customization. Customers demand individualized products with similar cost and delivery time characteristics as those of standardized products.

Postponement. This is one of the strategies for delivering market-specific and customized products. It implies location (in time and space) of the product finishing close to the point of demand.

Social responsibility. Supply chains are designed and operated with regard to social, cultural, and environmental issues.

Specific Problems

The main specific supply chain management problems are:

Demand planning and forecasting. Demand data are required for other supply chain management activities. Demand planning attempts to influence demand to make supply chain operations more efficient.

Product design. This is not an explicit supply chain management problem, although there are significant interactions between design and logistics activities and at this stage it is a major input for further supply chain management activities. From the supply chain management perspective, this problem concerns collaborative product design, balancing product design requirements and supply chain capabilities, and providing the bill of materials for further planning purposes.

Process design. This is a significant supply chain management problem because of the very large number of processes that can be potentially enumerated as the supply chain is functionally decomposed top-down from a tier → unit → function → process level, and then need to be properly managed. One of the key problems that arise is how to develop a composite process design of the supply chain that clusters these processes based on similarities in features and characteristics, and arranges clusters according to an optimal implementation schedule.

Network design. A network of supply chain units meeting product and process design requirements is established. Problems to be addressed concern location and role of supply chain units, allocation of products, strategic-level capacity planning, and establishing transportation and information exchange links.

Marketing and sales. The primary concerns of these managerial problems are attracting customers and processing their orders.

Logistics. Problems deal with delivering products and services to customers, including planning of distribution structure, inventory management, warehousing, and transportation activities.

Purchasing. This deals with procurement of materials and services that are needed from suppliers to satisfy customer demand. The problem includes such issues as identification of materials and services needed, supplier relationships (i.e., supplier selection, contract negotiation, supplier evaluation) and execution of procurement operations.

Manufacturing. These problems address creation of products and services in response to customer demand. It includes such supply chain management concerns as master production planning, capacity allocation, scheduling, maintenance of manufacturing facilities, and manufacturing quality.

Finance. In the supply chain management framework, this concerns planning of supply chain costs and controlling supply chain performance.

Personnel management. Workforce requirements are considered while dealing with the personnel management problem. This includes workforce planning, hiring, layoffs, promotion, training, and incentives.

2.3.2 Subset of Supply Chain Configuration Problems

As discussed earlier in the chapter, supply chain configuration is a high-level supply chain management problem, which either completely or partially incorporates some of the specific supply chain management problems. Problems that are relevant to supply chain configuration are as follows:

Network design. It is the core sub problem of the supply chain configuration problem, thus all its aspects are relevant.

Sales and distribution. Individual ordering and marketing activities do not contribute to identifying supply chain configuration problems. Such aspects as grouping customers and representing aggregated marketing costs, however, are important problem-solving characteristics. For instance, if a configuration model is used to make decisions when opening distribution facilities in new markets, then the cost of attracting new customers is an important parameter.

Logistics design. Deciding on the inventory and distribution approach, such as vendor-managed inventory, cross docking, third party logistics, and associated transportation mode, capacity, and main routes to be adopted.

Purchasing. In the context of configuration problem solving, decisions concerning which suppliers to use for specific materials and in what quantities are addressed. Other purchasing conditions, such as delivery price and lead time are determined.

Manufacturing. This involves deciding on the manufacturing approach, such as pull, push, and master production planning.

Information technology support. It provides the information and processing capabilities needed to support other supply chain management problems.

It is often difficult to draw a line between relevant and irrelevant problems because all supply chain management problems are closely interrelated. However, forecasting and demand planning interacts with configuration decision making by providing demand data or forecasting algorithms, and there are usually no specific forecasting components within configuration decision making models. Therefore, demand planning and forecasting can be perceived as a problem, which is not necessarily an area of expertise for a supply chain configuration analyst, even though configuration problem decision making would not be possible without demand data.

The finance problem area is also a particularly important problem in the context of global supply chains. It accounts for such factors as taxes, duties, and currency rate fluctuations.

2.3.3 Integration

One of the key issues in managing a supply chain process is information integration among its constituents (Bramham and McCarthy 2004). To facilitate this integration, supply chain information resources ought to be effectively organized and shared. Information integration provides channels that convey information from one supply chain constituent to another. One form of this problem involves the integration of existing implementations that have been built in heterogeneous infrastructures, such as different hardware platforms, operating systems, and database management systems. Presenting the data on which applications perform in a uniform, consistent way ensures that they share the same view of the supply chain. Another form of integration is concerned with working collectively on common problems by sharing an understanding of the problems' logic and applying best practices. This provides a common architecture in information sharing so that supply chain members' collaborative activities provide performance improvement to each member and to the entire supply chain.

Information sharing and joint (or collaborative) operational planning are basic ingredients in solving the integration issue in a supply chain. Implementation of CPFR (Aviv 2001; Ng and Vechapikul 2002; Caridi et al. 2005; Fliedner 2003), as reportedly carried out by Wal-Mart retail stores in their supply chain, and aided by information sharing through common software platforms such as Enterprise Resource Planning (ERP) are viable strategies (Akkermans et al. 2003). A manufacturing supply chain would require CPFR among the retailer, supplier, and the manufacturer of products. The main idea of this technique is to avoid carrying excess inventory through accurate forecasting and utilizing one commonly agreed-to demand data, information about which is shared among various supply chain partners (Anonymous 2000).

The management of a complex organization such as a supply chain can be accomplished by the integration of its business processes. Process-oriented management vs. function-oriented management is an important feature that makes the supply chain a distinct enterprise system class. Another facet of supply chain system complexity is its organizational dynamics and operational specifics. Organizational dynamics assume frequent changes in organizational structures such as control hierarchy, goal structure, members' network, and so on. Operational specifics are mainly related to the uncertainty in which supply chain organizations operate. Integration of supply chain processes assumes additional complexity when the decision-making mode (i.e., centralized vs. decentralized) is considered in the mix.

2.4 Supply Chain Configuration Dimensions

Supply chain configuration is based on the basic principles of configuration and is enunciated in the mold of a configurable system as described in detail in Chapter 1. In this configuration, parts are *members* of the supply chain (i.e., supplier, manufacturer, distributor, retailer), arranged (or rearranged) to form the *whole* (i.e., the supply chain) in accordance with a plan executed by implementing various strategies and policies to meet a common objective(s).

Because the objective in configuring a supply chain is essentially similar to that of a generic configurable system, it can be construed that a configured supply chain is a special class of the configurable system. The primary difference between these two types of systems is that, in configuring a supply chain, the system dimensions considered are attributable to a supply chain system, and more particularly to the logistics network represented by it.

To fully appreciate the concept of supply chain configuration, it is important to understand its various system dimensions. In this section, we shed light on some of the significant dimensions.

2.4.1 Horizontal Extent

The supply chain is usually divided into tiers (or stages, or echelons). Each tier consists of units with the same general functionality. The concept of tier should be treated with care, however, as differentiation between tiers is often fuzzy and units can belong to multiple tiers. That has become even more profound as supply chains assume networked structures. Still, tiers help structure the supply chain configuration problem and facilitate identification of common features of supply chain units.

The typical supply chain tiers (see Fig. 2.2), which can be further decomposed, are

- Customer tier – the most downstream tier
- Distribution tier
- Manufacturing tier
- Supply tier – the most upstream tier

Demand for supply chain products or services originate at the customer tier and it is transmitted upstream along the supply chain. In many cases, techniques where customers aggregated into customer zones according to their geographical location (Simchi-Levi et al. 2003), using the zip code as a grouping criterion for consumer products). Each customer can be represented as an individual node in studies considering industrial customers.

The distribution tier receives customer requirements and is responsible for delivering required products or services. It involves such general units as warehouses, distribution centers, and cross-docking points. These units are grouped into distribution sub-tiers. Alternatively, supply chain units in the distribution tier can be classified as wholesalers, retailers, and brokers Third-party logistics providers present a special case for belonging to the distribution tier. In some situations, these can be represented by a single supply chain node.

There are two distinct scenarios to organize the supply chain's operations. The first, where manufacturing tier directly creates products or services demanded by the supply chain's customers. It receives demand information from the distribution tier. In return, it provides products to the distribution tier and orders materials from the supply tier. In the second scenario, the manufacturing tier can also be divided into several sub-tiers, such as pre-processing, assembly, final assembly and finishing. Manufacturing outsourcing can be represented either in the manufacturing tier or in the supply tier. The first scenario is more relevant to representing the manufacturing tier for an engineering company such as *Ericsson*, which has outsourced almost all manufacturing operations and retained only product and process design as their primary competency, or in the case of capacity sharing agreements. The second scenario is more relevant for representation of manufacturing of components (for instance, the Ford and Visteon case).

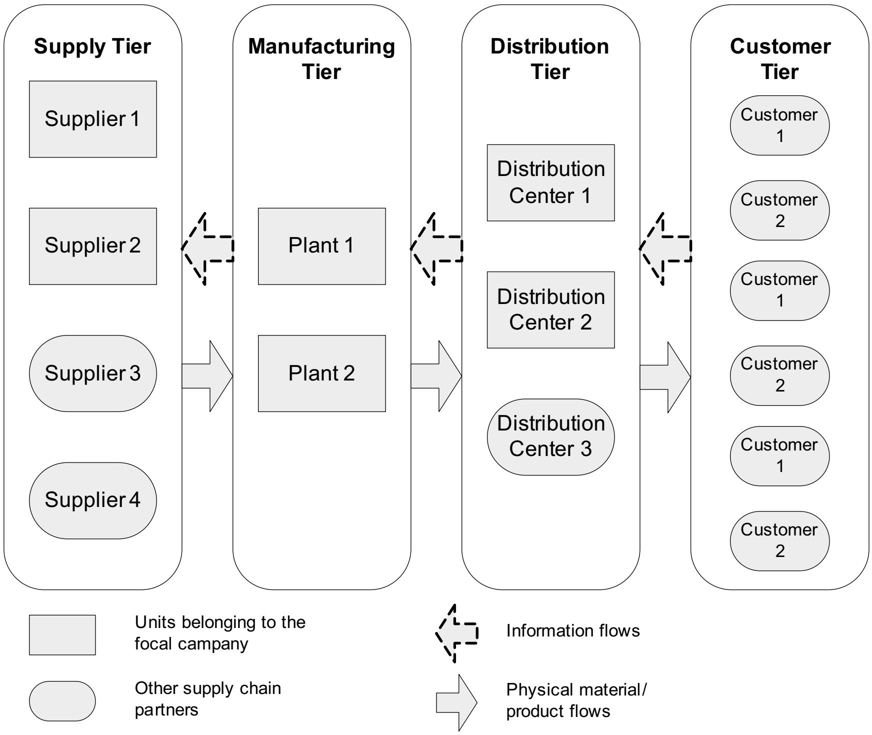

Fig. 2.2 A typical supply chain structure.

The supply tier provides materials to manufacturing according to orders received. This tier can be divided into sub-tiers, linking raw materials suppliers, secondary suppliers, and direct suppliers. Representation of the supply tier depends upon the importance of supplied materials. Suppliers providing widely available materials do not need to be represented by individual nodes.

One additional supply chain tier not sufficiently exposed in the literature is the utility tier. This tier includes providers of basic infrastructural services such as electricity, water, and recycling. That could be of particular concern for global supply chains, because availability, cost, and quality of such services vary substantially.

Definition of this supply chain configuration dimension includes specifying the number of tiers in the supply chain, defining general types of units in each tier, and identifying specific constraints for the tier as a whole (for instance, the number of suppliers required).

2.4.2 Vertical Extent

As noted earlier, a supply chain consists of several members spread across many tiers (echelons, or stages). Each of the tiers consists of one or many business units (entities). Each of these business units is, by itself, an enterprise comprising functional areas such as design, marketing and sales, production planning and control, inbound and outbound logistics (procurement, receiving, warehousing, shipping), and so on. Each unit may also pursue its own independent strategies to manage its functions and strive to achieve specific goals and objectives.

A *within* unit (local) vertical integration would entail synchronizing and coordinating strategies and policies, for example, between its sales and marketing and manufacturing functions to achieve a common objective for the unit.

A *between* (global or supply chain level) vertical integration within a tier (comprising all units) would be to implement common strategies and policies to achieve a common (global) objective across units in their tier.

Vertical integration could be achieved at strategic, tactical, and operational levels of decision making within a tier of the supply chain. This is primarily achieved by means of implementing strategies and policies appropriate at these levels that are aimed at achieving long-term, mid-term, and short-term goals and objectives.

Definition of this supply chain configuration dimension includes specifying the number of units in each tier in the supply chain and identifying specific constraints and objectives: (a) within a unit at high level and by functional areas at low level, and (b) between units at high level and across functional areas at low level.

2.4.3 Objectives and Criteria

Decision-making objectives are chosen according to general strategic objectives. Certain quantitative criteria or metrics are associated with each identified objective.

General managerial concerns related to the supply chain configuration problem are

- What is the current supply chain performance?
- "What if" analysis?
- How to improve customer service?
- How to improve supply chain robustness and delivery reliability?
- Could supply chain be made more profitable?
- Is supply chain sufficiently flexible?

- How to improve cooperation?
- How to comply with local requirements?
- Whether to pursue outsourcing?
- Which partners to choose?
- Where to locate supply chain facilities?

Answering these questions leads to formulation of general supply chain configuration decision-making objectives. These objectives can be formulated on the basis of performance attributes identified in the Supply Chain Operations Reference (SCOR) model (Stewart 1997):

- Objective 1: To improve supply chain delivery reliability.— the performance of the supply chain delivering the correct product, to the correct place, at the correct time, in the correct condition and packaging, in the correct quantity, with the correct documentation, to the correct customer.
- Objective 2: To increase supply chain responsiveness.— the velocity at which a supply chain provides products to the customer.
- Objective 3: To increase supply chain flexibility. — the agility of a supply chain in responding to marketplace changes to gain or maintain competitive advantage.
- Objective 4: To optimize supply chain costs. — the costs associated with operating the supply chain.
- Objective 5: To improve supply chain asset management efficiency — the effectiveness of an organization in managing assets to support demand satisfaction. This includes the management of all assets — fixed and working capital.

Objectives can similarly be identified on the basis of discussion provided by Beamon (1998), such as

- Objective 1: To improve customer satisfaction and customer responsiveness.
- Objective 2: To improve flexibility and risk aversion.
- Objective 3: To improve information and material flow integration.
- Objective 4: To optimize costs (other related performance measures are total cost, sales value, profit, inventory holding cost, return on investment, and others).
- Objective 5: To optimize suppliers' performance.

A large number of criteria are used for solving the related supplier selection problem. Weber et al. (1991) provides a comprehensive survey of supplier selection criteria used. The survey is based on the list of criteria compiled by Dickson (1966). The most frequently considered criteria, which can be attributed to the suppliers' performance objective although they contribute to other objectives as well, are

- Net price
- Delivery
- Quality
- Production facilities and capacity
- Geographic location
- Technical capability
- Management and organization
- Reputation and position in industry

Other important criteria are financial position, performance history, repair service, and attitude.

It is surprising that in the supply chain configuration framework only the supply tier is being evaluated under such a wide range of criteria, because location of manufacturing and distribution facilities is evaluated in a similar fashion in practice. For instance, companies consider incentives offered by local governments as a major decision-making factor.

2.4.4 Decisions

Initially, general supply chain configuration decisions are identified following the supply chain configuration decision-making objectives. These are subsequently specified using particular decision variables. Five groups of decisions are defined, characterizing structure, links, quantity, time, and policies used.

Structural decisions are

- Location of supply chain facilities at different tiers
- Facility opening
- Supplier selection
- Product allocation
- Definition of facility's capabilities

Decisions characterizing links among supply chain units are:

- Establishing a fixed link among a pair of units–if a link between units cannot be established on the spot, decisions must involve which units' link should be established
- Restricting cooperation to specified links–implies that a particular unit can cooperate only with a limited group of other units (i.e., a customer zone is served by only one particular distribution center)

- Choice of products or services delivery mode
- Choice of information exchange mechanisms

Alternative production location according to ownership, international/global, and product state are described by Meixell and Gargeya (2005).

Decisions characterizing quantity are:

- Quantity of purchased materials
- Quantity of products produced
- Quantity of products processed
- Quantity of products delivered
- Quantity of products stored in inventory
- Shipment quantities along supply chain links
- Capacity-related decisions

Decisions characterizing quantity often differ by their interpretation and level of detail. For instance, manufacturing capacity is specified for each product separately at a plant or for the entire plant. The main decision characterizing time is delivery time.

Decisions characterizing policies are

- Choices of manufacturing strategies. The most general values of these decisions are make-to-plan (make-to-stock), make-to-order, and assemble-to-order. The choice of the manufacturing strategy influences propagation of demand information along the supply chain and functions performed by different units
- Adoptions of information sharing policies. Information sharing policies affect manufacturing, inventory, and transportation, as well as several other decisions and characteristics. They also influence requirements towards information exchange infrastructure, where possible values of decisions are deployment of Electronic Data Interchange (EDI), or use of the Internet. Other IT-related decisions, such as implementation of ERP and manufacturing execution systems can also be considered
- Choice of distribution channels. Values these decisions assume include Internet-based distribution, third-party logistics, direct sales, quick response, continuous replenishment, and vendor-managed inventory. Some of the policies may be represented in relation to the horizontal extent dimension. For instance, the direct shipment policy implies the absence of intermediate distribution tiers. Multiple distribution strategies can be used in a single supply chain
- Choices of procurement policies. Some alternatives include volume consolidation, alliances and partnerships with suppliers, just-in-time

(JIT), and manufacturing resource planning (MRP). From a technical perspective, various types of e-procurement can be chosen (for instance, EDI, Internet-based business-to-business (B2B) approaches, and trading networks)

- Adoption of outsourcing. Decisions apply to separate supply chain functions and indicate whether these are outsourced or not. That influences the way supply chain costs are accounted for. For instance, outsourcing may reduce fixed costs associated with a facility opening

Each of these policies can be parameterized by a set of particular structural, linkage, quantitative, and time parameters. For instance, if the decision is between using EDI or the Internet for information exchange purposes, a parameter characterizing a fixed cost for establishing links among manufacturing facilities and suppliers is larger for the first. Policies influence which supply chain management problems need to be addressed during decision-making. For instance, evaluation of the built-to-stock manufacturing strategy requires consideration of the inventory management problem.

The decisions listed above do not provide an exhaustive list of all supply chain configuration decisions. That, especially, applies to policy decisions. Decisions relevant to a particular decision-making problem, and decision variables characterizing these decisions, are defined during the supply chain configuration problem-solving process.

2.4.5 Parameters

Parameters usually are more specific to a particular decision-making problem compared to other supply chain dimensions discussed earlier. Some common features, however, can be identified.

Parameters are traditionally classified as internal and external. External variables for the supply chain configuration problem are customer demand and requirements in general, taxes, governmental regulations, and others.

The first group of internal variables represents structural characteristics. That includes representation of the existing supply chain structure, bill of materials, available capacity, and capacity requirements. This group also includes parameters describing attributes of alternative transportation channels (e.g., distance, speed).

Supply chain operations are described by cost- and time-related parameters. These are classified as fixed and variable parameters. Fixed cost parameters describe costs due to opening (closing) and operating supply chain facilities, capacity build-up costs and costs associated with establishing and maintenance of links among supply chain units. Inventory replenishment, manufacturing setup, and fixed transportation costs can also be considered. Variable costs are incurred per each processed product. Processing can assume various forms including transportation, assembly, inventory handling, and others. Parameters for representing processing time can also be used.

Specific parameters may be needed to describe various attributes of the supply chain management policies considered.

2.5 Aligning Objectives

One of the major tasks of any supply chain configuration effort is to align the objectives of the enterprise at both macro and micro decision-making levels. This is primarily due to the fact that objectives at individual business unit levels, at the tier (echelon or stage) level, as well as across tiers, are conflicting in relation to each other. To solve a composite supply chain problem with conflicting objectives, it is imperative that the objectives be organized according to some priority (or importance) in the optimization models. The resultant aligned objectives are the basis for the multi-criteria decision-making models, which are usually implemented for optimizing supply chain networks. We describe these concepts below.

Table 2.3 provides an example of performance measures for a business unit belonging to a supply chain tier whose objectives at a strategic level are closely aligned with its tactical and operational levels. For instance, marketing decisions are taken at strategic level, mainly dealing with, which product to introduce to the market. Row 1 lists objectives in marketing a new product, what policies will likely are implemented for it, and the specific goal to be achieved. Obviously, the objective, policy, and goal must be aligned, if the strategic marketing decision is to be successfully implemented. Similarly, a tactical decision related to procurement planning must have the maximizing inventory turns objective closely aligned with its just-in-time policy, and an inventory turnover goal of 2.5 to 3. The objective of minimizing merchandizing costs at the operational decision-making level must implement a same day shipment policy and achieve a 98 percent shipment fill rate of within 4 hours of order to be successful.

If we analyze column entries in Table 2.3, we can see that the objectives for marketing, procurement, and warehouse operations are closely aligned with each other. This is because we cannot meet the marketing objective of maximizing customer service unless the procurement planning objective of maximizing inventory turns is achieved and the warehousing operations objective of minimizing merchandising costs is met. We can also see clear alignment of policies in Column 3 and goals in Column 4. For example,

Table 2.3 Alignment of Objectives at Micro Level

Function	Objective (s)	Policy (ies)	Goal (s)
Marketing	Maximize customer service	Implement a procure-to-stock policy	Achieve a 98 percent order-fill-rate of within 4 days of order processing
Procurement Planning	Maximize inventory turns	Implement a just-in-time procurement policy	Achieve 2.5 to 3 inventory turns
Warehouse Operations	Minimize merchandising costs	Implement a same day shipment Policy	Achieve a 98 percent shipment-fill-rate of within 4 hours of order

for a procure-to-stock policy to be successful, a just-in-time procurement policy is desirable, and a same day shipment policy. We can analyze goals and observe that in order to achieve a 98 percent order-fill-rate, inventory turns of 2.5 to 3 must be met and achieving a 98 percent shipment-fill-rate is important.

Table 2.4 is analogous to Table 2.3, except that it represents decision-making at the macro level. In this case, the strategic, tactical, and operational level decision parameters, such as objectives, policies, and goals, are closely aligned. The objectives, policies, and goals at each of the three levels are also complementary to each other.

Table 2.4 Alignment of Objectives at Macro Level

Function	Objective (s)	Policy (ies)	Goal (s)
Marketing	Maximize customer service	Evaluate and implement a pull policy	Achieve an industry benchmark of 98 percent order-fill-rate within 48 hours
Production Planning	Maximize production under-runs Maximize inventory turns	Evaluate and implement a just-in-time scheduling or planned production scheduling policy	Achieve a 90% effective capacity utilization Achieve inventory turns of 4 or above
Plant Operations	Minimize manufacturing costs Maximize yield per production run	Evaluate and implement a just-in-time manufacturing policy	Achieve over 85 percent actual capacity utilization Achieve less than 2% rejects

2.6 Summary

In this chapter, we explore supply chain as a systems concept, and its configuration in the face of a dynamic business environment. We discuss various aspects of supply chain configuration problems, its classifications, and its various dimensions. We posit supply chain configuration as a supply chain management problem and argue that it can be successfully achieved if properly modeled around the decision-making levels and aligned with objectives at the macro and micro levels.

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3. Literature Review

3.1 Introduction

Supply chain configuration research has attracted significant attention in scientific literature. This chapter offers a review of these studies and identifies common characteristics of supply chain configuration research. This review is compiled in the form of a table categorizing each paper, considered according to several criteria along with short description of the paper. This table can be used as a quick reference for finding papers dealing with the supply chain configuration problem. The chapter also contains summarized results of the complete review.

As described in the previous chapter, supply chain configuration is tightly interrelated with many other supply chain management and general managerial problems. Therefore, some limits in the literature survey are introduced. The survey covers only the core of the supply chain configuration problem without including papers describing general supply chain management methods and technologies important to configuration.

There are several existing surveys on the supply chain configuration problem. Vidal and Goetschalckx (1997) review early papers. The review results are summarized in two tables according to general characteristics and international characteristics, respectively. General characteristics include stochastic features, dynamic characteristics, treatment of capacity, objective function, and the size of problems. Goetschalckx et al. (2002) expand the listing of the international characteristics. These characteristics include taxation, cash flow, and trade barriers. The international characteristics trait is further investigated by Meixell and Gargeya (2005). They analyze configuration models according to decision variables (facility location is included in all models considered), performance measures (after-tax profit minimization is important for global models), level of supply chain integration (majority of models consider just two tiers) and globalization considerations. The presentation follows the historical development of supply chain configuration models. Model complexity characteristics are briefly reviewed by Dasci and Verter (2001). Strategic, tactical, and operational level modeling of production-distribution networks is surveyed by Bilgen and Ozkarahan (2004). Gunasekaran and Ngai (2004) provide a focused survey of information technology usage in supply chain management. The computational perspective of network configuration problems is highlighted in the survey by Geunes and Pardalos (2003). Terzi and Cavalieri (2004) provide a survey on application of simulation in supply chain modeling.

The following section describes the design of the literature survey, including description of categorization criteria. Section 3.3 provides the complete review tables with regard to configuration dimensions and complexity criteria. Results of the review are analyzed in Section 3.4, and summary of the chapter is provided in Section 3.5.

3.2 The Design of the Literature Survey

The objectives of this state-of-the-art survey are to provide a comprehensive overview of the supply chain configuration problem, to identify main scientific and industrial focus areas, and to quantify the importance of different dimensions of the supply chain configuration problem.

The state-of-the-art review focuses on papers dealing directly with the supply chain configuration. It covers conceptual, model-based, and applied papers to provide a comprehensive overview of different aspects of supply chain configuration. However, it maintains an industrial engineering and computational emphasis.

The main sources of information for the survey are the Scientific Citation Index and Scopus. The main keywords searched for are combinations of “supply chain” or “supply network” with “configuration,” “design,” and “structure.” Some papers found according to these keywords were omitted because they cover issues beyond the scope of definition used in this book. That often occurred often with papers found by using the “design” keyword. Preconditions for including model-based papers in the review are consideration of at least two supply chain tiers and evaluation of multiple alternative supply chain configurations. The second precondition particularly affected inclusion of papers using simulation. Although several papers deal with issues related to strategic supply chain configuration, configuration is often treated as a fixed input parameter without considering any alternatives.

Chronologically, this survey covers the time period from 1995 to 2006, with a few earlier papers that have had a profound impact on supply chain configuration research (e.g., Bowersox 1972, Geoffrion and Graves 1974, Cohen and Lee 1989).

The supply chain configuration problem shares many common features with problems, such as distribution planning, supplier selection, manufacturing systems and facility location. Some references to the most important papers in these areas are included. Readers are referenced to survey papers in these areas for more detailed coverage: Owen and Daskin (1998) for facility location, De Boer et al. (2001) for supplier selection, and Shi and Gregory (1998) for manufacturing systems. The total number of papers reviewed is 91.

The literature is summarized by classifying papers according to the number of criteria and by evaluating complexity of supply chain configuration problems solved. The following sub-sections describe these criteria.

3.2.1 Classification Criteria

The literature classification criteria are chosen to represent the most important dimensions of the supply chain configuration problem, as well as describe general characteristics of papers. These dimensions have been identified in previous chapters of the book. Importance and values for each criterion are defined as follows.

Horizontal Focus

This criterion describes which tiers of the supply chain are considered in a paper. It allows judging about units assigning the largest value to configuration decisions. Typical values are supply tier, manufacturing tier, distribution tier, and customer tier. In many papers, the whole supply chain is covered, implying that all tiers are under similar levels of consideration.

Vertical Focus

It represents location of the problem investigated in the hierarchical decision-making structure comprising strategic, tactical, and operational decision-making levels. The supply chain configuration typically is a strategic problem. However, in order to represent its interactions with other areas of supply chain management, other decision-making levels are also included in decision-making models. Quantification of this criterion allows assessing of the importance of each decision-making level.

Specific Problem Area

Depending upon supply chain priorities and specific constraints, solving of the supply chain configuration problems can be more tightly coupled with some specific problem areas than others. For instance, inventory management can be of primary concern for supply chains delivering expensive products, while transportation is especially important for global supply chains delivering bulky products.

General Problem Area

As with specific problems, a particular general problem (e.g., globalization, coordination) can be the focus of a supply chain configuration study.

Modeling Technique

The criterion characterizes a modeling technique used to solve the supply chain configuration problem. Analysis of this criterion reveals the most often used techniques. Values of the criterion include different methods of mathematical programming, simulation, statistical analysis, data modeling, and hybrid techniques. Usually, one method is indicated unless several methods having similar importance to decision-making are used.

Application Area

This criterion indicates a particular industry.

Type of Paper

This criterion classifies papers as conceptual, model-based, technology, experimental, applied, and survey. Conceptual papers discuss general issues and methodological aspects of the supply chain configuration problem. Model-based papers propose some sort of supply chain configuration models, either quantitative or qualitative. Technology papers develop tools for supply chain configuration decision making or implementation. Extensive numerical studies are provided by papers categorized as experimental. Applied papers focus on solving a particular decision-making problem, and survey papers review existing works on the supply chain configuration.

Not all papers can be classified according to each criterion. For instance, the application area is not defined in all papers.

3.2.2 Complexity Criteria

The papers presenting quantitative models are also evaluated according to several criteria characterizing the complexity of considered supply chain configuration problems. This complexity evaluation is aimed at illustrating what types of problems can be solved in practice. The complexity criteria used in this review are as follows:

Number of units. This substantially influences the complexity of model building (i.e., data gathering is more complex) and the feasibility of model solving. This number generally counts as potential units.

Number of tiers. This influences the complexity of links among supply chain units. Customers are also counted as one supply chain tier.

Persistence. This characterizes whether supply chain configuration is perceived as relatively stable or if models contain some special constructions to represent quickly changing configurations.

Internationalization. Given the fact that many supply chains are multinational, international factors such as tax rates, exchange rates, and duties might have a major impact on configuration decisions. This criteria shows whether international features have been included in the model.

Product variety. Product variety influences the complexity of model development and the feasibility of model solving. This factor is of particular importance because of the increasing role of mass customization.

Integrity. Supply chains generally involve units representing relatively independent units. This criterion indicates whether models treat the supply chain as homogenous, or heterogeneity related issues are addressed.

3.3 Detailed Review

The detailed review is compiled in Tables 3.1 and 3.2, where papers dealing with supply chain configuration are categorized according to configuration dimensions and complexity criteria, respectively. The following abbreviations are used for the classification criteria in Table 3.1: HE – horizontal extent; VE – vertical extent; SP – specific problem; GP – general problem, MT – modeling technique; AA – application area; TP – type of paper.

Table 3.1 Detailed Review of Supply Chain Configuration Papers

#	Paper	HE	VE	SP	GP	MT	AA	TP	Short Description
1	Altiparmak et al. (2006)	A	S	—	MO	MIP, GA	Chemical	QN	A multi-objective supply chain configuration model is developed and solved using genetic algorithms. Methods for weighting objectives are proposed and evaluated.
2	Amiri (2006)	A	S	C	—	MIP	—	QN	A supply chain configuration optimization model is developed. Besides other variables, warehouse and plant capacity levels are used as decision variables. The Lagrangian relaxation-based solution procedure is developed.
3	Arntzen et al. (1995)	A	S,T	INV, TR	INT	MIP	Electronics	A	Applied supply chain configuration at the Digital Equipment Corporation. Global and computational issues are discussed. Reconfiguration has saved over $100 million.
4	Arntzen et al. (1998)	A	S,T	—	INT	MIP	Consumer	A	The model similar to that by Arntzen et al. (1995) is used to analyze impact of international factors on supply chain configuration at the 3M company.
5	Ballou (2001)	A	S	—	—	—	—	S	Definition of the network design problem is provided; open research issues such as data representation, scope extension, and comparison of methods used are identified.
6	Beamon (1998)	—	S	—	—	—	—	S	A survey of methods and performance measures used in strategic supply chain design and analysis is presented.

#	Paper	HE	VE	SP	GP	MT	AA	TP	Short Description
7	Bhutta et al. (2003)	M, D	S	INV,C	INT	MIP	Electronics	QN	Facility location model accounting for exchange and tariff rates is developed and applied to study policies at different levels of exchange rates.
8	Blackhurst et al. (2005)	A	T,O	—	CE	GR	Electronics	QL	A methodology for concurrent product and supply chain design is proposed. It facilitates identification of network improvement opportunities.
9	Bowersox (1972)	D	S,T	—	—	SIM	—	QN	The simulation model for long-range planning of distribution is developed for comparison of predefined configuration alternatives.
10	Camm et al. (1997)	D	S	—	—	MIP	Consumer	A	Optimization modeling and geographical information systems are combined to solve a supply chain configuration problem at Procter & Gamble.
11	Choi and Hong (2002)	S, M	S	—	PS	QA	Automotive	C	Supply networks for three automotive manufacturers are compared across formalization, centralization, and complexity dimensions.
12	Cohen and Lee (1989)	A	S	—	INT	LP	Electronics	QN	Supply chain structuring strategies for each supply chain tier are defined. An optimization model for total global after-tax profit is developed and used to solve supply chain configuration problems in the computer industry. Fixed values of integer decision variables are used according to the strategy

#	Paper	HE	VE	SP	GP	MT	AA	TP	Short Description
									under consideration.
13	Dasci and Verter (2001)	D	S	FL		LP	—	QN	Continuous model for distribution network design is developed as an alternative to discrete models.
14	Demeter et al. (2006)	S, M	S	—	PS	—	Automotive	C	Two automotive supply chains in Hungary are analyzed from the perspective of local suppliers.
15	Ding et al. (2006)	A	S, T	INV	MO	HY	Automotive, textile	QN, T	The decision support system based on application of a multi-criteria simulation based optimization is developed and applied to supply chain configuration problem solving.
16	Dogan and Goetschalckx (1999)	A	S, T	INV	—	MIP	Food	QN	Develops a multi-period production-distribution planning model. The solution algorithm along with some computational experiences is presented.
17	Dotoli et al. (2003)	A	—	IT	—	—	—	T, QN	The decision support system for supply chain configuration and its application process are elaborated. The process includes steps of pre-selection, selection, and evaluation.
18	Dotoli et al. (2005)	A	S, T, O	—	MO	AHP, DEA, MIP	Electronics	C, QN	The three steps of supply chain configuration procedure is developed. It involves pre-selection using statistical methods, optimization using mathematical programming and evaluation using simulation.
19	Dotoli et al. (2006)	A	S	—	MO	MIP	Electronics	QN	The supply chain is formally described using the graph theory and a multi-objective

#	Paper	HE	VE	SP	GP	MT	AA	TP	Short Description
									optimization model is developed. Energy consumption and CO_2 emission are among the optimization criteria.
20	Erengüç et al. (1999)	A	S, T	—	INT	MIP	—	QN, S	Reviews typical issues and problem formulations for all supply chain stages.
21	Eskigun et al. (2005)	D	S, T	TR	—	MIP	—	QN, EX	Design of outbound supply chain network is considered with respect to customer service performance measures. A Lagrangian relaxation-based model-solving heuristic is proposed and evaluated in experimental studies.
22	Fine (2000)	A	S	—	RC, CE	—	Electronics	C	High level supply chain design strategies are discussed on the basis of industrial case studies. Forces influencing supply chain dynamics are described.
23	Geoffrion and Graves (1974)	D	S	—	—	MIP	Commodities	QN	Model for strategic distribution planning and its solving procedure based on Bender's decomposition is developed.
24	Geoffrion and Powers (1995)	A	S	IT	—	—	—	S	Overview of supply chain design from the applied perspective, with emphasis on software capabilities is offered.
25	Goetschalckx et al. (2002)	A	S, T	TR	INT	MIP	—	QN, S	Importance of global factors is stressed and papers considering these factors are surveyed. Models for determination of transfer prices in a global system and for design of local logistics systems and their solutions are discussed.

#	Paper	HE	VE	SP	GP	MT	AA	TP	Short Description
26	Graves and Willems (2005)	M	S, T	INV	PT	DP	Electronics	QN	Supply chain configuration model based on selection between multiple available options at each stage is developed and applied for configuration of notebook manufacturing supply chain.
27	Gunasekaran and Ngai (2004)	—	—	IT	ING	—	—	S	Issues of IT for supply chain management are surveyed.
28	Gupta et al. (2002)	D, M	S	INV, M	—	LP, MIP	Consumer	A	Decision support system based on mathematical programming models for optimization of manufacturing and distribution networks at Pfizer is developed.
29	Harland (1996)	A	S	—	—	—	Healthcare	C, A	Supply chain design strategies are discussed. Supply networks for various healthcare products are defined.
30	Harland et al. (2001)	—	—	—	RC, PS	QA	—	C	Classifies supply chain networks according to degree of dynamics and influence of a focal firm.
31	Harrison (2001)	—	S	—	—	—	—	C	General (e.g., initial state, organizational) and global (taxes and local content) issues influencing supply chain design are discussed. Typical analysis and analysis methods are listed.
32	Hassan (2006)	A	S	—	—	HD	—	C	Supply chain is analyzed from the perspective of the system theory. Several hierarchical decomposition schemas of supply chains are provided.
33	Helo and	A		IT	ING	QA		C, T	A brief overview of software used in supply

#	Paper	HE	VE	SP	GP	MT	AA	TP	Short Description
	Szekely (2005)								chain management. is offered Functionality needed at different supply chain tiers is identified.
34	Huang et al. (2005a)	A	S	—	—	PM	—	QL, T	A descriptive supply chain process model is developed using concepts defined in the SCOR model. A software tool for process modeling is implemented.
35	Huang et al. (2005b)	M	S, T	INV	CE	MP, GA	Electronics	QN	Product design driven supply chain configuration models are developed and solved using genetic algorithms. Supply chain configurations with different levels of parts commonality are compared. Suppliers are selected with regard to manufacturing lead time and customer service criteria.
36	Hwang (2002)	D	—	—	CS	MIP	—	QN , T	The distribution network is established subject to service level requirements. Tools for visualization of modeling results are implemented.
37	Jang et al. (2002)	A	S, T	PP	INT	MIP	—	QN	The supply chain network design model is developed. The Lagrangian relaxation-based approach to solving the model is proposed, which is shown to speed up computations. The production planning model based on input from the design model is elaborated.
38	Jansen et al. (2001)	D	S, T	TR	—	SIM	Food	QN	Simulation modeling is used to analyze several logistics scenarios in a catering supply chain. Stochastic workload and transporta-

#	Paper	HE	VE	SP	GP	MT	AA	TP	Short Description
									tion delay parameters are included in the model.
39	Kim and Rogers (2005)	—	S	—	RC	OO	—	QL	Proposes a framework for building flexible supply chain business models using UML.
40	Kim et al. (2002)	S	S	—	OUT	SP	Electronics	QN	Supplier selection optimization model under stochastic demand and an iterative model-solving procedure are developed. Sensitivity of results with regards to capacity limits is analyzed.
41	Kirkwood et al. (2005)	A	S	—	MO	SA	Electronics	A	Decision support system for multi-objective supply chain configuration is developed and applied at IBM.
42	Ko et al. (2006)	D	S	TR	CO	HY	—	QN	Optimization model solved using genetic algorithm establishes supply chain configuration from the perspective of third-party logistics provider, and simulation model is used to evaluate the configuration with regard to demand and transportation uncertainty.
43	Ko and Evans (2007)	A, R	S	—	RL, PS	MIP, GA	—	QN	Supply chain configuration model, including reverse logistics facilities, is developed and solved using genetic algorithms. The configuration problem is analyzed from the perspective of third-party logistics providers.
44	Korpela et al. (2001)	—	S	—	—	AHP, PM	—	C, QL	Identification of supply chain objectives and definition of core processes is investigated.
45	Koutsoukis et	M,	S	—	—	MIP	—	C, QN,	Develops a decision support system, which

#	Paper	HE	VE	SP	GP	MT	AA	TP	Short Description
	al. (2000)	D						T	consists of MIP for network design under various scenarios, LP for aggregation of results, and OLAP for data analysis.
46	Kouvelis et al. (2004)	A	S	—	INT	MIP	—	QN, EX	Supply chain configuration model for evaluating various types of incentives (e.g., government financing and tax breaks) is developed. Experimental studies to illustrate the impact of incentives are conducted. Detailed case study data are provided.
47	Lakhal et al. (2001)	M	S	C	OUT	MIP	Appliances	QN	The supply chain configuration model is developed with emphasis on identification of outsourcing opportunities. The model-solving heuristic is developed.
48	Lamothe et al. (2006)	M	S	BOM	CE	MIP	Automotive	QN	A two-step procedure for concurrent product and supply chain design is proposed. Expressions for representing product design alternatives are elaborated. Model application is illustrated.
49	Laval et al. (2005)	D	S	TR	—	MIP	Electronics	QN, A	Optimization and scenario analysis are combined for comprehensive evaluation of configuration decisions at Hewlett-Packard. Collaboration of cross disciplinary project team is discussed.
50	Lee et al. (2002a)	A	S, T, O	INV, TR, M	—	SIM	—	QM	Application of simulation at different supply chain planning levels is discussed. A high level supply chain simulation model is developed and main parameters and variables

#	Paper	HE	VE	SP	GP	MT	AA	TP	Short Description
									at each tier are identified.
51	Lee et al. (2002b)	A	S, T	INV, PP	—	HY	—	QN	Integrated production planning is performed using the hybrid optimization-simulation approach for a fixed supply chain configuration. The simulation model accounts for uncertainty of manufacturing operations.
52	Li and O'Brien (1999)	A	S, O	INV	ING, MO	MIP	—	QN	A two-stage supply chain optimization model according to multiple criteria is developed. Each candidate unit attempts to optimize its performance to meet requirements set at the chain level.
53	Lieckens and Vandaele (2007)	R	S	INV	RL	NP, GA	—	QN	A non-linear programming model is formulated for configuration of reverse logistics network. Non-linear expressions allow accounting for inventory dynamic and demand uncertainty. Genetic algorithms are used to solve the model.
54	Lowe et al. (2002)	M	S	—	INT	SA, LP	—	C, QN	A two-phase approach to screening multiple alternative locations according to multiple criteria in the presence of exchange rate uncertainty is developed and illustrated by solving the Applichem, Harvard Business School case study.
55	Meixell and Gargeya (2005)	A	S	—	INT	—	—	S	Configuration research with emphasis on global models is surveyed in chronological order. Various alternatives of locating global supply chain units are defined.

#	Paper	HE	VE	SP	GP	MT	AA	TP	Short Description
56	Melachrinoudis and Min (2006)	D	S	—	—	MIP	Packaging	QN, A	A model for redesign of extensive network of warehouses is developed and applied in solving an industrial case study. Design alternatives are discussed. Detailed discussion on input data and sensitivity analysis of results obtained are provided.
57	Mentzer et al. (2001)	A	—	—	—	—	—	C	Defines supply chain management and its scope.
58	Mills et al. (2004)	A	—	—	—	—	Automotive	C	General characteristics of supply networks are analyzed with emphasis on dynamic evolution of these networks.
59	Mourtits and Evers (1995)	—	S,O	—	ING	HY	—	C, T	The network design decision support system, consisting of arrangement, deployment, flow, and operation models is proposed. The system is aimed at narrowing the gap between formal modeling and judgment-based final decision making.
60	Persson and Hager (2002)	M	S,T	M	—	SIM	Electronics	QN	A simulation model for evaluation of alternative configurations of manufacturing supply chain is developed.
61	Piramuthu (2005)	—	—	—	RC	AI	—	C, QN	A framework for automated supply chain configuration based on machine learning is developed and experimentally evaluated.
62	Pirkul and Jayaraman (1998)	M, D	S	—	—	MIP	—	QN, EX	A model for network design is developed along with its solution algorithm base in Lagrangian relaxation. Extensive computational efficiency evaluation studies are con-

#	Paper	HE	VE	SP	GP	MT	AA	TP	Short Description
									ducted
63	Pontrandolfo and Okogbaa (1999)	A	—	—	CO	—	—	S	Describes decisions made at different levels and stages of supply chain decision making.
64	Romeijn et al. (2006)	D	S, O	INV	—	MIP	—	QN, EX	A configuration model, including inventory and capacity utilization aspects, is developed and a general model-solving framework is proposed.
65	Ross et al. (1998)	A	S	TR	—	DEA, MIP	Petrol	C, QN, A	A methodology for supply chain reconfiguration on the basis of current performance evaluations is described. The test case is presented.
66	Ross (2000)	D	S	TR	—	MIP	—	QN, EX	Simulated annealing is proposed as the configuration model solving procedure. Efficiency of the algorithm is evaluated.
67	Sabri and Beamon (2000)	A	S,O	INV	MO	MIP	—	QN	A multi-objective model accounting for both strategic and operational factors is described.
68	Samaddar et al. (2006)	A	S	—	CO	—	—	C	Propositions regarding types of information sharing depending upon supply chain configuration are discussed.
69	Santoso et al. (2005)	A	S	—	INT	SP	Packaging	QN, EX	Stochastic programming models for network optimization, and its solving algorithm based on sample average approximation, are developed. Several acceleration schemas are proposed and numerically evaluated.
70	Schmidt and	D	S,T,	—	—	MIP	—	QN	Describes a general supply chain design

#	Paper	HE	VE	SP	GP	MT	AA	TP	Short Description
	Wilhelm (2000)		O						model along with a discussion of modeling issues. Related tactical and operational level models are also provided.
71	Senter and Flynn (1999)	M, S	—	—	—	—	Automotive	S	Evolution of supply chain structure and its drivers in the automotive industry are discussed. Future trends are identified.
72	Sery et al. (2001)	D	S	—	—	LP	Chemical	A	A model for reconfiguring BASF's distribution network is developed and model implementation results are reported. Reconfiguration is performed following the three-step procedure.
73	Shapiro (2001)	—	—	—	ING	—		C	Five aspects of supply chain modeling from the IT perspective are discussed.
74	Shen (2006)	D	S	TR	FL	MIP	-	QN	Distribution facilities location decisions are made with regard to demand choice flexibility. Modifications accounting for capacity and demand uncertainty are analyzed.
75	Stadtler (2005)	—	S, T, O	—	CO, ING	—	—	S	Describes advanced planning systems, which include network design modules. Directions for refinement of these systems including integration with other SC management systems and decentralized decision making are discussed.
76	Syam (2002)	D	S	TR	—	MIP	—	QN, EX	A distribution network planning model, which accounts for shipment consolidation, is solved using a combined simulated annealing and Lagrangian relaxation-based algorithm.

#	Paper	HE	VE	SP	GP	MT	AA	TP	Short Description
77	Talluri and Baker (2002)	A	S	—	CS	DEA, MIP	—	C, QN	A three-phase methodology for supply chain design is developed; it involves pre-evaluation of candidate units.
78	Themistocleous et al. (2004)	A	—	IT	ING	QA	Various	C, T	Describes supply chain integration technologies according to the type of information systems.
79	Truong and Azadivar (2005)	A	S	INV	—	HY	—	QN	Supply chain configuration methodology is developed. Genetic algorithms are used to set policy variables; mathematical programming is used to establish configuration according to inputs from genetic algorithms, and an automatically generated simulation model is used to evaluate decisions made.
80	Tsiakis et al. (2001)	A	S,T	TR	—	MIP	Chemical	QN	A multiple-period supply chain configuration optimization model with non-linear transportation costs is developed. Demand uncertainty is accounted for by using scenarios.
81	Van der Vorst et al. (2000)	A	S, O	INV, IT	MO	SIM	Food	QN	Simulation modeling is used for supply chain configuration in the food industry with emphasis on performance measures such as product freshness and write-offs. The Petri net formalism is used to define the simulation model. Information technology deployment policies are the strategic level configuration decision variables considered in the applied study.

#	Paper	HE	VE	SP	GP	MT	AA	TP	Short Description
82	Van der Zee and Van der Vorst (2005)	D	S, T	INV	—	SIM	Retail	C, QN	An object-oriented supply chain simulation framework is introduced. Representation of decision=making capabilities in simulation models is emphasized. An illustrative case study is provided.
83	Verwijmeren (2004)	A	—	IT	ING	—	—	C, T	Describes software component-based architecture for supply chain management, which supports integration and reconfigurability.
84	Vidal and Goetschalckx (1997)	A	S	—	INT	MIP	—	S	A survey of quantitative modeling in global supply chains is presented. It lists features of surveyed model and identifies directions for further research.
85	Vidal and Goetschalckx (2001)	M, D	S	—	INT	LP	—	QN, EX	After-tax profit of global supply chain is maximized. The model includes transfer price and cost allocation as decision variables. A solution procedure is elaborated and experimentally evaluated.
86	Vila et al. (2006)	A	S	M, INV	INT	MIP	Lumber	QN, A	Supply chain configuration is established for a given divergent manufacturing process. The model is applied to supply chain design in the lumber industry.
87	Viswanadham and Gaonkar (2003)	S, M	S, T	TR, PP	CS	MIP	Electronics	QN	A manufacturing supply chain optimization model is developed. Fixed ordering and setup costs are included in the model. Information sharing requirements for deploying the model are discussed.

#	Paper	HE	VE	SP	GP	MT	AA	TP	Short Description
88	Vonderembse et al. (2006)	—	S	—	—	—	—	C	Classifies supply chains as lean, agile, and hybrid, and characterizes typical products for each type.
89	Wu and O'Grady (2004)	S, M	S	—	—	GR, GA	Electronics	QN	Supply chain configuration is defined as a graph with AND and OR nodes. Genetic algorithms are used to optimize initial supply chain design.
90	Yan et al. (2003)	A	S	BOM	—	MIP	Electronics	QN	Supply chain design model is developed, where bill-of-material is represented using logical constraints.
91	Zhang et al. (2006)	M	S, T, O	—	RC	AI	—	T	An agent-based approach to management of manufacturing supply chain is proposed to enable supply chain reconfiguration to cope with dynamic changes. The supply chain reconfiguration is considered from the manufacturer's point of view.

Key:
HE: A – all supply chain tiers (not including reverse logistics), D – distribution tier, M – manufacturing tier, S – supply tier, R – reverse logistics
VE: S – strategic decision-making, T – tactical decision-making, O – operational decision-making
SP: BOM – bill-of-materials, C – capacity, FL – facility location, INV – inventory, IT – information technology, M – manufacturing, PP – production planning, TR – transportation
GP: CE – concurrent engineering, CO – coordination, CS – customer service, FL – flexibility, ING – integration, INT – internationalization, MO – multiple objectives, PS – power structure, OUT – outsourcing, RC – reconfigurability, PT – postponement, RL – reverse logistics

MT: AI – artificial intelligence, AHP – analytic-hierarchical process, DEA – data envelopment analysis, DP – dynamic programming, GA – genetic algorithms, GR – graphs, HD – hierarchical decomposition, HY – hybrid, LP – linear programming, MIP – mixed integer programming, NP – nonlinear programming, OO – object-oriented modeling, PM – process modeling, QA – qualitative analysis, SA – statistical analysis, SIM – simulation, SP – stochastic programming

TP: A – applied, C – conceptual, EX – experimental, QL – qualitative, QN – quantitative, S – survey, T – technology

Table 3.2 Detailed Evaluation of Complexity of Selected Supply Chain Problems

#	Paper	Number of Units	Number of Tiers	Time Horizon	Internationalization	Product Variety	Integrity
1	Arntzen et al. (1995)	<100	4	Multiple (18 months)	Developed countries	Medium	High
2	Bhutta et al. (2003)	<10	2	Multiple	Global	Low	High
3	Camm et al. (1997)	<100	3	Single	Local developed	Medium	High
4	Dogan and Goetschalckx (1999)	<1000	3	Multiple	—	Low	High
5	Geoffrion and Graves (1974)	<100	2	Single	Local	High	High
6	Jang et al. (2002)	<100	5	Single	—	Low	—
7	Kim et al. (2002)	<10	2	Single	—	Low	—
8	Kouvelis et al. (2004)	<100	3	Multiple	Europe, Asia, North America	Low	High
9	Pirkul and Jayaraman (1998)	<100	3	Single	—	Low	—
10	Ross et al. (1998)	<1000	3	Single	Local developed	Low	High
11	Ross (2000)	<5000	2	Single	—	Low	—
12	Sabri and Beamon (2000)	<100	4	Single	—	Low	—
13	Santoso et al. (2005)	<1000	4	Single	Local, global	Low	—
14	Syam (2002)	<100	3	Multiple	—	Low	—
15	Truong & Azadivar (2005)	<100	4	Single	—	Low	—
16	Tsiakis et al. (2001)	<100	4	Multiple	Developed countries	Medium	High

#	Paper	Number of Units	Number of Tiers	Time Horizon	Internationalization	Product Variety	Integrity
17	Van der Vorst et al. (2000)	<10	3	Multiple	Local	Low	Medium
18	Yan et al. (2003)	<10	4	Single	Local emerging	—	—

3.4 Focus Areas for Supply Chain Configuration

Results of the detailed review are cross-tabulated to identify focus areas of supply chain configuration research. Tables 3.3 and 3.4 report the cross-tabulation results according to horizontal and vertical extent dimensions, respectively. A majority of papers attempt to cover all supply chain tiers, while distribution gains the main attention if a separate part of the supply chain is of particular interest. That can be explained by a relatively higher level of flexibility in relocating distribution facilities and recent changes in distribution strategies due to advances in information technology and the organizational structure of enterprises (e.g., mergers, globalization). Indication that distribution is the horizontal focus, for instance, does not imply that only the distribution tier is considered. It shows that the main configuration decisions are made regarding the distribution tier. Although it is acknowledged that configuration decisions can be best evaluated in relation to other supply chain management decisions, a majority of papers still concentrate on the operational level.

Table 3.3 Number of Papers According to the Horizontal Extent (HE) Dimension

Value	Whole supply chain	Distribution	Supply	Manufacturing	Reverse
Number of papers	45	22	6	15	2

Table 3.4 Number of Papers According to the Vertical Extent (VE) Dimension

Value	Strategic	Tactical	Operational
Number of papers	77	23	11

The results for the vertical focus dimension relate to the most often considered specific problems (see Table 3.5). The table reports only those specific problems that have been addressed in more than one paper. Inventory management is the most often considered specific problem. Usually it is addressed in multi-period models, and safety stock requirements are also included in some models. While transportation flows are present in almost any configuration model, more detailed representation of the transportation problem is in 13 papers. That includes non-linear transportation costs, detailed choice of transportation mode, and analysis of transit time. Issues related to information technology related are generally investigated in papers exclusively devoted to this problem.

Table 3.5 Papers Considering Particular Specific Problems (SP)

Specific Problem	Paper
BOM (2)	Lamothe et al. (2006), Yan et al. (2003)
C (3)	Amiri (2006), Bhutta et al. (2003), Lakhal et al. (2001)
INV (17)	Arntzen et al. (1995), Bhutta et al. (2003), Ding et al. (2006), Dogan and Goetschalckx (1999), Graves and Willems (2005), Gupta et al. (2002), Huang et al. (2005b), Lee et al. (2002a), Lee at al. (2002b), Li and O'Brien (1999), Lieckens and Vandaele (2007), Romeijn et al. (2006), Sabri and Beamon (2000), Truong and Azadivar (2005), Van der Zee and Van der Vorst (2005), Van der Vorst et al. (2000), Vila et al. (2006)
IT (7)	Dotoli et al. (2003), Geoffrion and Powers (1995), Gunasekaran and Ngai (2004), Helo and Szekely (2005, Themistocleous et al. (2004), Verwijmeren (2004), Van der Vorst et al. (2000)
M (4)	Gupta et al. (2002), Lee et al. (2002a), Persson and Hager (2002), Vila et al. (2006)
PP (3)	Lee at al. (2002), Jang et al. (2002), Viswanadham and Gaonkar (2003)
TR (13)	Arntzen et al. (1995), Eskigun et al. (2005), Goetschalckx et al. (2002), Jansen et al. (2001), Ko et al. (2006), Laval et al. (2005), Lee et al. (2002a), Ross (2000), Ross et al. (1998), Syam (2002), Shen (2006), Tsiakis et al. (2001), Viswanadham and Gaonkar (2003)

NOTE: The number of papers for each specific problem is given in parenthesis.
See key from Table 3.1 for abbreviations.

Owing to the multi-national character of supply chains, analysis of global supply chains is the most often considered general problem (see Table 3.6). However, it still represents just 15 percent of all papers surveyed. Balancing of multiple objectives, supply chain coordination, and integration are other often investigated general problems. More recently, significant interest in concurrent supply chains, process, and product design has arisen. Such important problems as power structure and the broker's position have gained only minor exposition in the literature. That is also apparent in analysis according to the complexity criteria, which reveals that in quantitative models, supply chains are treated as relatively homogeneous entities. Heterogeneity is more often addressed in papers dealing with issues related to information technology.

In the context of this book which advocates the importance of reconfigurable supply chains, there are just five papers that explicitly address the problem of dynamic supply chain reconfiguration.

Table 3.6 Papers Considering Particular General Problems (GP)

General Problem	Paper
CE (4)	Blackhurst et al. (2005), Fine (2000), Huang et al. (2005b), Lamothe et al. (2006),
CO (4)	Ko et al. (2006), Pontrandolfo and Okogbaa (1999), Samaddar et al. (2006), Stadtler (2005)
CS (3)	Hwang (2002), Talluri and Baker (2002), Viswanadham and Gaonkar (2003)
FL(1)	Shen et al. (2006)
ING (8)	Stadtler (2005), Gunasekaran and Ngai (2004), Helo and Szekely (2005, Mourits and Evers (1995), Shapiro (2001), Themistocleous et al. (2004), Verwijmeren (2004), Li and O'Brien (1999)
INT (14)	Arntzen et al. (1995), Arntzen et al. (1998), Bhutta et al. (2003), Cohen and Lee (1989), Erengüç et al. (1999), Goetschalckx et al. (2002), Jang et al. (2002), Kouvelis et al. (2004), Lowe et al. (2002), Meixell and Gargeya (2005), Santoso et al. (2005), Vidal and Goetschalckx (1997), Vidal and Goetschalckx (2001), Vila et al. (2006)
MO (8)	Altiparmak et al. (2006), Kirkwood et al. (2005), Ding et al. (2006), Dotoli et al. (2005), Dotoli et al. (2006), Li and O'Brien (1999), Sabri and Beamon (2000), Van der Vorst et al. (2000),
OUT (2)	Kim et al. (2002), Lakhal et al. (2001)
PS (4)	Choi and Hong (2002), Demeter et al. (2006), Harland et al. (2001), Ko and Evans (2007)
PT (1)	Graves and Willems (2005)
RC (5)	Kim and Rogers (2005), Fine (2000), Harland et al. (2001), Piramuthu (2005), Zhang et al. (2006)
RL (2)	Ko and Evans (2007), Lieckens and Vandaele (2007)

NOTE: The number of papers for each general problem is given in parenthesis.. See key from Table 3.1 for abbreviations.

Mixed-integer programming is the most often used modeling technique. Simulation is the second most often used technique. However, given that simulation models have wider scope than mathematical programming models, it is often difficult to decide on categorization of simulation models. Application of hybrid models in supply chain configuration is increasing. Genetic algorithms are usually used to solve these models.

Table 3.7 lists papers reporting applications in particular industries. The electronics industry is most often considered. Configuration of computer manufacturing supply chains is particularly popular application case.

Table 3.7 Papers Reporting Application in a Particular Industry

Industry	Paper
Automotive (6)	Choi and Hong (2002) , Demeter et al. (2006), Ding et al. (2006), Lamothe et al. (2006), Mills et al. (2004), Senter and Flynn (1999)
Chemical (3)	Altiparmak et al. (2006), Sery et al. (2001), Tsiakis et al. (2001)
Consumer (3)	Arntzen et al. (1998), Camm et al. (1997), Gupta et al. (2002)
Electronics (16)	Arntzen et al. (1995), Bhutta et al. (2003), Blackhurst et al. (2005), Cohen and Lee (1989), Dotoli et al. (2005), Dotoli et al. (2006), Fine (2000), Graves and Willems (2005), Huang et al. (2005b), Kim et al. (2002), Kirkwood et al. (2005), Laval et al. (2005), Persson and Hager (2002), Viswanadham and Gaonkar (2003), Wu and O'Grady (2004), Yan et al. (2003)
Food (3)	Dogan and Goetschalckx (1999), Jansen et al. (2001), Van der Vorst et al. (2000)
Packaging (2)	Melachrinoudis and Min (2006), Santoso et al. (2005)

NOTE: The number of papers for each industry is given in parenthesis.

Finally, categorization of the papers according to the type of paper (see Table 3.8) shows that the majority of papers are devoted to quantitative modeling. There are a fair number of papers addressing conceptual issues of supply chain configuration. However, that is often done in an informal manner, which is also confirmed by the small number of model-based qualitative papers. Although applications are reported in many papers, detailed real-world supply chain configuration results, along with implementation experiences, are provided with just nine papers.

Table 3.8 The Number of Papers According to Their Type

	C	QN	QL	T	EXA		S
Number of papers	24	55	4	10	8	11	11

NOTE: Types are abbreviated as: A – applied, C – conceptual, EX – experimental, QL – qualitative, QN – quantitative, S – survey, T – technology.

Analysis of the review results according to the problem complexity criteria shows that solving relatively large and complex problems has become possible. Thus, Dogan and Goetschalckx (1999) solve multi-period problems with nearly a thousand potential supply chain units. However, one notable observation is that larger problems are usually solved in papers explicitly devoted to developing efficient model-solving algorithms, while papers oriented toward applications and expanding modeling scope usually treat problems of smaller sizes.

The majority of papers either do not address the internationalization problem, or they indicate that they deal with local problems. One of the key limitations of existing models is low product variety and the lack of mechanisms for representing realistic product designs. This issue has recently attracted significant attention in the framework of concurrent engineering. As already noted above, existing models tend to represent supply chains as relatively homogeneous entities.

3.5 Summary

Ninety-one papers have been identified as dealing directly with the supply chain configuration problem. These papers are categorized according to supply chain configuration dimensions and problem complexity criteria. The list of papers is representative though we cannot claim covering all possible papers.

The literature review suggests that there are several emerging areas of supply chain configuration research, such as:

- Application of hybrid optimization-simulation models
- Concurrent supply chain, process, and product design
- Integration of reverse logistics aspects into overall supply chain configuration models
- Investigation of dynamic supply chain reconfiguration

At the same time, important issues such as supply chain power structure have attained limited exposure in current literature. Additionally, models tend to address only the general or specific problems. For instance, coordination and integration are usually investigated in relation to the information technology problem, while they are investigated together with inventory management to a limited extent.

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4. Reconfigurable Supply Chains: An Integrated Framework

4.1 Introduction

The importance of supply chain management is increasing because companies face the necessity to improve customer service, which is not possible by considering just separate organizations. This need has been driven by increasing customer expectations, growing global competition, and technological developments, which have jointly contributed to greater uncertainty and volatility of enterprise management processes. However, as described in previous chapters, supply chain configuration, which forms the backbone of supply chain management, remains a long-term decision limiting the supply chain's ability to react to changing customer demand and operating environments.

One of the possibilities, to alter supply chain configuration with relatively minor resource requirements, would be a desirable supply chain characteristic. It depends upon multiple factors, both logical and technological. However, intelligent decision-making and the ability to adequately implement decisions forms the basis for resolving problems associated with other factors. This chapter presents the concept of reconfigurable supply chains and outlines a general approach to enabling reconfigurability. The described approach puts forward the decision-making aspect and proposes model-integration as a cornerstone of efficient decision making.

Section 4.2 introduces the concept of reconfigurable supply chains. It is followed by a description of multiple perspectives on supply chain configuration decision making, presented in the form of supply chain configuration problem taxonomy. Finally, an integrated framework supporting supply chain reconfigurability is presented.

4.2 The Concept of Reconfigurable Supply Chains

Reconfigurable supply chains is the next step in the evolution of supply chain structures. Forces driving this evolution and conditions for attaining reconfigurability are discussed. Reconfigurability also brings certain advantages and disadvantages to supply chain management, which are also discussed in the following subsections.

4.2.1 Need

Modern supply chains have enabled enterprises to improve their performance by coordinating activities among supply chain members. Supply chain configuration has been the backbone of this cooperation, defining members involved in the supply chain and the physical and logical links among them. Establishing supply chain configuration is a long-term decision with a planning horizon of two to five years. Such a long-term orientation has enabled supply chain partners to implement highly efficient models of collaboration covering the entire product life cycle, starting with product design and ending with reverse logistics operations. Effective information exchange, process integration, materials and product movement, and collaborative planning mechanisms can be established and fine tuned during the lasting cooperation. However, this approach has encountered multiple challenges in the last decade. Customer demand uncertainty is one of the primary challenges. This uncertainty shows up in multiple ways, such as increasing customer expectations for price, quality and delivery performance, demand for customized products, shortened product life cycle, and erratic demand behavior. These factors are supplemented by traditional uncertainty concerning demand volume.

The customer demand satisfaction challenge is tightly related to increasing global competition and technology development challenges because these drivers encourage customers to ask for more. Global competition offers an increased number of alternative providers of goods and services. Additionally, characteristics of these goods and services such as prices and quality, exhibit high variety. The technology development challenge offers less time to get acquainted with new technologies. On the other hand, technology development increases flexibility of manufacturing and service operations and simplifies the technical aspects of supply chain integration, which is an important enabler of efficient supply chain collaboration. However, this also allows companies to leave their current supply chain partners more easily and pursue involvement in other, more lucrative supply chains.

As a result, supply chains can no longer be expected to preserve their structure over a long horizon because they risk loosing their competitiveness or face internal collapse. The supply chain configuration must be able to respond to changing customer demands and operating environments. Reinforcement and modification of supply chain configuration is one of the solutions of meeting these requirements. Therefore, appropriate mechanisms for supporting reconfigurability should be embedded in supply chain configuration decisions.

4.2.2 Definition

The reconfigurable supply chain is a network of independent enterprises possessing the flexibility of altering its structure with relatively minor resource requirements and without loosing its operational efficiency in response to changing customer demands and operating environment (See Fig. 4.1).

By definition, a configurable (hence also reconfigurable) system can be designed, modeled, and configured for specific applications, and upgraded and reconfigured rather than replaced. With a reconfigurable system, new products and processes can be introduced with considerably less expense and ramp-up time.

Static and reconfigurable supply chains can be compared according to the role of tactical planning in the supply chain management process. At this supply chain planning level, configuration of the static supply chain is assumed as fixed (Chopra and Meindl 2004) and it defines constraints within which planning is performed. Reconfigurability, however, implies that strategic planning defines supply chain competitiveness and customer service targets, as well as the structural basis of the supply chain, (i.e., key units and links) and tactical planning can alter decisions with which partners involved in supply chain operations can achieve the set targets.

A hypothetical example of reconfigurable supply chains can be the transition from film cameras to digital cameras. The reconfigurability would imply that existing manufacturers are able to convert their manufacturing facilities to produce digital cameras. New products are designed in a way that the optical components require only minor redesign, and the existing film development network can be used for printing and distributing digital photos. However, reconfigurability does not imply preserving the *status quo*; hence, new component suppliers, such as extension memory manufacturers, are involved and new Internet-based distribution channels for digital photos are established. Some industrial examples of reconfigurable supply chains include production and distribution of DVDs by Disney's Buena Vista Home Entertainment unit (Hofman and Cecere 2005) and the supply chain of Unilever's Indian subsidiary, which relies on business process automatization through advanced Information Technology (IT) capabilities to connect with a large number of suppliers and customers (Jaiswal and Kaushik 2005). Principles of reconfiguration have also been adopted in the electronics industry (Kirkwood et al. 2005; Narayanan and Raman 2004).

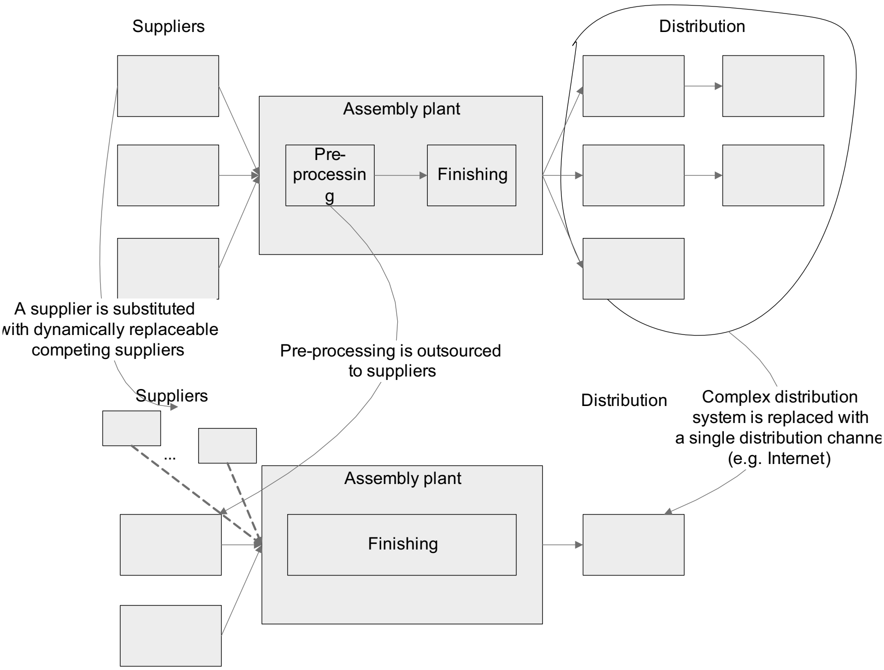

Fig. 4.1 A reconfigurable supply chain.

The problem of reconfigurable supply chains has three main aspects:

- *Decision-making*. Decisions about supply chain configuration are made, monitored and updated.
- *Physical implementation*. Building, opening, and operating manufacturing and service facilities, establishing and maintaining product flows, providing information technology infrastructure and designing and manufacturing reconfigurable products.
- *Logical implementation*. Business processes related to supply chain configuration and information systems support requirements are implemented.

The decision-making aspect determines what activities related to supply chain configuration are required. The physical infrastructure is built according to the decisions that are made. The logical implementation concerns utilization of physical implementation to achieve supply chain configuration and overall supply chain management objectives. It is also governed by the supply chain configuration decisions that are made.

The decision-making and logical implementation aspects are mainly afflicted by organizational difficulties and lack of knowledge. These deficiencies can be addressed by developing systematic and comprehensive decision-making and implementation procedures. Physical implementation is constrained by limited flexibility of available manufacturing technologies and high time and investment requirements. However, increasing use of outsourcing and third-party services in many situations eliminates the need for building an investment-heavy infrastructure. Similar improvements have also been achieved concerning manufacturing technologies.

4.2.3 Advantages and Difficulties

The main advantages of reconfigurable supply chains are

- *Robustness*. The supply chain is able to withstand external and internal shocks, such as loss of suppliers, labor disputes, and natural disasters, because suppliers can be replaced, manufacturing can be switched to alternative facilities, and transportation routes can be rearranged.
- *Flexibility*. Changing customer requirements can be accommodated by finding less expensive parts suppliers, choosing faster transportation channels, increasing product output volume, and introducing modified products.
- *Agility*. New business opportunities can be captured by engaging in relationships with innovative supply chain partners. Utilization of various Internet-based distribution options is a prominent example of supply chain redesign to find new business opportunities.

The main difficulties characteristic of reconfigurable supply chains and obstacles hampering their development are.

- *Organizational difficulties*. Time available to get accustomed to new partners, make decisions, and implement new business processes is limited. Lack of prior experience complicates decision making and performance evaluation.
- *Technological constraints*. Manufacturing facilities may not support the processing of materials supplied by different suppliers and the production of different variations of products, or product design may not allow for easy modification and the relative independence of some of the parts suppliers.

- *Trust*. Partners may not engage in close collaboration and information sharing, partially because of the possibility that cooperation will be relatively short.

The reconfigurable supply chain assumes a dual position in regard to the lean manufacturing paradigm. It contradicts lean policies by maintaining extra capabilities needed to facilitate quick transitions from one configuration to another. For instance, flexible manufacturing equipment might be required despite lower efficiency compared to dedicated equipment. Possibility of frequent changes of configuration also hampers the fine-tuning of supply chain operations. On the other hand, reconfigurability requires keeping the supply chain simple and transparent, which coincides with requirements to achieve lean operations. For instance, many automotive companies are not able to restructure their manufacturing networks and increase efficiency of manufacturing operations because of highly entrenched labor agreements.

4.2.4 Requirements

Following the definition of the main supply chain configuration problem areas given above, the main requirements to be met to achieve reconfigurability are divided into two groups:

- *Technological requirements* covering the physical implementation aspect
- *Logical requirements* covering the decision-making and logical implementation aspects

The technological requirements concern aspect such as IT infrastructure, product design, and manufacturing and logistics technologies. The requirements on IT infrastructure imply that supply chain units should be able to exchange information and integrate processes. The product design requirements imply that product structure can be flexibly altered following changes in the supply chain configuration (i.e., replacement of parts suppliers). The manufacturing requirements imply that manufacturing technologies possess flexibility to change product mix and production volume. The logistics requirements imply that material and product distribution channels can be switched and that their capabilities are adjustable.

Significant progress has been made in meeting technological requirements for supporting reconfigurability. Requirements concerning IT infrastructure are discussed in Chapter 11 of this book. Product design and manufacturing and logistics technologies issues are discussed by Singhal and Singhal (2002), Koren et al. (1999), and Anosike and Zhang (2006).

Modular product design allows the replacing of components of products more easily. Therefore, suppliers can be substituted more easily, even though components that they supply are not physically identical to those used previously. Similarly, manufacturing automation systems allow for quicker adjustment to the new properties of materials used and products demanded by customers as well as reallocating manufacturing to other facilities. Finally, utilization of third-party logistics services allows for flexibility in choosing transportation channels, thus enabling cooperation with partners located across the globe and offering the required degree of delivery responsiveness.

Satisfaction of business requirements is a challenging problem currently under active investigation. For purposes of further discussion, the following hierarchy of the business requirements is offered:

1. Commitment by entities involved in the supply chain.
2. Data and process integration.
3. Joint decision-making capabilities.
4. Joint decision-implementation and monitoring capabilities.
5. Data and process modification.
6. Modification of decision-making models.

Potential and existing supply chain partners must commit themselves to joint collaboration. Efficiency of decisions made often depends directly upon the willingness of supply chain members who need to agree on sharing potential supply chain benefits and losses, as well as sharing information and supporting cross-organizational business processes.

Data integration implies that consistent and current information necessary for decision making and decision implementation is available within an organization, as well as across the supply chain. This requirement does not imply that all data need to be shared. Process integration implies that supply chain members are able to execute cross-organizational business processes. For instance, configuration decisions made by a system operated by one supply chain partner can be used to generate simulation-based decision evaluation models run by other supply chain partners or third-party logistics providers is automatically notified about replacement of a supplier to reroute shipments. Data and process integration enables joint decision making, perceived as involvement of all supply chain members in the decision-making process which involves data gathering, decision making, and analysis of results. Supply chain partners are informed about the judgment behind decisions made, which is important to provide some level of certainty to supply chain members engaged in a dynamic structure such as reconfigurable supply chains. There are two additional requirements concerning decision-making, such as representation of impact of uncertainty and treatment of temporal issues. These requirements imply that a reconfigurable supply chain is to be built with respect to stochastic influences and expected dynamic changes of the structure. Decisions need to be uniformly implemented across the supply chain. Data and process integration play important roles in achieving this requirement. Readers are referred to Linthicum (2003) for more information on data and process integration.

Finally, methods and tools for relatively inexpensive updating of data, processes, and models are needed as the supply chain is continuously reconfigured. Otherwise, the supply chain would lag behind planned changes.

The main attention in this book is devoted to business requirements, especially to joint decision-making capabilities.

4.3 Configuration Problems and Methods

The requirements defined above must be met for all supply chain management problems included in the supply chain configuration scope definition (see Chapter 2). The problem space is reduced by focusing mainly on the decision-making aspect of supply chain configuration, as defined in Section 4.2.

The supply chain management problems are classified as general and specific. General problems mainly deal with aspects of supply chain coordination and integration, and the solving of a general problem includes solving several specific problems. Specific problems deal with a particular subject matter and can exist independently outside the supply chain environment. Supply chain configuration problems belong to the class of specific supply chain management problems. It involves multiple general and specific sub-problems. Furthermore, comprehensive evaluation of configuration decisions is not possible without considering interactions with other supply chain management problems.

To systemize accumulation and representation of supply chain management knowledge, a taxonomy of supply chain management and, particularly, supply chain configuration problems can be constructed. Development of a comprehensive, general taxonomy is a challenging task. However, supply chain members can develop their own taxonomy backed by industry-wide best practices as they accumulate supply chain management knowledge. Such taxonomy represents problems that a supply chain has dealt with and provides a basis for documenting problem-solving approaches. A segment of the supply chain configuration problem taxonomy is shown in Fig. 4.2. It shows only selected specific and general supply chain configuration problems. For instance, the network design problem includes aspects such as choice of network structure, selection of nodes, and establishing links among the nodes. If more detailed analysis is carried out, sub problems such as facility location and product-to-facility allocation are also addressed. All problems and sub problems can be further decomposed according to the circumstances characterizing these problems. For instance, the facility location problem has such lower-level specific problems, such as static or dynamic facility location, or single or multiple facility location. Similarly, the short-term forecasting problem can be further decomposed according to criteria characterizing demand properties. This decomposition cannot be represented using simple linear classification trees. Classification tables categorizing low-level problems according to multiple criteria are needed.

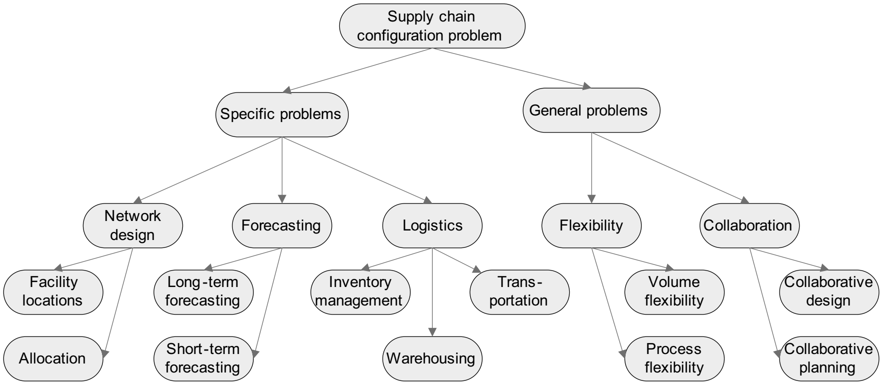

Fig. 4.2 A sample classification of selected supply chain configuration problems.

Each problem can be addressed from multiple perspectives or views, such as data, process, space, and time. The data perspective characterizes the information required to make and implement supply chain configuration decisions. It also describes the structure of the supply chain configuration problem. The process perspective describes supply chain processes in relation to supply chain configuration. The space perspective addresses issues of locating supply chain units and other physical aspects of supply chain configuration. The time perspective allows the analyzing of dynamic properties of supply chain configuration.

Simchi-Levi et al. (2003) show that the supply chain configuration problem has an explicit multi-dimensional characteristic that requires the application of different integrated decision models. Obviously, multiple interactions exist between decision components implementing configuration decision-making and other parts of the information system. Dotoli et al. (2003) has analyzed the configuration problem from the information systems perspective. They describe a decision support system for supply chain configuration emphasizing identification of data sources and the need for using multiple models to evaluate configuration decisions.

Given the variety of problems and their evaluation perspective, no single model can cover all aspects of supply chain configuration. These methods can be represented using the taxonomy of supply chain configuration methods. This taxonomy is part of the overall supply chain management taxonomy and includes references to problem-solving methods interacting with configuration problem solving (Chandra and Tumanyan, 2005).

Classification of supply chain models constitutes the upper level of the taxonomy. Beamon (1998) distinguishes between deterministic analytical models, stochastic analytical models, economic models, and simulation models. Similar classification is also given by Dong (2001). It includes a more detailed division between types of analytical models. Min and Zhou (2002) add hybrid and IT-driven models. The hybrid models are referred to as models incorporating features of stochastic and deterministic models. The IT-driven models include various software applications used in supply chain management. The importance of IT models is further emphasized by Kim and Rogers (2005) by adding a category of business process reengineering models. Riddalls et al. (2000) emphasize the usefulness of continuous differential equations in modeling supply chain dynamics.

Supply chain configuration models can be classified as follows (see Fig. 4.3):

- *Information models*. These describe the supply chain configuration problem from an information processing perspective. This category also includes IT-driven and business process reengineering models described in the literature.
- *Analytical models*. These mainly include mathematical programming models, which can be either deterministic or stochastic.
- *Simulation models*. These describe dynamic properties of supply chain configuration.
- *Hybrid models*. This combination of other types of supply chain configuration models are not necessarily confined just to combination of analytical and simulation models.
- *Statistical models*. Various statistical approaches are used to gain understanding about the supply chain configuration problem on the basis of accumulated historical data. These models so far are mainly considered as providing supporting functions, such as data preprocessing.

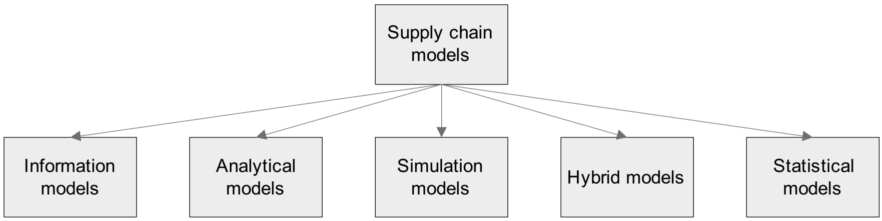

Fig. 4.3 Types of models used in supply chain configuration.

Further elaboration of taxonomy leads to identification of particular modeling methods for each type of models. However, this task is complicated by modeling methods belonging to various classes of models and methods. The taxonomy of supply chain methods would be a useful tool for identifying methods suitable for a particular decision-making situation. Some ideas for mapping between supply chain configuration problems and methods by using the supply chain taxonomy are presented in Chapter 6.

Several existing classifications of methods are usually confined to a single problem domain (e.g., forecasting (Makridakis et al. 1997) or inventory management (Kobbacy and Liang 1999). Few other classifications have been developed to cover a wider range of supply chain management problems. Slats et al. (1995) lists informal mapping between logistics activities and modeling techniques used to tackle these activities. The logistics activities listed include location of warehouses, locating potential suppliers, and arranging capacity and choice of information systems, which are highly relevant to the supply chain configuration problem, as well as several operational level activities. More detailed classification is provided by Sarmiento and Nagi (1999). Models dealing with integrated production-inventory-distribution problems are classified. Following the classification path, one can identify appropriate modeling methods down to references to particular models developed in the literature. However, the classification is limited to transportation features considered in particular models.

4.4 Integrated Frameworks

As highlighted in the previous section, the supply chain configuration problem possesses a high degree of complexity. Addressing only individual aspects of the problem is not sufficient to ensure high performance of the entire supply chain as well as that of individual units. Comprehensive problem solving for a large set of interrelated sub problems, however, is a challenging task. Therefore, an integrated framework enabling decision making and implementation of decisions is required.

The framework for the supply chain configuration is an instantiation of a more general supply chain management problem-solving framework, as both share common principles and requirements. However, the supply chain configuration framework is more focused, which allows analysts to lower the complexity of the problem without loosing overall supply chain perspective. The main differences occur at the framework application level, where knowledge, models, and tools are specifically designed to address supply chain configuration needs.

The integrated framework is developed in a spirit of a recent general drive for enterprise and extended enterprise integration, where decision making is advanced as one of the main beneficiaries (Cummins 2002). This allows companies to achieve competitive advantage over other companies. Delen and Benjamin (2003) and Delen and Pratt (2006) actively promote a general integrated modeling framework that links enterprise description models, enterprise analysis models, and enterprise knowledge base.

4.4.1 Existing Frameworks

The need for integrating models representing various problems from different views is conceptually widely acknowledged. A large number of specialized integrated models have been developed. However, the integrated framework should support model integration in general.

Shapiro (2000, 2001) emphasizes that such a framework requires a tight integration between decision modeling and information technology support tools. The described supply chain optimization framework has a database management system as its central component. This system processes input data from corporate databases and maintains a supply chain decision database. The model generator is used to develop an optimization model using data provided by the database management system. The advanced optimizer is used to solve the optimization model. Results obtained are stored in the decision-making database and are made available for further processing by spreadsheet programs and other analysis tools.

The supply chain configuration framework proposed by Dotoli et al. (2003) includes data analysis, network design, and solution evaluation modules. The data analysis module is used to preselect potential supply chain members by analyzing data accumulated in the company's database. The network design model is used to optimize supply chain structure. The solution evaluation module is used to evaluate the supply chain configuration by means of simulation. Evaluation is performed for various scenarios and informal feedback between evaluation and optimization is considered. Additionally, a search for consensus among decision-making parties at each decision-making stage is emphasized.

Dolk (2000) structures supply chain decision making around data warehousing, which provides a means for gathering information from various sources and presenting this information in a form suitable for conducting data analysis using Online Analytical Processing (OLAP) tools. The data warehouse is supplemented by a library of models, which use data from the warehouse. Organization of models in the library is discussed.

The decision-making and decision-implementation framework developed by Piramuthu (2005) specifically addresses the supply chain reconfiguration problem. Each supply chain unit dynamically chooses the available option for cooperation with supply chain partners. Decisions are based using the knowledge base in possession of each supply chain unit. Knowledge can be extracted from the knowledge base using various intelligent decision-making algorithms. The framework assumes that appropriate infrastructure is in place to implement any decisions made.

The object-oriented supply chain design modeling framework is developed by Kim and Rogers (2005). The modeling is driven by supply chain management goals and vision. The complex supply chain management problem is split into packages according to Supply Chain Operations Reference model (SCOR) division of supply chain process domains. Four views for each domain are developed to represent all aspects of the supply chain management problem. These views include function, structure (data), process, and behavior views, which are described using the Unified Modeling Language(UML) syntax. Business rules for transaction processing in the supply chain are added to the developed model. The obtained supply chain model can be used for implementation of a supply chain information system and are aimed to support relatively easy modification of this system. This framework emphasizes the information systems development aspect while the decision-making aspect is elaborated to a lesser degree.

4.4.2 Proposed Frameworks

The key principle underlying the proposed supply chain configuration framework (see Fig. 4.4) is model synergy. The model synergy implies that each model complements others to provide different perspectives of supply chain configuration decision making, and at the same time development and application of models is highly integrated to reduce complexity and to avoid inconsistencies and redundancies.

The proposed supply chain configuration framework starts with defining the decision-making capabilities of individual supply chain units. It is built on the basis of a common repository defining common concepts pertinent to the supply chain configuration problem. The problem taxonomy and the methods taxonomy are developed using concepts defined in the repository.

The supply chain configuration problems relevant to a particular decision-making situation can be mapped to problem-solving methods defined in the taxonomy of the supply chain configuration methods.

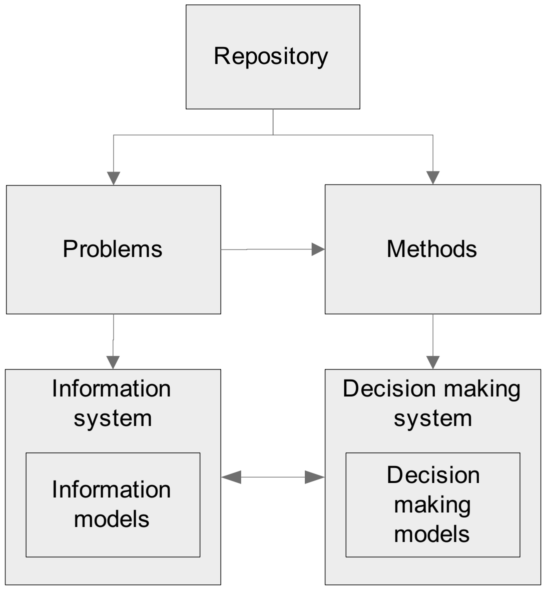

Fig. 4.4 The supply chain configuration framework.

A supply chain configuration decision model can be developed by extracting appropriate decision-making methods from the taxonomy. To address the multi-dimensionality of the configuration problem, the decision modeling systems consist of multiple sub-models, which will be discussed in the following chapters. At the same time, information models are used for a descriptive analysis of the decision-making problem for defining the decision-making process, and data exchange mechanisms between the decision-modeling system and other parts of the enterprise-wide information system. Similar to the decision-making models, the information models are also interrelated and form a consistent part of the information system. They use data extracted from problem and methods taxonomies to determine the parts of the enterprise-wide information system that are relevant to a particular decision-making problem and the data that are needed to solve the problem.

The decision-making capabilities of individual supply chain members are brought together to enable joint decision making and technological implementation of decisions (see Fig. 4.5). The supply chain configuration system brings together individual supply chain units. It is designed according to the architecture of the proposed configuration framework (see Fig. 4.4). Each supply chain unit has its own supply chain management system, which also implements the proposed framework as one of its modules. Supply chain configuration decisions are made through the collaboration of the overall supply chain configuration systems and supply chain management systems of individual units. The supply chain configuration system can be a centralized system maintained by one member or a group of supply chain members. In this case, a central supply chain configuration model is developed, which may also invoke models maintained by individual supply chain members. It can also be a distributed system, although such an approach appears to be more suitable for configuration monitoring and maintenance purposes. This approach to defining a supply-chain wide decision-making body relates to work by Pontrandolfo and Okogbaa (1999). They describe the supply chain decisions that can be made locally and those that require centralized coordination. Supply chain configuration decisions are attributed to decisions requiring centralized decision making. Local and global planning capabilities are also considered in the SCOR model.

The common knowledge refers to industry standards and generally accepted supply chain management concepts. The common knowledge facilitates established mappings between concept definitions in repositories maintained by individual supply chain units, thus leading to easier establishment of the common repository used by the supply chain configuration system.

An abstract interface is shown in Fig. 4.5. It provides data and process integration during both the decision-making process and the implementation of configuration decisions. Technological solutions for implementing this interface are discussed in Chapter 11.

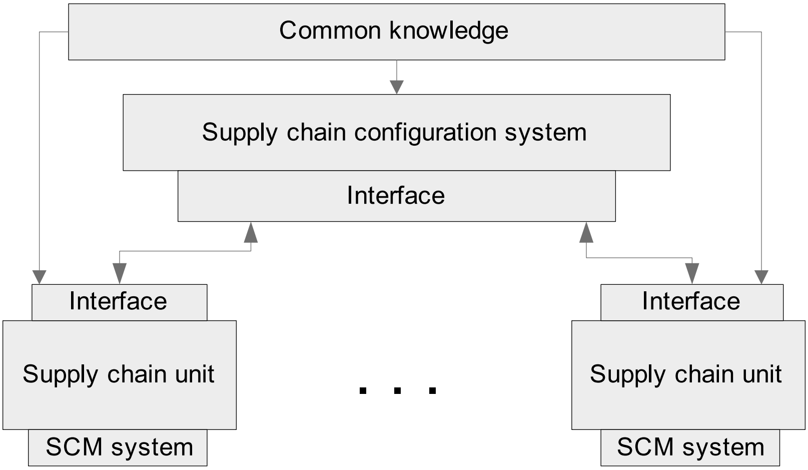

Fig. 4.5 Joint decision-making and decision-implementation approach based on the integrated supply chain configuration framework.

Application of the proposed framework in the supply chain configuration process is described in the Chapter 5 which presents a supply chain configuration methodology, while practical implementations of the framework are discussed in Chapters 7, 10, and 11.

4.5 Summary

The proposed framework has brought together existing ideas on supply chain configuration decision making and decision implementation. It also emphasizes concepts needed to support reconfigurability. The main features of the framework are

- Modeling synergy and maintenance of consistent and up-to-date models
- Support for collaborative decision-making
- Utilization of decision-making capabilities of individual supply chain units as well as those of the entire supply chain
- Integration between decision modeling and the supply chain management information system
- Knowledge-driven approach
- Emphasis on efficient implementation of decisions

The framework enables reconfigurability by providing a means for efficient and comprehensive decision making, streamlining the implementation of decisions and incorporating new members into the supply chain.

This is mainly achieved by maintaining integrated and consistent information and decision-making models. Changes in the supply chain can be quickly represented into decision-making models and supply chain execution information systems.

Mapping between problems and available methods to a specific problem-solving model is performed by a decision analyst. Knowledge structuring remains a principal hurdle in the automation of this process.

It has been indicated that product design and manufacturing and logistics technologies play important roles in supporting reconfigurability. Several recent works address these issues, although these areas remain insufficiently integrated. Wang et al. (2004) point out that supply chain design decisions should be driven by product characteristics and product life cycles. Therefore, a supplier selection model is structured to address these product life cycle-related issues. Concurrent engineering practices so far primarily have been applied in relation to manufacturing systems. Their extension toward including supply chain design is an obvious direction of further developments. Blackhurst et al. (2005) propose a methodology for the design of supply chain operations by also considering the product and process design. Several other studies on coordinated product, process, and supply chain design are assembled by Rungtusanatham and Forza (2005) and Forza et al. (2005).

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5. Methodology for Supply Chain Configuration

5.1 Introduction

The previous two chapters have highlighted the magnitude of the supply chain configuration problem. Before starting with the description of models and tools available for solving the identified problems, a systematic approach for dealing with the configuration problem is laid out in this chapter. A systematic approach defined by a methodology would facilitate binding together different aspects of the configuration problem and provide problem-solving guidelines.

This chapter describes a general supply chain configuration methodology that aims to cover all major aspects of supply chain configuration. The methodology consists of 11 steps. It starts with conceptual modeling of the supply chain configuration problems and gradually moves towards quantitative analysis. A description of the methodology includes guidelines and a set of methods and tools suited for performing specific steps. These methods and tools are outlined in this chapter and are discussed in more detail in Part II. Given that solving the configuration problem requires support of multiple computational tools, architecture of the decision support system implementing the methodology is also developed.

The supply chain configuration methodology has a similar pattern to many other modeling methodologies. The main processes comprising the methodology are identification and definition of the problem, solving the problem and validation and implementation of results. Completion of every process is marked by specific deliverables. Providing the resources required (in this case, data, model-solving approaches, and tools) is another issue to be addressed by almost any methodology.

The rest of this chapter is organized as follows. Section 5.2 lays out the background for developing a methodology for supply chain configuration. Section 5.3 discusses the key issues to be addressed by the methodology. The entire configuration process is discussed in Section 5.4. Steps of the methodology are elaborated in more detail in Section 5.5, which include outlining models available for performing each step. Architecture of the configuration decision support system is given in Section 5.6. Section 5.7 summarizes the chapter's contents.

5.2 Background

The methodology described in this chapter also draws upon several supply chain configuration methodologies proposed in the literature. Supply chain configuration methodologies typically cover decision-making stages, such as preparation for supply chain configuration problem solving, establishing the supply chain configuration, and an evaluation of decisions made.

The Cardiff Methodology for supply chain reengineering developed by the Logistics Systems Dynamics Group at the University of Wales (Naim 1996) is one of the first comprehensive methodologies for supply chain analysis at the strategic level. This methodology is primarily oriented toward an analysis of system dynamics using simulation on the basis of a supply chain business process model. It starts with defining business objectives followed by system input/output analysis. Construction of the conceptual model is the next step, aided by the library containing generic modeling components. The conceptual model is used in developing several quantitative models. Results obtained by means of quantitative modeling are verified and validated. Special attention is paid to model tuning and analysis of business scenarios. The methodology includes multiple feedback loops.

Ross et al. (1998) develop supply chain reconfiguration methodology, which focuses on the need for reconfiguration as a result of performance analysis of existing configurations. Best practices are identified during the first stage of the methodology. These are incorporated into the reconfigured supply chain. The authors list some of the methods available for performing each step. Consensus-building processes are emphasized.

Talluri and Baker (2002) develop a three-phase supply chain configuration methodology. The first phase identifies and evaluates candidate supply chain units. The second phase establishes a supply chain configuration. The third phase deals with tactical planning on the basis of the established configuration. Mathematical models for each stage are provided. Two distinct features of this methodology are the presence of a broker representing the supply chain power structure and detailed discussion on the preselection of candidate supply chain units.

The supply chain configuration methodology developed by Dotoli et al. (2003) includes the creation of a decision-making team, data acquisition, preselection of candidate supply chain members using data envelopment analysis, and optimization and evaluation of the configuration. All major steps are followed by a discussion of the results. Piramuthu (2005) proposes a methodology for automated supply chain reconfiguration. This methodology is based on exploration of accumulated supply chain management knowledge.

Establishment of configuration and evaluation stages are considered in the methodology presented by Truong and Azadivar (2005). It is split into two parts: 1) determination of qualitative policy variables, and 2) determination of quantitative variables. These decisions are made in an iterative manner. Evaluation is performed using simulation modeling, where the simulation model is automatically generated according to optimization outcomes.

De Boer et al. (2001) devote their main attention to activities during the preparation stage. The problem-solving path to be followed is shown to depend upon initial decision-making circumstances. Particular decision-making methods in each situation are identified. While this methodology is aimed at dealing with supplier selection problems, some principles can also be applied in the wider, supply chain configuration context.

Simchi-Levi et al. (2003) and Shapiro (2001) provide a general discussion of steps to be performed in supply chain modeling. Bowersox et al. (2002) provide an excellent overall description of issues related to the supply chain configuration. That also includes a planning methodology consisting of feasibility assessment, project planning, data collection, analysis (i.e., configuration modeling), development of recommendations, and implementation steps. General aspects and available main methods are also discussed by Chopra and Meindl (2004), as well as in several other general supply chain management textbooks. There are a number of other works structuring the supply chain configuration problem; however these works have a relatively narrow focus. They will be considered during the discussion of individual steps of the proposed methodology. The Supply Chain Operations Reference Model (SCOR), along with its application guidelines (Stephens 2001) provides a widely accepted source of reference to many supply chain management and decision-making activities. Software developers such as SAP (*www.sap.com*) and Manugistics (*www.manugistics.com*) also provide the means for systematic approaches to supply chain configuration from the tool usage perspective.

These existing methodologies cover some aspects of the configuration problem. A more comprehensive methodology built upon the existing knowledge is described in the following sections. The main attention is devoted to identification of choices to be made at each step.

5.3 Key Issues

The methodology includes multiple steps common to many modeling methodologies, such as definition of performance measures, data gathering, execution of models, and analysis of results. There are also several issues relatively unique to supply chain environments and supply chain configuration. Many of these issues are defined by the distributed character of supply chains, which are often formed by relatively loosely coupled organizations.

The supply chain power structure is one of the major unique factors. The concept of a broker is adopted here (Ross et al. 1998). The supply chain configuration problem is formulated substantially differently depending on relationships between the organizations involved; thereby influencing parameters included in the model and considered performance measures.

The completely centralized supply chain owned by a single company is the most rigid case of the supply chain power structure. The decision-making process also can be centralized in the case of one dominating supply chain unit that picks its partners. However, even in this case, the dominant unit should account for the interests of other units to some extent because the notion of mutual dependence between supply chain members is widely recognized. In contrast to the centralized supply chain, a supply chain can be composed of independent units having approximately equal importance. In this case, the configuration decisions can be coupled with some compensation mechanisms, whereby some supply chain members compensate other members who bear additional configuration-related expenses to establish more efficient overall structure.

Although data gathering is the common function for any modeling effort, the distributed character of supply chains brings in an additional dimension to this problem. Data should be gathered not only from multiple sources in one organization, but also from multiple organizations. That is made difficult by both technical and trust issues. Depending upon the configuration methods used data requirements vary greatly. However, even though mathematical programming seemingly requires only a little data, the data volume needed to estimate parameters accurately might be large. Data availability issues are softened by the increasing popularity of integrated information systems, such as Enterprise Resource Planning (ERP) systems.

Comprehensive evaluation of the configuration problem requires using several alternative models. It is well known that mathematical programming models are well suited to deal with the spatial aspects of a configuration problem while they struggle to deal with temporal aspects (Ballou 2001). Simulation is more appropriate to deal with the latter. The methodology should address the problem of efficient development of multiple models.

Appraisal of modeling results poses two major difficulties: 1) combination and interpretation of results given by multiple models; and 2) balancing quantitative results with assumptions made by a human decision maker. Multiple models present different views of the problem. It is crucial to evaluate results with respect to derived confidence bounds. Additionally, long-term strategic decisions involving huge costs and made by top executives are often adjusted on a judgmental basis. Although these adjustments representing factors not captured by models are often valuable, the balance between trust in quantitative results and judgmental decisions is to be defined to avoid nullifying the modeling effort.

To summarize this discussion, the main requirements for the methodology are outlined below:

- Parties involved and the power structure are clearly defined
- Data are well-structured to enable construction of multiple models
- Means for efficient selection of appropriate models and development of selected models are provided
- Guidelines for evaluation and approbation of modeling results are provided

The methodology is also required to provide guidelines for addressing organizational issues, and to support the development and maintenance of a modeling repository, which accumulates information about decision-making processes.

5.4 Configuration Steps

The decision-making process can be initiated by a need to either establish a new supply chain or reconfigure an existing one. The supply chain configuration initiative is put forward by a broker. It is assumed that the broker knows the purpose of the supply chain to be established. The broker can represent a diverse range of organizational structures. Some of these structures include

- Dominating unit
  - specialized
  - with different supply chain functions
  - consortium
- Supply chain-wide consortium
  - consortium of several units

- equal power units

Given that the supply chain configuration initiative has been initiated, the supply chain configuration process follows the methodology outlined below:

*Step 1 — Initiation of the configuration initiative.*Given that there is a need for solving the configuration problem, the first step develops a formal justification for undertaking the configuration initiative. Objectives of the configuration initiative are defined. Decision-making circumstances are identified. Feasibility and expected returns are evaluated to decide on acceptance of the configuration initiative. Identification of the impact of expected configuration decisions on other supply chain management processes is important.

*Step 2 — Decision-making circumstances and modeling scope.*Definition of the modeling scope is done according to the framework established in Chapter 2. The main dimensions to be specified are the evaluation criteria, decision variables, and parameters involved.

Step 3 — Information modeling. On the basis of modeling requirements defined during the first two steps, information models of the configuration problem are developed. These include a workflow model demonstrating the cooperation of decision makers and other parties involved, a process model showing relationships between configuration problems and other managerial problems (as well as functionality of the supply chain configuration), and the data model defining data needed for solving the configuration problem and their sources. Integration between these models and the supply chain-wide information systems is identified in this step.

Step 4 — Reevaluate objectives subject to data availability. Data availability can be a major hurdle, especially in the case of a newly designed supply chain. Decision-making objectives and needs are evaluated subject to data availability.

Step 5 — Establish a decision-making plan. Situations to be evaluated and acceptance criteria are defined. The acceptance criteria are particularly important given that evaluation is performed using multiple models, results are to be examined by different supply chain members, and quantitative results are likely to be adjusted by human decision makers.

Step 6 — Preselection. Supply chain configuration is typically established from a set of candidate units, possibly of different types. This step reduces the number of candidate units. It is necessary to reduce computational burden at the following selection step and because different selection criteria are often used at the preselection stage.

*Step 7 — Development and execution of selection models.*Qualitative or quantitative models for final selection of candidate units and establishing links between these units are developed and executed. There can be more than one model, and different parameters and configuration performance evaluation criteria can be used for each model. Additionally, combinations of models (i.e., hybrid models) are often considered. Verification and validation of models is also a part of this step.

Step 8 — Analysis of output data. Absolute and relative performance of evaluated configurations is summarized. Confidence bounds for the results obtained are established. Sensitivity analysis to identify the most important parameters is conducted.

Step 9 — Acceptance of results. Two levels of acceptance are distinguished. At the first level, the configuration decision-making group finds its consensus about modeling results and makes any necessary adjustments. At the second level, the top management decides on adoption of configuration decisions proposed. Adjustments are introduced at this level, too.

Step 10 — Implement the configuration decisions. Physical location of supply chain units and the establishing of flows among units is the main concern of implementation. However, there are many logical aspects, as well. Adoption of configuration decisions triggers development of models for tactical and operational decision making. Some of the configuration models or their parts might be used in a continuous manner.

Step 11 — Evaluate the implemented configuration decisions. After the configuration decisions are implemented, the performance measures are monitored to check their correspondence to values expected during the modeling. Additional performance measures can be formulated to test real-life performance of the supply chain configuration and decide on further configuration activities as required.

The modeling methodology is iterative, and feedback loops exist to return to previous steps (see Fig. 5.1). The most important feedback loops are those going from either Step 8 or Step 9 to Step 5. These loops deal with adjusting experimental plans depending on newly identified issues and data requirements.

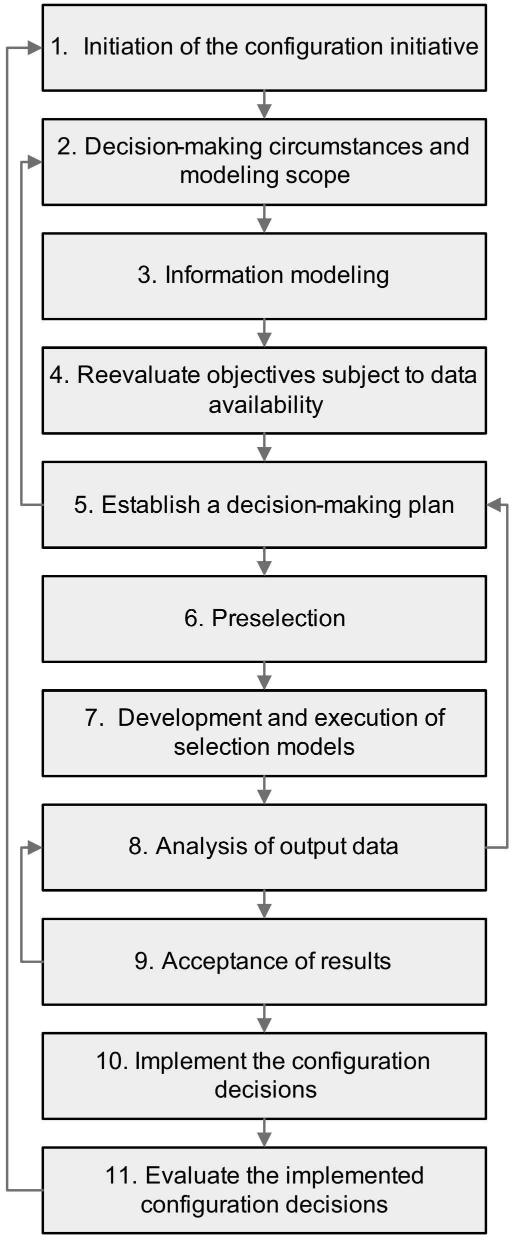

Fig. 5.1 Schematic representation of the configuration methodology.

Overlapping among several steps is possible. The most obvious case is relationship between Steps 2 and 3. Development of information models already can be used to formalize the scope definition. Steps 7 and 8 may also overlap in several situations. For instance, there are two models with different execution cycles. One of the models can still be used to establish the configuration, while sensitivity analysis is already conducted for another model.

5.5 Elaboration of Steps

This section elaborates the steps of the methodology in more detail. Steps are categorized as management and engineering steps. The level of discussion depends upon the category and more attention is devoted to the engineering steps. The engineering steps are Steps 3, 5, 6, 7 and 8. Steps 2, 4, 9 and 11 are mixed engineering and management steps. Step 10 is also a mixed engineering and management step, although it includes mainly activities classified as external to the configuration decision making. For each step, major decisions to be made and available decision-making methods are outlined. The discussion is wrapped up by a summary of relevant issues.

5.5.1 Initialization of Configuration

As discussed in the Chapter 2, on the scope of supply chain configuration problem, there are multiple drivers behind the configuration effort and organization have different objectives in undertaking this effort.

Initialization of configuration problem solving is caused by strategic supply chain decisions. These decisions are based on an assessment of the current supply chain situation (Bowersox et al. 2002). The situation assessment includes internal review of supply chain structure and performance, assessment of market and competition, evaluation of the relationship between supply chain partners, and assessment of technological factors. This situation assessment is further refined during the initialization step. Bowersox et al. (2002) provides guidelines for conducting the situation assessment.

Assessment of returns is made with regard to both modeling costs and costs associated with implementation of configuration results. In many cases, modeling costs are substantially smaller. Therefore, even if configuration decisions are not expected to yield positive returns, a broker can proceed with the modeling effort to gain a better understating of the problem and to obtain more precise estimates. However, modeling costs also can be high enough to cancel the configuration initiative if returns on implementing configuration results are not positive. In this case, a scaled-down version of a supply chain configuration initiative is likely to arise.

Assessment of returns is repeated during later steps of the methodology as more information becomes available.

As noted before, it is assumed that the need for reconfiguration has been identified and strategic objectives have been set. It has to be acknowledged that the literature concerning these issues in the supply chain management context (and even more so in the supply chain configuration context) is surprisingly scarce. Korpela et al. (2001) use analytical hierarchical process to identify general supply chain design objectives and the properties associated with these objectives. Vonderembse et al. (2006) categorizes supply chain design situations according to type of products and the stage of the product's lifecycle. This categorization allows for identification of the type of supply chain design needed: lean, agile, or hybrid. Attributes characterizing each type are provided. An enterprise can evaluate its current situation with regard to this categorization and identify structural changes needed in its supply chain. Ross et al. (1998) emphasize in their methodology that the need for modification arises from analysis of accumulated performance data. Harland (1996) positions supply chain configuration in the cycle of strategic priorities formulation, supply network structure development, and implementing appropriate infrastructure.

Readers are referred to Chandler (1962) for discussion on the managerial approach, and to Bubenko et al. (1998) or Kosanke et al. (1999) for discussion on the engineering approach to defining strategic objectives.

5.5.2 Decision-Making Circumstances and Modeling Scope

Modeling scope describes configuration objectives, objects, parameters and costs involved, and relevant constraints. Decision-making circumstances are also defined at this step. This information provides the basis for further formalization of the decision-making problem during the information-modeling step.

Decision-Making Circumstances

Table 5.1 lists attributes characterizing decision-making circumstances. Values of the power structure attribute are similar to those of the broker. However, the decision-making situation is defined by a combination of power structure and broker. For instance, the supply chain configuration initiative is put forward by a broker representing the minority unit in the supply chain environment with the dominating unit. The specialized dominating unit power structure implies that a dominating unit concentrates just on its core competencies while the non-specialized dominating unit power structure implies that a dominating unit assumes various functions and different supply chain stages. For instance, many automotive Original Equipment Manufacturers (OEM's) are transforming themselves from a non specialized dominating unit to a specialized dominating unit by outsourcing the manufacturing of many components and abandoning plans to enter distribution.

Decision-making is greatly influenced by the initial state of the supply chain. The initial state influences collaborative decision-making processes because the level of trust among potential partners might vary substantially. This attribute also relates to the information availability attribute. In the case of a new supply chain, little information is available for appraisal of parameters characterizing links between supply chain units. For instance, a potential supply chain partner can evaluate its delivery lead time and quote it for supply chain modeling purposes. However, this quote may not account for specific time delays caused by interactions between this particular supplier and a manufacturer.

More efficient supply chain decisions can be made and implemented if information is shared among supply chain partners. In the case of complete information sharing, the main problem is establishing physical and logical channels of information exchange. The complete information sharing applies only to information needed for supply chain configuration decision making and implementation of decisions. In the case of limited or no information sharing, a broker relies on publicly available data, indirect observations (e.g., historical sales orders), and assumptions. Use of indirect observations leads to problems such as the bullwhip effect (Lee and Whang 2000). Limited information sharing is frequently a problem in early decision-making stages, and one should assess whether information sharing will improve upon engagement in supply chain execution.

Data availability relates to information sharing. However, even if complete information sharing is in place, historical data might not be available. This problem is especially severe in the case of the design of a completely new supply chain network. Many statistical analysis methods used in the preselection stage depend upon data availability, which varies among supply chain partners. Therefore, accuracy of estimates for individual units needs to be taken into account during evaluation of the supply chain network.

The number of alternatives characterizes such factors as number of alternative suppliers, number of alternative locations for manufacturing and distribution facilities, and number of transportation modes. The number of alternatives substantially influences the selection of decision-making models. A large number of alternative suppliers usually require preselection of suppliers. A large number of alternative locations requires initial continuous search for optimal locations. Abundance of alternatives complicates data gathering and model-solving tasks. The product variety also needs to be accounted for. Aggregation of products is usually considered in the case of high product variety.

Table 5.1 Attributes Characterizing Supply Chain Configuration Decision-Making Circumstances

Attribute	Values
Power structure	Specialized dominating unit
	Non-specialized dominating unit
	Supply chain wide consortium
	Consortium of several units
	Equal power units
Initial state of the network	New supply chain
	Existing supply chain with minority of units fixed
	Existing supply chain with majority of units fixed
Information sharing	Complete information sharing
	Limited information sharing
	No-information sharing
Data availability	Historical records available
	No historical records available
	Some historical records available
Number of alternatives	No alternatives
	Few candidates
	Large number of alternatives

The power structure directly influences the definition of configuration objectives. For instance, a dominating unit can focus almost exclusively on its own objectives, while a consortium of equal partners needs to consider the objectives of all partners in the multi-objective framework. A choice of relevant parameters and costs is particularly influenced by a broker. For instance, from the point of view of a manufacturer, he/she is only concerned about the cost of raw materials, but not about the other internal costs of a potential supplier. Questions about accounting for transportation costs also need to be resolved — either these are included in the purchasing cost, paid by the supplier, or paid by the manufacturer.

Decision-making problem definition also depends upon the type of broker and the power structure. For instance, a broker representing a minority unit also analyzes costs incurred to the dominating unit, even if he/she does not account for these costs directly.

Scope

The definition of scope provides an initial description of the decision-making problem. This initial description will be formalized and further refined in the next step by means of information modeling. Issues represented in the scope definition correspond to those identified in Chapter 2.

Table 5.2 shows a sample scope definition for an arbitrary supply chain configuration problem.

Table 5.2 A Sample Scope Definition

Scope Parameter	Values
Objectives and criteria	Improve supply chain performance Total cost
Horizontal extent	Supply, manufacturing
Vertical extent	Strategic, tactical
Decisions	Location of assembly plants Purchasing quantity from suppliers Quantity of products produced at each assembly plant
Parameters	Purchasing cost Transportation cost Production cost Fixed plant opening/operating cost
Processes and functions	Inventory management

Definition of decision-making circumstances and modeling scope relates to describing supply chain typology (Meyr and Stadtler 2005). This typology describes a supply chain by a set of functional and structural attributes. Four categories of functional attributes are procurement type, production type, distribution type, and sales type. Some attributes of the procurement type that are important for the configuration problem are the number of products sourced, flexibility of suppliers, and supply lead time. The production type is mainly characterized by the operational characteristics of manufacturing. The distribution type is characterized by distribution structure and transportations means. The sales type includes such attributes as demand and degree of customization. The structural attributes are directly tied with the configuration problem. These include characteristics of network structure, degree of globalization, location of decoupling point, power structure, and degree of information sharing.

5.5.3 Information Modeling

The information modeling step is used to formalize the configuration problem and to establish a sound foundation for further decision making. Information modeling also can be referred to as descriptive modeling. The three main issues to be addressed during this step are: (a) location of the configuration decision-making process in the overall decision-making framework of organizations involved to develop decision-making workflow, (b) modeling of processes relevant to the configuration problem, and (c) modeling of data relevant to the configuration problem.

The first problem is addressed using enterprise integration methodologies such as GIM, ARIS and GRAI (Kamath et al. 2003). These approaches can also be used to model the workflow of the decision-making process. Detailed discussion on this issue is beyond the scope of this book.

Process modeling can be used for two purposes: 1) to describe the basic structure of the supply chain (traditional supply chain representation as shown in Fig. 2.2, actually incorporates both structural and dynamic aspects of supply chains); and 2) to depict processes in the supply chain. Fig. 5.2, shows a sample process model of the supply chain structure developed using an Unified Modeling Language (UML) activity diagram (Arlow and Neustadt 2005). Using this representation, candidate units and possible links can be defined. Parameters and variables also can be identified. In this example, one can observe that components inventory and packaging capacity are important parameters, and they are subsequently relevant to manufacturing and distribution stages.

Utilization of UML enables the linking of this diagram with other information models to use it in further semi-automated model development. However, that does not show some aspects specifically important to supply chain configuration. Therefore, modified process diagrams are useful to show the basic structure of supply chains (see Chapter 7). Additionally, other types of process-modeling diagrams can be used (e.g., IDEF, EPC). The choice substantially depends upon intended use of models, especially with regard to modeling automation.

Fig. 5.3 shows an example where process modeling is used to describe configuration-related processes in a supply chain. In this example, suppliers for selected materials are chosen specifically for a particular customer order (process *Select suppliers*). The transportation mode is also selected for each order according to delivery requirements. Manufacturing is represented as a related process that would require receiving materials from selected suppliers before manufacturing can be started and products released. The event-process chain (EPC) business process modeling language (Curran and Ladd 2000) is used for this example.

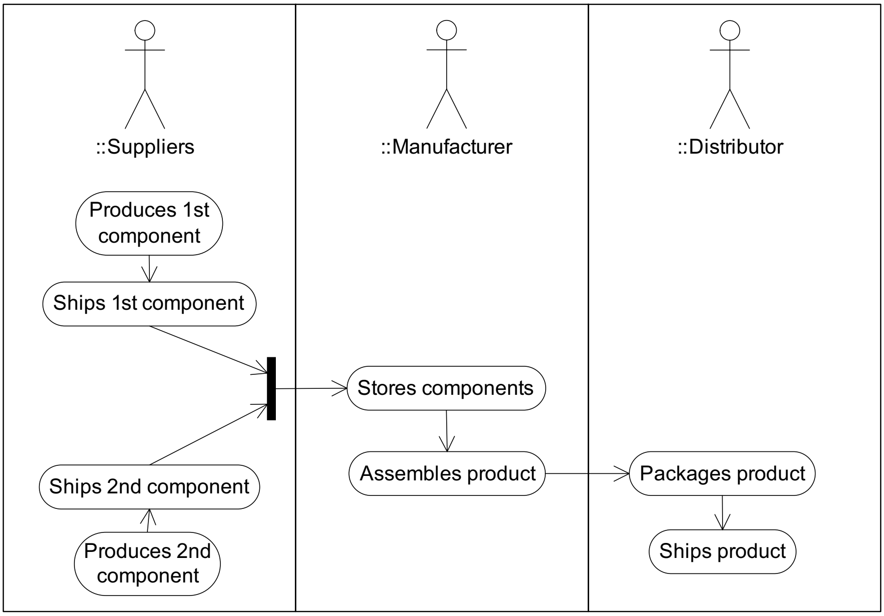

Fig. 5.2 The process model of the basic structure of the supply chain.

The main advantage of process models is that they provide a sufficiently formalized representation of decision-making problems suitable for further elaboration, and at the same time are understandable for problem domain specialists who might not be familiar with modeling techniques. The SCOR model is a process model specifically developed for supply chain management purposes. It can be used as a reference model to facilitate development of supply chain configuration process models.

Data modeling is used to define information requirements. It describes objects of the current configuration problem, their parameters, and the relationships between objects. Fig. 5.4 shows a fragment of a supply chain configuration data model represented using the UML class diagram. Entities relevant to the configuration problem are represented as classes (in this case, product and supply chain unit classes are shown). Each entity has its parameters. For instance, a manufacturing unit has parameters *Capacity* and *fixedCost* describing product independent capacity of the unit and fixed cost for operating of the unit. *ProductPlant* is an association class describing supply chain features characteristic of a combination of products and units. For instance, parameter *quantityProduced* describes how many units of a particular product are produced at a specific manufacturing unit. Details on using an object-oriented approach in the construction of supply chain data models are provided in Chapter 7.

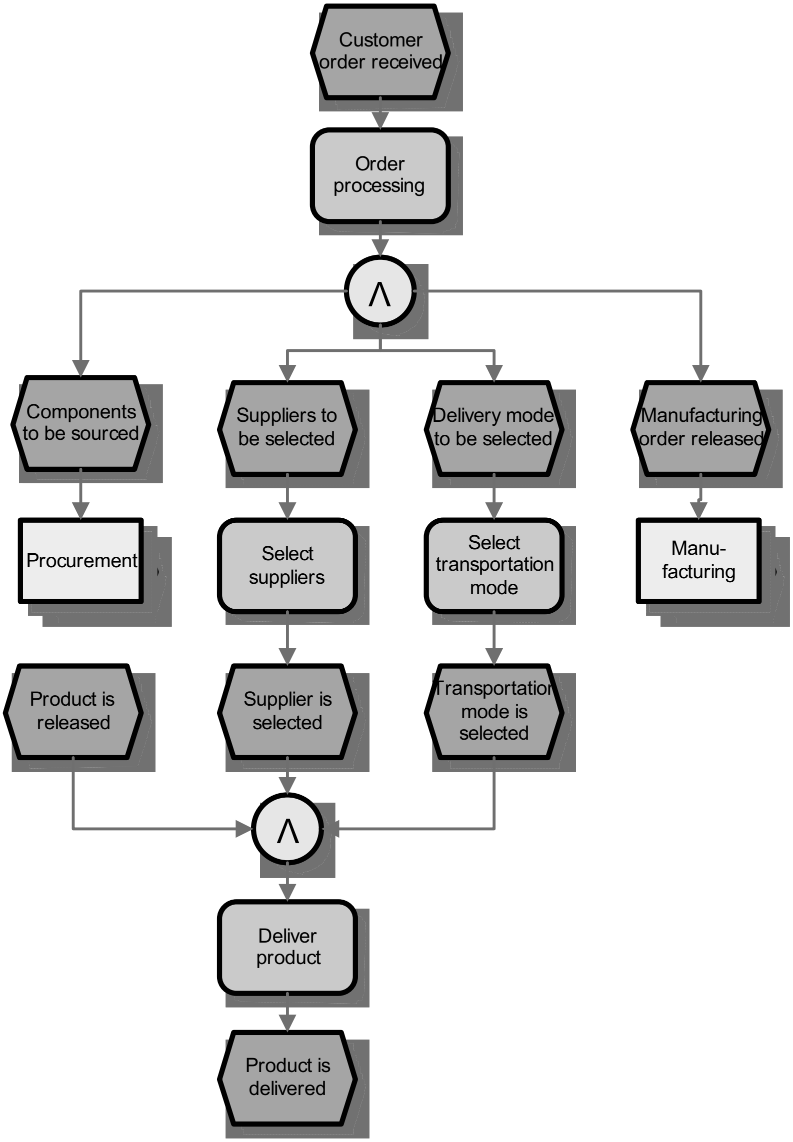

Fig. 5.3 An example of processes in a reconfigurable supply chain.

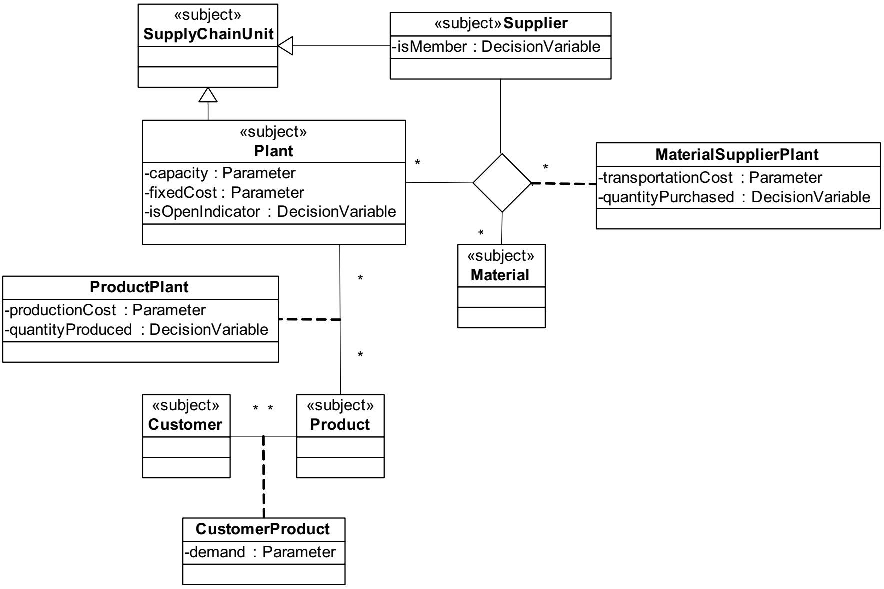

Fig. 5.4 The object model of the configuration problem.

The data model defines all objects, parameters, and costs relevant to the specific supply chain configuration problem. Values are assigned to these parameters and costs using mapping between data sources and supply chain objects instantiated from the defined classes. Types of data sources are

- Actual data – e.g., transportation costs as quoted by providers
- Empirical estimates – e.g., processing times if no automated recording is available
- Theoretical estimates – e.g., capacity costs and inventory holding costs are often difficult to estimate. Theoretical and judgmental approaches can be used in this case
- Forecasts – e.g., demand forecasts
- Transactional data – e.g., processing time, if automated recording of operations is performed. Aggregates of transactional data are typically used

Memory depth (i.e., how many historical records are available) of transactional data is also important. For additional information on data processing issues, data types, and their sources, readers are referred to Shapiro (2001).

Information modeling for supply chain configuration is not performed as a separate activity. To achieve information modeling efficiency, it is based on the existing enterprise and supply chain information models, and is conducted in relation to information modeling for other decision-modeling and supply chain information system development activities. However, if supply chain configuration problem solving is indeed a unique one-time activity, a decision modeler should critically evaluate effort requirements for information modeling.

5.5.4 Preselection

Steps 2 and 3 of the methodology define the types of units needed, their functions, and evaluation criteria. During this step, a list of potential candidates for each type of units is compiled and candidates are evaluated according to the evaluation criteria.

Data availability for conducting evaluations is a major concern during the preselection step. Candidate units have different data-sharing policies and it is also expensive for a broker to collect extensive data for a large number of candidates. The level of data availability may vary for each criterion, causing difficulties in assessing the accuracy of a composite criterion. The broker must prioritize data requirements and pay attention to units responsible for most important processes and to key criteria. Table 5.4 provides classification of some of the data availability situations. A majority of models reported in literature pay little attention to information availability and sharing issues during the preselection and selection steps. Generally, it is assumed that all necessary information (e.g., material prices, lead times) is available. For instance, Li and O'Brien (1999) build their supply chain design model under an assumption that partners provide all necessary information to evaluate their performance.

Table 5.4 Classification of Preselection Situations

	New Supply Chain	Existing Supply Chain
Information sharing	Partners' performance data are available but benchmarking basis might not be available.	Performance requirements can be identified from current performance data and compared to those supplied by partners.
Limited information sharing	Preselection is based upon assumptions and indirect observations.	Indirect observations can be evaluated with regard to actual performance observations.

A number of methods are available for preselection. These include ranking and weighting, benchmarking, statistical analysis, data envelopment analysis, analytical hierarchical process, and several artificial intelligence-based methods.

Weber et al. (1991) and De Boer et al. (2001) reference articles using linear weighting and statistical methods for the evaluation of suppliers. Analytical Hierarchical Process (AHP, Vaidya and Kumar 2006) is used for supplier preselection according to multiple criteria, although a similar procedure could be applied for preselection of other supply chain stages, too. This method is promoted as a more systematic approach compared to simpler weighting methods. It describes decomposing a complex problem into a multi-level hierarchical structure of objectives, criteria, and alternatives. AHP starts with the identification of criteria influencing decision making. A hierarchy of the criteria is built. Each criterion is compared with all other criteria according to a specified scale to assert its relative importance. Consistency of the assessment is checked. As a result, a relative importance weight is obtained for each criterion and can be applied to rank suppliers.

Wang et al. (2004) use AHP to obtain an aggregated AHP weight for each candidate supplier according to multiple criteria, which have varying degrees of importance. The key first-level criteria are delivery reliability, flexibility and responsiveness, cost, and assets. The weights computed are used afterwards for final supplier selection. Ghodsypour and O'Brien (1998) also assign ratings to candidate suppliers using AHP.

Choy et al. (2002) use case-based reasoning and neural networks to evaluate and benchmark potential suppliers. Performance of these evaluation methods depends upon data provided by potential suppliers and availability of historical data. The disadvantage of artificial intelligence-based methods is their lack of generality, and subsequently only basic features are usually used.

Data envelopment analysis (Charnes et al 1994) is used to evaluate the efficiency of supply chain units by Ross et al. (1998) and Talluri and Baker (2002). Data envelopment analysis (DEA) is a method for determining and benchmarking the efficiency of decision units such as potential supply chain partners. Each decision unit has a number of outputs converted into output performance indicators. Efficiency is measured as a ratio between the weighted sum of outputs and the weighted sum of inputs. The efficiency for each unit is optimized relative to other units by finding optimal values of the weights for the given unit. The efficiency measure can be used to make preselection decisions concerning the given unit. In both papers referred to above, efficiency measures for candidate units are computed. These measures are afterwards used in optimization of the supply chain configuration. Talluri and Baker (2002) additionally split between determining the number of units needed and actual product quantities assigned to each unit.

The special case of preselection is the continuous facility location method. If facilities can be located in a large number of locations, continuous facility location methods (Drezner and Hamacher 2002) identify appropriate location area, and a specific location can be chosen among several alternative locations in this area. Owen and Daskin (1998) survey the main types of facility location models, which locate facilities only according to some kind of coverage criterion. Therefore, they have to be combined with methods that also account for other criteria.

5.5.5 Selection

This is the key step of the methodology. It includes three major tasks of developing supply chain configuration models, validation of the models developed, and application of these models. Completion of these tasks depends upon the type of models used for selection purposes, such as statistical, knowledge-based, optimization, and simulation (see Fig. 5.5). The types of models are discussed in detail in Part II of this book.

Statistical models are mainly used for preselection purposes. However, they can be used for establishing the final supply chain configuration as well, if further refinement of results is not deemed possible or necessary. Availability of information is crucial to applicability of statistical models. In Fig. 5.5, Statistical models are designated for situations with a large number of alternatives and a few fixed units. Knowledge-based and optimization models still should perform better in this quadrant, although model development and solving, respectively, could be a major obstacle for applicability of these models.

Knowledge-based models (Piramuthu 2005, Choy et al. 2002) are well-suited in situations where the base supply chain has been established and inclusion of a limited number of units needs to be regularly reassessed.

However, optimization and simulation models remain key model types used in the selection step of supply chain configuration. Optimization models are used to establish the supply chain configuration if the number of alternatives is large. Simulation can be used if the number of alternatives is small. It is also preferable that some of the units are fixed to allow for easier validation of simulation models. Additionally, both models are frequently used together. Optimization models are used to establish the supply chain configuration by evaluating a large number of alternatives, while simulation is used to evaluate optimization results in a more detailed manner according to multiple evaluation criteria (for more detailed discussion on differences between optimization and simulation see Part II of this book and Law and Kelton (2000)). A combination of optimization and simulation models does not exclude other model combinations. Hybrid modeling, where optimization and simulation models are tightly integrated, is often used to attain benefits from using both optimization and simulation.

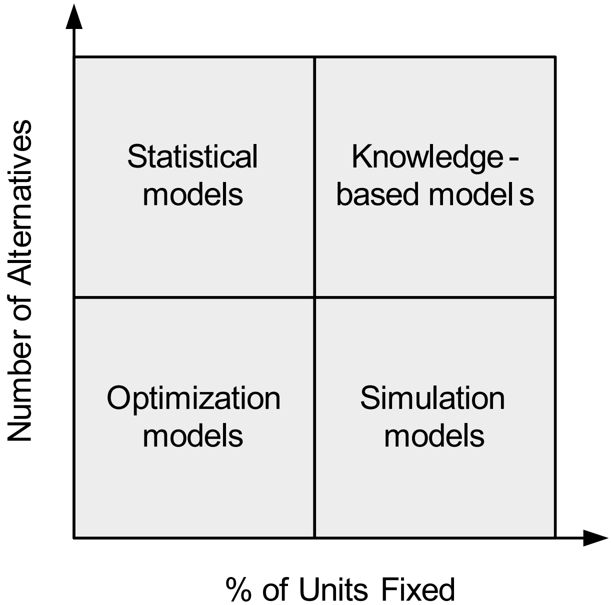

Fig. 5.5 Selection methods according to decision-making circumstances.

There is a large variety of optimization models used in supply chain configuration. A majority of them are mixed-integer programming models. Stochastic and multi-objective programming models are also becoming popular. Similarly, discrete-event simulation is the dominant simulation modeling technique used for supply chain configuration.

The development of simulation models typically is more time consuming than the development of optimization models. The same applies to application of models. However, for many large-scale problems, direct solving of optimization models can also be time consuming. Therefore, specialized solution procedures need to be developed for solving optimization models. The proposed methodology and supply chain configuration framework, emphasizes automated model building. That is especially important if simulation modeling is used to evaluate optimization results. To avoid repeated development of a simulation model for each optimization outcome, simulation models can be automatically generated according to optimization results.

Validation of configuration models is difficult even in the case of existing supply chain reconfiguration, because the feedback loop between decision-making and implementation results is long and often obscure. Therefore, expert judgment is one of the main approaches to results validation.

Additionally, application of multiple models can also be used as a form of validation. The situation is better if a majority of units are fixed and the effect of replacing individual units can be easily observed through performance measures, such as on-time delivery and material cost.

5.5.6 Analysis of Output Data

The selection step yields a set of alternative configurations, along with appropriate performance measures. During the analysis step, configuration results are summarized and additional analyses are conducted to assess sensitivity.

Traditional statistical data analysis techniques, such as analysis of variance and regression, can be used. Meta-modeling is an attractive technique for analyzing simulation results (Kleijnen 1987). However, it has limited capabilities to deal with the binary variables used in supply chain configuration. Therefore, meta-modeling can be used to analyze the supply chain configuration problem for a fixed structure.

5.5.7 Approbation of Results

This subsection briefly covers Steps 9 through 11 of the methodology.

Step 9, on acceptance of results, pertains to a managerial decision-making problem area (Maccrimmon and Taylor 1976). One of the key problems during this step is interpretation of results given by multiple models and distilling the final decision and contingency plans. Malhotra et al. (1999) discuss theoretical aspects of decision-making using multiple models. A framework for decision-making using multiple models is provided. It shows that the final decision is a combination of outputs from various models adjusted by managers' judgmental decisions. Methods for consensus building are also incorporated in some decision support systems (Tung and Turban 1998; Limayem and DeSanctis 1999)

Implementation of configuration decisions includes dealing with both logical and physical aspects of implementation, as discussed in Chapter 4. Physical implementation is beyond the scope of this book, although this issue has not received adequate coverage in literature. Information technology-related issues of implementation are discussed in Chapter 11.

The performance of the established configuration needs to be monitored and evaluated according to decision-making criteria used during decision making, and key performance indicators, which are important to the individual units and the entire supply chain. Traditional engineering control mechanisms, such as control charts, can be used (Montgomery (1996) for description of monitoring methods). Monitoring of appropriate performance measures can be implemented using a link between supply chain transactions processing, and decision making provided by information modeling data-mapping functionality. Abu-Suleiman et al. (2004) describe a framework for supply chain performance management. The framework is based on the Balanced Scorecard approach, and uses performance metrics defined in the SCOR model.

In Part III of this book, where applied studies are discussed, approbation and the impact of configuration decision-making results are discussed in more detail.

5.6 Architecture of the Decision Support System

The computational complexity of the configuration problem requires the assistance of a comprehensive decision support system. The decision support system provides not only core services like data integration, model building, and model solving, but also supporting services for organization of the decision-making process, maintaining modeling repository, and preliminary analysis of results. Additionally, the decision support system must be incorporated in the overall supply chain management system.

Fig. 5.6 shows a schematic representation of the architecture of the decision support system. This architecture complies with the integrated framework described in Chapter 4 and provides a complete set of tools for carrying out the supply chain configuration methodology.

The two most important parts of the decision support system architecture are the decision-modeling system and the information-modeling system. The decision-modeling system is used to make configuration decisions mainly associated with Steps 6 and 7 of the methodology. The information-modeling system is used for information-modeling purposes (Step 3). Another major function of this system is linking the decision-modeling system with the supply chain management information system.

The decision-support system is a part of the supply chain information system. The supply chain information system is a system tracking all supply chain transactions and containing references to other decision-making applications. It is a major data source for decision-making purposes. Additionally, it supplies the information-modeling system with existing enterprise and supply chain information models. Data sources are shown separately because besides information from the supply chain management information system, external data sources can also be used. Data warehousing has become a frequently used technology for organizing and presenting data from various sources for decision-making purposes (Kimball et al. 1998). However, not all data need to be stored in data warehouses because some of them have small volume and are rather specific. Forecasting is set separately from other decision-modeling components because in the case of supply chain configuration, many forecasts are made on a judgmental basis as a part of overall strategic supply chain management. The groupware module is included to support collaborative decision-making.

The information-modeling system is used to develop information models for supply chain configuration purposes on the basis of available supply chain-wide information models. Information modeling is used to link data sources, including data warehouses, with the decision-modeling system and the decision-modeling database. Technically, this system could be an Extraction-Transformation-Loading (ETL) tool in combination with an information-modeling tool. The information-modeling system also should facilitate updating of the supply chain information system according to modeling results, and implementation of decision-modeling components for real-time decision making. In the general case, the decision support system shares the information-modeling system with the supply chain management system.

The decision-modeling system manages execution of experiments with multiple decision-making models; each implemented using different decision-modeling components. Following the types of models most frequently used in supply chain configuration, optimization, simulation, and statistical analysis components are identified. Geographical information systems are among the most frequently used other components.

The decision-modeling data base differs from the data warehouse by storing data in various formats, including informal data. The data include models, modeling scenarios, and raw modeling results.

Sample implementations of this architecture are discussed in Chapter 11 of this book, along with a general discussion of IT tools that support supply chain configuration decision making and decision implementation.

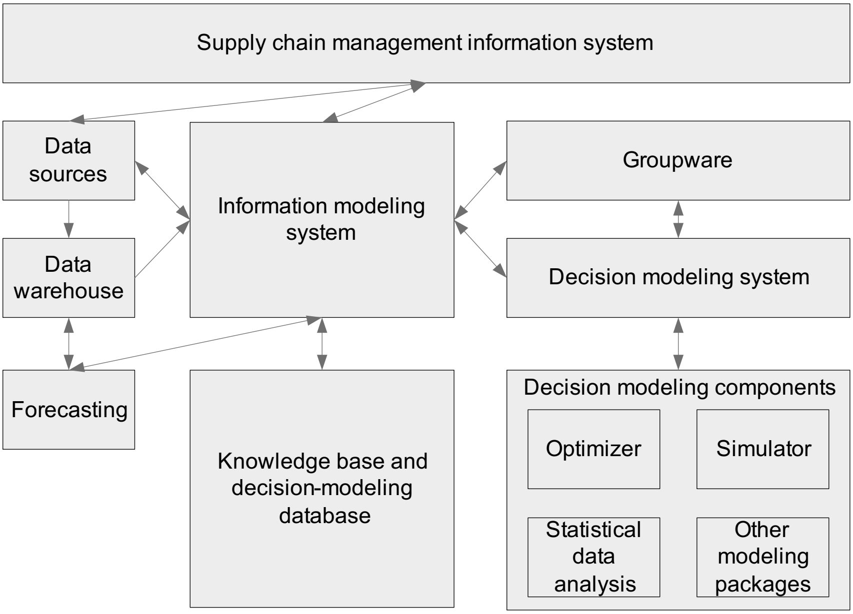

Fig. 5.6 Architecture of the supply chain configuration decision support system.

5.7 Summary

The supply chain configuration methodology has been presented in this chapter. It is aimed at addressing a whole range of issues arising during decision making and the implementation of decisions. The methodology emphasizes the importance of model integration to enable the supply chain configuration problem for a comprehensive evaluation. Additionally, efficiency of model development is also stressed. However, the extent to which the methodology is applied varies from case to case (i.e., not all steps are always required, and the importance of each step also varies).

Another aspect of the methodology is that it aims to position the supply chain configuration problem solving in the overall supply chain decision-making and decision-implementation framework, as well as in relation to the overall supply chain management information system. Information modeling is the major mechanism in achieving this integration. If integration with other decision-making processes and the supply chain management system is not an important objective, then information modeling can be accomplished in a less formal manner.

Application of the methodology is not possible without using various decision-modeling tools. The architecture of the supply chain configuration decision support system described in this chapter depicts the main tools used and the relationships among these tools. Support for collaborative decision making and the accumulation of knowledge are emphasized in the architecture. Again, the supply chain configuration decision support system should share many components with other modeling applications and rely on efficient use of the supply chain information technology infrastructure.

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Part II Solutions

6. Knowledge Management as the Basis of Crosscutting Problem-Solving Approaches

6.1 Introduction

In Chapter 2, we argued that supply chain configuration is one of the principal supply chain management decisions and that it has a profound impact on other subsequent managerial decisions. As described therein, the supply chain configuration problem is a complex problem, which is comprised of several sub problems. It was also emphasized that the solutions to these problems require design, modeling, and problem-solving techniques based on knowledge from various fields such as Systems Science, Systems Engineering, Operations Research, Industrial Engineering, Decision Sciences, Management Science, Statistics, Information Sciences, Computer Science, and Artificial Intelligence. Some of the prominent techniques utilized from these fields are information modeling, process modeling, simulation modeling, data mining, and optimization. We build on this proposition by adopting a key problem of *information integration* in the supply chain, which has an embedded structure representing various sub problems, and how its management relates many of the concepts espoused in this book about supply chain configuration. Also, this problem serves as a prime example of how crosscutting approaches drawn from the various disciplines highlighted above may be adopted in devising solutions for the complex supply chain configuration problem. Before we proceed further, let us first develop a clear understanding of the information integration problem in the supply chain.

The Supply Chain and the Information Integration Problem. One way to look at a supply chain is as an alignment of firms that bring products or services to the market (Lambert et al. 1998). This alignment is in the form of an extended enterprise, where firms collectively organize the supply, production, and distribution of products and services.

The management of such a complex organization can be brought to the integration of its business processes. Process-oriented management vs.

function-oriented management is an important feature that makes the supply chain a distinct enterprise system class. Another facet of supply chain system complexity is its organizational dynamics and operational specifics. Organizational dynamics assumes frequent changes in organizational structures such as control hierarchy, goal structure, members' network, and so on. Operational specifics are mainly related to the uncertainty in which a supply chain organization operates. Integration of supply chain processes assumes additional complexity when the decision-making mode (i.e., centralized vs. decentralized) is considered in the mix.

One of the key issues in managing a supply chain process is information integration among its constituents. To facilitate this integration, supply chain information resources ought to be effectively organized and shared. Information integration provides channels that convey information from one supply chain constituent to another. One form of this problem involves the integration of existing implementations that have been built in heterogeneous infrastructures, such as different hardware platforms, operating systems, and database management systems. Presenting the data on which applications perform in a uniform, self-consistent way ensures that they share the same view of the supply chain. Another form of integration is concerned with working collectively on common problems by sharing an understanding of the problems' reasoning logic and applying best practices. This provides a common architecture in information sharing so that supply chain members' collaborative activities provide performance improvement to each member and to the entire supply chain.

The problem of process integration, and its surrogate information integration described above, needs an appropriate solution. In this context, we advocate the necessity of applying system principles and knowledge management methodologies based on the following reasons: (1) the extent of knowledge becomes intractably large, (2) business units are geographically decentralized but more closely networked, (3) collaboration among individual workers is important, and (4) challenges are faced in eliciting requirements when user partners are large, decentralized, and unknown.

In this chapter, we propose a framework and implementation mechanisms for designing a knowledge management system capable of supporting organizational dynamics and operational uncertainty, as well as facilitating process integration in a supply chain. Taxonomies and ontologies are viewed as a means for conceptualizing the knowledge to share and utilize in decision-modeling applications. They bring formalism into the knowledge management system, thus offering standards for communication, which is necessary for collaborative problem solving.

The general trend in process integration is to develop information models that system users can share, thereby sharing the same view of the world (CIMOSA (Kosanke 1995), TOVE (Gruninger et al. 2000)). The gap seen in these and other research efforts is the absence of a system *reference model* that can identify information model components and define mechanisms for their design and implementation. This reference model formally represents the source system, such as supply chain, its informational needs, and constructs that need to be built to support system processes. The ultimate target and value of the proposed approach, and hence the reference model is taxonomy and ontology development as a platform for integrated supply chain knowledge management.

Further, the proposed reference model enables fulfilling the purpose of this chapter in laying the ground work for integrated solutions proposed in Chapters 7 to 11. The importance of this chapter is to highlight that solutions to supply chain configuration problems must integrate complex modeling and analysis techniques drawn from a host of disciplines.

The chapter is organized as follows. Section 6.2 describes the motivation, focus, and significance of crosscutting approaches. Section 6.3 discusses the notion of taxonomy and ontology and how it contributes to system integration. Section 6.4 introduces the knowledge management system development framework, which starts from the source system, goes through system component decomposition, and presents knowledge-modules design for these components. Section 6.5 formally presents the knowledge management system reference model, relating elements in the proposed framework and describing their meaning. Section 6.6 presents four stages of the knowledge management system development life cycle, as well as describes how the reference model can be implemented for each stage.

6.2 Crosscutting Approaches – Motivation, Focus, and Significance

Supply chain configuration draws from an array of fields as far as framework, models, and methodologies are concerned. This is primarily owing to the impact of any configuration effected on a supply chain, on its strategic, tactical, and operational decision-making environments. In this section, we discuss the motivation behind developing an integrated supply chain configuration framework and a reference model for designing knowledge and its management, with the aim of improving supply chain management.

6.2.1 Motivation and Focus

The motivation and focus of the research methodology proposed in this chapter is to integrate various problem-solving approaches from a host of fields in the design of proposed supply chain configuration problem-solving methodologies. It is characterized by two main purposes: *general* and *specific*.

The *general* purpose is to develop a common body of inter disciplinary knowledge to understand issues and problems related to reconfigurable systems.

The *specific* purpose is to (a) develop methodology and tools for supply chain reconfiguration, (b) elaborate framework for knowledge-based problem analysis and model building, and (c) quantify factors influencing supply chain reconfiguration.

The general problems in reconfigurable systems can be classified as related to the system's environment, availability of appropriate modeling tools, interconnectedness of decisions at various levels of supply chain, and availability of common knowledge throughout the system. These can be listed as follows:

- Increasing competitive pressures and consumer focus requires innovative supply chain modeling and management tools
- Spply chain modeling tools must capture complex interactions within the supply chain
- Spply chain configuration decisions have significant impact on other decisions at all levels
- Knowledge assumes a critical role in a firm's success, and, therefore must be captured, organized,and utilized effectively

Problem-solving strategies applied to reconfigurable manufacturing systems entail developing (a) domain independent solution(s) templates at the macro level, (b) capability models for application specific domain dependent problems at the micro level, and (c) coordination models to integrate models developed in (a) and (b).

6.2.2 Problem Solving for Configurable Systems

To provide an integrated overview of interconnectedness of crosscutting research areas for configurable systems, three problem-solving approaches are proposed: systemic, reductionist, and analytic. These are defined as follows:

- *Systemic Approach* This incorporates the abstract level. This *level of inquiry* deals with issues of scalability of system, meta-modeling of systems, and defining the dynamic knowledge problem domain model
- *Reductionist Approach.* This incorporates the activity level. This *level of inquiry* consists of dynamic knowledge problem domain model, internal state, and goals and objectives of the enterprise *units*, (producer, plant, department, supplier, vendor, etc.), and strategic management models
- *Analytic Approach.* This incorporates the implementation level. This *level of inquiry* consists of internal state, goals and objectives of the enterprise units, strategic management models, and shared goals and objectives of the enterprise

We discuss below related research in direct comparison to these three problem-solving approaches.

At the *systemic* level, a supply chain is a general class of system that exhibits a cooperative behavior within its business and market environment (Klir 1991). The foundation of this system is built on a network architecture that has various demand and supply nodes as it provides, as well as receives goods and services to and from its customers and suppliers, respectively (Chandra 1997; Lee and Billington 1993; Swaminathan et al. 1998). Supply chain system frameworks describe general foundational elements of integration between its marketing and production functions. These are in the form of general theories, hypotheses, standards, procedures, and models that are based on well-founded principles in these disciplines (Cohen and Lee 1988, 1989; Deleersnyder et al. 1992; Diks and Kok 1999; Drew 1975; Graves 1982; Hackman and Leachman 1989; Lee 1993; NIST 1999; Tzafestas and Kapsiotis 1994; Younis and Mahmoud 1986). Systems modeling deals with general modeling issues of this class of systems, such as how to represent, quantify, and measure cooperation, coordination, synchronization, and integration (Little 1992, Morris 1967; Pritsker 1997). Systems engineering describes methodologies for structuring systems as these are implemented in various application domains (Blanchard and Fabrycky 1990). System integration deals with achieving common interface within and between different components at various levels of hierarchy in an enterprise (Shaw et al. 1992), as well as different architectures and methodologies (ISO TC 184/SC 5/WG 1 1997, IMTR 99, Hirsch 1995), using distributed artificial intelligence and intelligent agents (Gruber 1995; Stumptner 1997; Wooldridge and Jennings 1995).

At the *reductionist* level, a supply chain configuration must be based on its local, as well as global, environmental constraints. These constraints are partly imposed as the supply chain negotiates and compromises to adapt to its cooperative behavior (Jennings 1994). Enterprise modeling as a technique has been used effectively in decomposing complex enterprises, such as a supply chain. Ontologies are defined to describe unique system descriptions of supply chains that are relevant to specific application domains (Gruninger 1997). The classic problem for a supply chain is an inventory management problem requiring coordination of product and information flows through a multi-echelon supply chain. This class of problem has been solved by integration of the front and back ends of the supply chain with costs and lead times as key measures of its performance (Clark 1972; Clark and Scarf 1960; Diks et al. 1996; Diks and Kok 1998, 1999; Hariharan and Zipkin 1995; Pyke and Cohen 1990).

The *analytic* approach for the general class of supply chains has its origins in economic models of supply and demand coordination. Game Theory principles for payoffs among market competitors have been used effectively to design competitive strategies for supply chains (Gupta and Loulou 1998; Masahiko 1984). Coordination and cooperation— dealing with interfaces between strategies, objectives, and policies for various functions of an enterprise, has received much attention in optimizing the performance of a supply chain (Malone 1987; Malone and Crowston 1994; Thomas and Griffin 1996; Whang 1995). Various aspects of cooperation have been prescribed for effective management of supply chains (Sousa et al. 1999).

Starting from the evaluation of existing enterprise integration architectures (CIMOSA, GRAI/GIM, and PERA), the IFAC/IFIP Task Force on Architectures for Enterprise Integration has developed an overall definition of a generalized architecture framework called GERAM or Generalized Enterprise Reference Architecture and Methodology (ISO TC 184/SC 5/WG 1 1997).

6.2.3 Significance of This Approach

Supply chain management strategies have the potential of being one of the major catalysts to achieve *Manufacturing Visions* identified by the manufacturing community at large (National Research Council 1998). The key technologies to nurture in this endeavor are

- Adaptable, and integrated equipment, processes, and systems that can be readily reconfigured
- Manufacturing processes that minimize waste
- System synthesis, modeling, and simulation for all manufacturing operations
- Technologies to convert information into knowledge for effective decision making
- Software for intelligent collaboration systems

- New educational and training methods that enable the rapid assimilation of knowledge

The common thread in the deployment of these technologies is achieving (a) reconfigurability, (b) efficiency, and (c) complex modeling and analysis in decision making related to managing advanced manufacturing systems.

This emphasis on developing enhanced manufacturing capabilities and technologies to support infrastructure mandates research in following crosscutting areas

- Adaptable and reconfigurable manufacturing systems
- Information and communication technologies
- Processes for capturing and using knowledge for manufacturing
- Adopting and incorporating IT into collaboration systems and models focused on improving methods for people to make decisions, individually and as a group
- Enterprise modeling and simulation
- Analytical tools for modeling and assessment
- Managing and using information to make intelligent decisions among a vast array of alternatives
- Adapting and reconfiguring manufacturing enterprises to enable formation of complex alliances with other organizations

The objective of the research presented in this chapter is to formalize the capture and management of supply chain management knowledge accumulated in various domains of science, engineering, and technology, and using various problem-solving techniques.

6.3 Taxonomy, Ontology, and System Integration

To see linkages between problems and decision-making models utilized in a complex enterprise such as a supply chain, it is imperative that these componets be formally represented. Taxonomy and ontology provide the means to classify the supply chain problems and represent formal knowledge, which is used in decision-making. We take up discsussion on this topic next.

6.3.1 Taxonomy

According to the American Heritage® Dictionary of the English Language, Fourth Ed. (2000), *taxonomy* is the classification of organisms in an ordered system that indicates natural relationships. It is the science, laws, or principles of classification. Further, it is an arrangement by which systems may be divided into ordered groups or categories according to common characteristics.

System taxonomy reflects information about relationships both inside the system, and with its surrounding environment. Supply chain system taxonomy aims to provide a multidisciplinary representation of supply chain activities and characteristics. The review of research in the field of supply chain taxonomy development reveals that most of them are based on single case studies, providing taxonomy for a sub set of information. System taxonomy is organized for the entire system. Organizing information representation for a part of a system or for one problem jeopardizes decision making because it may miss some key aspects. The supply chain is an organization whose components are interrelated to each other. This cohesion makes the system unmanageable if it is considered as one unbreakable unit. Based on biological classification, system taxonomy provides mechanisms for dividing a supply chain system into relatively independent units, providing as minimal a coupling between units as possible by collecting characteristics in groupings by their similarity. Further, iterative decomposition of groupings and creating new groupings can build a robust hierarchy of describing system characteristics.

System taxonomy serves two purposes: 1) standardization of terms and definition, and 2) unification of information representation. This brings out reusability of developed information models, as well as organization and structure, to knowledge management. Scalability and traceability are the most important features that system taxonomy provides so new features can be added and existing ones easily found.

6.3.2 Ontology

In the Artificial Intelligence (AI) literature, ontology is defined as the study of the kinds of things that exist (Sowa 2000). In AI, programs and logic deal with various kinds of objects, and we study what these kinds are and their basic properties (McCarthy 2003). Over the years, ontology has become more than an abstract representation of objects and their properties and is becoming a part of the software application domain with application to other branches of AI, such as heuristics and epistemology. The latter is a study of the kinds of knowledge that are required for solving problems in the world, and the former is a way of trying to discover something, or an idea embedded in a program. Along with shaping its pragmatic purpose, ontology has found its application in many fields, such as knowledge representation, system integration, enterprise modeling, conceptual modeling, and Semantic Web.

The above definition of ontology by Sowa (2000), as a study of the kinds of things that exist, is very generic. However, during the last two decades, several features of ontology have evolved that define its broader and more diverse scope and purpose in designing information support for decision making. A review of the pertinent literature offers the following contrasting definitions and interpretations of ontology to validate our above assertions:

- Ontology is an explicit specification of conceptualization (Gruber 1993), meaning that ontology defines kinds of things, their possible relationships, and plausible implementation
- Ontology is a catalog of types of things that are assumed to exist in a domain of interest, D, from the perspective of a person who uses a language, L, for the purpose of talking about D (Sowa 2000). This feature of ontology assumes the existence of a language with enough expressiveness for representing the domain of interest
- Ontology refers to an engineering artifact, constituted by a specific vocabulary that is used to describe a certain reality and by a set of explicit assumptions regarding the intended meaning of words in the vocabulary (Guarino 1995). This definition of ontology adds a new feature requiring that it must have mechanisms and terminology for describing the meaning of words and vocabulary as well as their interpretations

Ontology as a tool for information modeling has been adopted for a large body of research initiatives. As part of the research described in this chapter, a number of ontology tools, languages, and research projects have been studied to understand the role of ontology in information support systems, particularly for information integration. Some of them, such as Ontolingua (Farquhar et al. 1997) and OntoBroker (Fensel et al. 2001), investigate ontology narrowly as a stand alone discipline. Other projects, such as TOVE (Fox and Gruninger 1999; Fox et al. 2000) and DOGMA (Meersman 2001), combine knowledge organization with specific domains, investigating agents for which knowledge is organized. Others look at the problem more widely, including development of ontologies in enterprise modeling systems, such as Enterprise (Stader 1996) and Process Handbook (Malone et al. 1999), aiming to support organizations effectively in change management. What is common in all of these projects, however, is that ontology explicitly defines the vocabulary presented with a language in which queries and assertions are exchanged among users. The next section describes the knowledge management system development stages in a framework.

6.4 Knowledge Management System Development: A Proposed Framework

The framework for knowledge management system conceptualization is depicted in Fig. 6.1. Based on the theoretical background developed in the Section 6.3, a technique is proposed for conceptualizing supply chain organization and problem knowledge. The proposed advances offer integration of knowledge components with decision support systems and their consumption by software applications or agents. Knowledge components encompass ontology models and the infrastructure supporting their creation, storage, and use.

To serve the needs of an knowledge management system in formalizing and delivering knowledge to decision-modeling applications, several requirements are imposed on ontology conceptualization, such as (1) systematic principles for knowledge conceptualization, (2) the problem-specific nature of ontology constructs, (3) the modularity and object nature of formed knowledge, (4) reusability of created knowledge, (5) integration of distributed data, and (6) machine-readable format of delivered knowledge.

The genesis of the proposed framework is *taxonomy* and its amplifications to problems and problem-solving techniques, particularly when applied to supply chain management.

6.4.1 Taxonomy

Taxonomy is a systematic representation of a system's existence (McKelvey 1982). Accordingly, taxonomy is built based on principles of system theory. It is a mechanism for structuring the knowledge about a certain system domain. The process of taxonomy development consists of information collection, systematic analysis, and classification of system attributes.

Problem taxonomy provides the overall framework under which problem-oriented information system components can be designed and implemented.

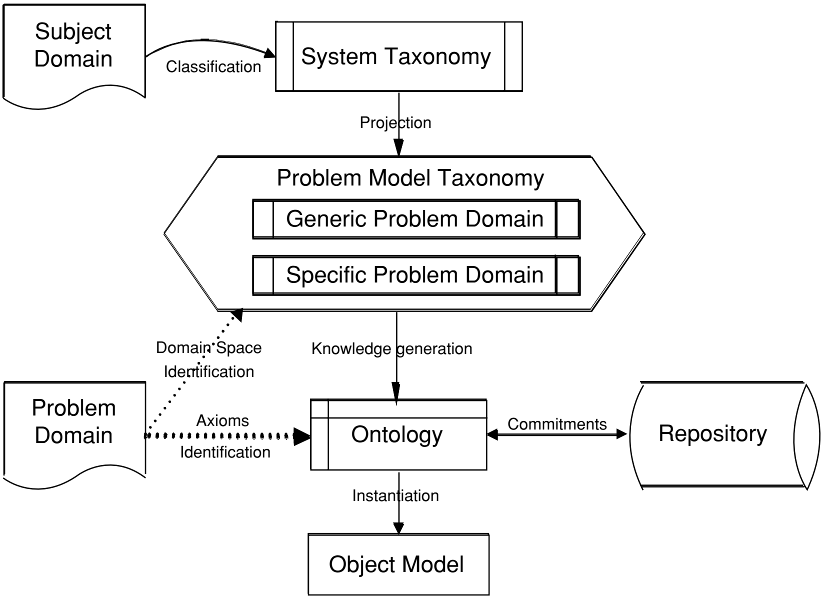

Fig. 6.1 The conceptual framework of a knowledge management system**.**

Supply chain problem taxonomy comprises: (a) classification of supply chain problems, (b) classification of problem solving methodologies for supply chain management, and (c) hierarchical classification of variables or factors necessary for dealing with such problems. We explain this concept with the help of one of the fundamental problems in the supply chain management literature— the *bullwhip effect.*

The Bullwhip Effect

The most downstream supply chain unit observes an external demand, transmitted up on a supply chain as inventory replenishment orders move from one unit to another. It has been observed that substantial information distortion may occur during this transmission. This information distortion, known as the bullwhip effect, appears as an order variance increase as one moves up the supply chain.

Classification of the Bullwhip Effect Problem

The bullwhip effect is a prime example of problems encountered in a complex system, such as the supply chain. In these systems, problems are multi-faceted with a primary problem and many related sub problems. For instance, the bullwhip effect, one of the fundamental problems in supply chain management literature (Lee et al. 1997a), has several secondary problems, such as order management, demand forecasting management, inventory management, and shipment consolidation. Further, Lee et al (1997a) formally identify the main causes of the bullwhip effect, while Lee et al. (1997b) discusses their managerial implications. They state that if the following conditions hold— 1) demand is mean stationary and no signal processing is used, 2) lead time is zero, 3) fixed ordering cost is zero, and 4) no price variation occurs— then the order variance increase does not occur. However, if some of these conditions are relaxed, the bullwhip effect may be observed.

Classification of Techniques

We need to discuss some of the published techniques utilized in managing the bullwhip effect to highlight their classification. Chen et al. (2000a) use the simple moving average forecasting technique to obtain forecasts and investigate the bullwhip effect according to lead ime and information sharing. Chen et al. (2000b) and Xu et al. (2001) use the exponential smoothing technique in forecasting. Chen et al. (2000b) also show that, if a smoothing parameter in exponential smoothing is set to have equal forecasting accuracy for both exponential smoothing and moving average methods, then exponential smoothing gives larger order variance. Graves (1999) demonstrates the presence of the bullwhip effect, if external demand, which is the first-order integrated moving average process, is forecasted using exponential smoothing with an optimally set smoothing parameter. Metters (1997) measures the impact of the bullwhip effect by comparing results obtained for highly variable and seasonal demand against the case with low demand variability and weak seasonality. Cachon (1999) proposes methods to reduce the bullwhip effect using balanced ordering.

Problem model taxonomy is a projection of system taxonomy, and thus inherits system structure and vocabulary. A problem domain is presented at two levels— generic problem domain and specific problem domain. Generic problem domain taxonomy is a class of problems that can occur in a supply chain, such as *coordination of production activities* It is a highly generic problem that comprises several tasks, such as *scheduling of production* or *inventory replenishment*, which are problems describing more specific issues. Usually, specific problem domain taxonomy is represented by domain-dependent (or specialized) model(s). Splitting problem representation modeling into the above defined two parts provides the means for developing generic and specific problem models.

The process of problem model taxonomy development starts with problem domain space identification. This involves analysis and design of functional requirements for the problem and proposing a structured representation of relevant information. For example, for a *scheduling of production* problem, the model comprises its input and output variables, underlying sub tasks or activities, tools and mechanisms for solving the problem, problem-oriented goals, roles and agents involved in performing them in accomplishing tasks to achieve identified goals, and external environmental issues. The purpose of problem taxonomy (PT) is the systematic representation of supply chain domain constituents, such as problems and their content.

Different problem models have the same representation format and characteristics vocabulary, thus providing standardization of information representation in the supply chain domain. Problem model taxonomy serves as a meta-model for knowledge model generation and ontology engineering. Ontology inherits concepts, subsumption relationships, and characteristics from the problem model, thus providing consistency in representing various problems. Ontology development components enrich the problem model with constructs, thus turning it from an abstract problem representation into a knowledge model by formulating rules and regulations related to the problem domain. These constructs are: (1) axioms, defining rules specific to the problem domain; (2) algorithms, providing step-by-step procedures for approaching the problem and solving it; and (3) commitments, linking characteristics to data and assigning variables with values. The first two components are modeled through a comprehensive analysis of the problem. System analysis and design techniques, such as process modeling and object-oriented design, are applied for this purpose. The identification of the first two components is the most important part of ontology development. Ontology by itself is a vocabulary with rules on its use. Real world applications require data to operate. Ontological commitments provide these data.

Object model generation is a software engineering practice. If parallels are drawn with software engineering, ontologies can be considered as classes, while object models are their instances encapsulated into software entities. Object models are tangible software constructs, where problem-specific data are represented in a common programming language, encapsulated in a formal model, and accompanied with descriptions of what to do with the data and how to do it.

The next section formalizes the proposed framework with the help of a knowledge management system reference model.

6.5 Knowledge Management System Reference Model

The knowledge management system reference model is proposed as a theoretical foundation for building knowledge-based information systems. It follows various stages in the above-described framework and formally represents its component types, their meaning, and functions. The reference model is divided into three parts: source system representation (system taxonomy), supply chain functional requirements representation (problem taxonomy), and formal knowledge representation (ontology). First, notation to represent the reference model is presented. Next, the reference model is formally enumerated in the form of a set of equations.

Notations related to general problem representation

S	System
T	Thing symbolizing the elements of a system
R	Relationships among things of a system defined on T
GP	Generic problem model
at_i	Attribute (the index i here and afterwards signifies the ith attribute in the set of attributes)
At_i	Set of instances of at_i attribute
vv_i	Variable that can be assigned to attribute at_i for generic problems
VV_i	Set of possible values that variable vv_i may possess
ww_i	System generic state for vv_i respectively
WW_i	Set of possible states of ww_i

Notations related to specific problem representation

Ob	Object model
b_i	Observation channel
B_i	Set of possible b_i states
SP	Specific problem model
v_i	Variable that can be assigned to attribute at_i for specific problems
V_i	Set of possible values that variable v_i may possess
w_i	System specific state
W_i	Set of possible states w_i
o_i	Observation channel for attributes at_i
$\tilde{O}$	Relationship between object system and problem system
W	Class instances of S for supply chain domain (general representation of W_i)

Notations common for specific and general problem representations

Ê Relationship between specific and generic systems

e_i Relationship between V_i, VV_i

k_j Relationship between W_j, WW_j (the index j signifies the jth relationship between general WW_j and specific W_j system states as well as between B_j and W_j)

S_w Specific system for supply chain domain (an instance of S)

T_w Things specific to supply chain domain (an instance of T)

R_w Set of relationships held on T_W

Notations for ontology

M Data model for a supply chain domain

I Ontological commitments.

V Set of variables (General representation of V_i)

B_w Observation channels for defining variables

B_C Observation channels for defining constraints

B_H Observation channels for defining algorithms

J Set of Interpretation functions I

M_w Data model for a supply chain problem

C Constraints on data

O Ontology model

A Set of axioms

H Algorithm or heuristics

G Set of equations

The system consists of interrelated elements. Ackoff (1971) identifies system characteristics, such as an abstract and a concrete system, system state, its changes, and so on. These characteristics guided us during the development of the reference model. System taxonomy is an abstract system whose elements are concepts. Problem taxonomy has two system representation forms— abstract system representation, where problem-relevant elements are presented as concepts: and concrete system representation, where these elements are presented as objects. Ontology presents the states of the system from both static and dynamic perspectives. Ontology also presents system behavior such as response or reaction.

The approach for source abstract system representation is adopted from (Klir 1984) and can be formulated as follows:

$$S = (T, \mathrm{R}) \tag{6.1}$$

Formally, a supply chain system can be represented as a collection of all possible instances of a generic system applied to a supply chain, with corresponding relationships

$$S = (T, W, R) \tag{6.2}$$

Eq. (6.1) is a highly generic and domain-independent system representation. Equqtion (6.2) is still generic, but is a domain-dependent representation. Only those things and their relationships are considered to exist in system instances W. Equqtion (6.2) is the system taxonomy formalism, where W is the supply chain domain. A detailed description of the taxonomy of a system in general can be found in Chandra and Tumanyan (2003). For each possible system instance $w \in W$, the intended structure of w according to S is the structure (problem classification in problem taxonomy)

$$S_w = (T_w, \mathrm{R}_w) \tag{6.3}$$

R_w is the set of extensions (relative to w) of elements of T_w

$$R = \{R_w \mid w \in W\},\ T = \{T_w \mid w \in W\} \tag{6.4}$$

We denote with S the set of all the intended system instance structures of the system

$$S = \{S_w \mid w \in W\} \tag{6.5}$$

Eqs. (6.4) and (6.5) reveal that for each system instance w, there is only one system structure S_w with one set of things T_w and one set of relationships R_w. Each S_w is a description of a problem (model) defined as a part of problem taxonomy for which a solution is to be found. S_w contains the names of parameters identified in the problem description, with corresponding relationships organized in a structured hierarchy. Problem model development based on this formalism offers two sublevels of the problem-modeling layer: problem object model and problem formal model.

Problem Object Model and Problem Formal Model

The notion of *thing* is abstract. To investigate a single thing, we separate it from the outside world, and examine it as an object.

$$Ob = (\{(at_i, At_i) \mid i \in N_n\}, \{(b_j, B_j) \mid j \in N_m\}) \tag{6.6}$$

where N_n = {1,2,...,n} is the number of attributes that the object Ob possesses; and N_m= {1,2,...,m} is the number of observation channels where attributes are examined and collected. N_n and N_m are the rows and columns, respectively, of a two-dimensional matrix with *n* rows and *m* columns. Observation channels are situations, circumstances, processes, narrative descriptions, or any other sources where the problem can be investigated. The set of possible observation channels is denoted by B_j. Different observations where attributes are examined are called backdrops. When investigating a more specific system, backdrops can be considered as situations, where we examine the same attribute. These situations can be subdomains or problems. $(\mathrm{at_i}, \mathrm{At_i})$ denotes an attribute and a set of its appearances (possible values that the attribute can possess), respectively. (b_j, B_j) denotes an observation channel and a set of its states, respectively. Ob is the object (an instance of a thing). Variables are used for an operational representation of an attribute. Each attribute has a name, which is taken from the set of possible values (At_i).

Attributes define two types of variables general and specific for use in general and specific models, respectively. General and specific variables are components of three primitive systems: object system, specific problem system, and general problem system. The last two primitive system representations connect observed domain attributes to real world variables, which this book classifies as ontological commitments. Separation of generic and specific objects is comparative. In some situations, only one problem model is required, while in other cases two or more problem models are necessary to alleviate the complexity by separating problem domains into information models with various levels of abstractions. Two levels of abstraction are discussed: generic Eq. (6.8) and specific Eq. (6.7).

$$SP = (\{(v_i, V_i) \mid i \in N_n\}, \{(w_j, W_j) \mid j \in N_m\}) \tag{6.7}$$

$$GP = (\{(vv_i, VV_i) \mid i \in N_n\}, \{(ww_j, WW_j) \mid j \in N_m\}) \tag{6.8}$$

SP contains variables v_i related to a specific problem, and GP contains variables related to a general problem vv_i. Both specific and general variables may have sets of states (values $vv_i; VV_i$) and participate in a set of system states (situations $ww_j; WW_j$). A specific problem model contains variables related to a set of abstractions (one for each variable), expressing the relationships between specific and general problem systems. It can be called an abstraction channel, which formally can be represented in Eq. (6.9) as

$$\hat{E} = (\{(VV_i, V_i, e_i) \mid i \in N_n\}, \{(WW_j, W_j, k_j) \mid j \in N_m\}) \tag{6.9}$$

The relationship between the object system and the problem system Eq. (6.10) is expressed by an observation channel consisting of individual observation channels for each attribute in the examined system.

$$\tilde{O} = (\{(At_i, V_i, o_i) \mid i \in N_n\}, \{(B_j, W_j, w_j) \mid j \in N_m\}) \tag{6.10}$$

The notion of *thing* about a particular problem can be formulated as

$$T_w = (Ob, GP, SP) \tag{6.11}$$

Relationships among things can be formulated as

$$R_w \cup \tilde{O} \cup \hat{E} \tag{6.12}$$

Eq. (6.12) comprises all possible relationships that may exist in system instance w. To keep the model simple, we will refer to the problem model Eq. (6.3) as the object model and to the set of relationships as R_w. A problem model S_w is an abstract representation of a problem domain— a meta-model. Ontological commitments are for developing a data model out of this meta-model. These commitments are interfaces between abstract problem representation and real world data storage. Rearranging the standard definition, we can define a model *M* as a structure (*S, I*), where *S*=(*T, R*) is a global structure (standard system definition) and *I* is an interpretation function assigning elements of *T* to constant symbols (variables) of *V*.

$$M = (S, \mathrm{I}) \tag{6.13}$$

$$I = (V \rightarrow T_w \cup \mathrm{B}_w) \tag{6.14}$$

I in Eqs. (6.13) and (6.14) is a function that through observation channel *B* assigns attributes of *T* to variables of *V*. This intentional interpretation can be classified as the first ontological commitment. Observation channels are situations where the system state is captured to observe variables *V*. These can be process models, where required variables participate. Studying the documented process model may reveal the meaning of variables and where they can be taken from. Another example of an observation channel can be database schema, precisely describing how variables can be queried and stored. The model representation can be used for more general cases:

$$M = (T, \mathrm{W}, \mathrm{R}, \mathrm{J}) \tag{6.15}$$

These are data models for a system in general, including all of its instances and possible interpretations. Eq. (6.15) is not practical, because it will never be implemented for presenting actual system data models.

Rather, data model presentations for specific system instances are more practical. If we assume $S_w \in S$, for each instance $w \in W$

$$M_w = (T_w, R_w, I) \tag{6.16}$$

M_w is a projection of M, but we will refer to it as a model, not a model instance, because model M in reality will never be implemented. A model can describe a situation common to many states. The second ontological commitment is the application of logical axioms designed to account for the intended meaning of vocabulary, and assigning constraints to system variables. Ontology can be represented as a continuation of problem representation by adding new features to it.

$$O = (M, A, H) \tag{6.17}$$

A is a set of axioms for assigning constraint C to variables through the B_C observation channel.

$$A = (C \rightarrow V \cup B_C) \tag{6.18}$$

H is a set of algorithms for assigning mechanisms (G) to data model processing through the B_H observation channel.

$$H = (G \rightarrow M \cup B_H) \tag{6.19}$$

6.6 Development of Components of Knowledge Management System

Ontology development is the implementation of the reference model described in the previous section in capturing its elements, assembling them using a computational language, and storing them in an environment that would facilitate dissemination and usage. Particularly, software tools and techniques will use the developed ontology as part of supply chain decision modeling, the other significant part of supply chain configuration, which is taken up for discussion in Chapters 7 to 11 of this book. Various stages of ontology development are described next.

6.6.1 Capture

This stage involves the following activities: (1) identification of key concepts and relationships in the domain of interest, (2) production of unambiguous text definitions for such concepts and relationships, and (3) identification of terms to refer to such concepts and relationships (Uschold and Gruninger 1996). Development of a system taxonomy aims to achieve the first two activities for the supply chain domain in general. Identification of concepts for a specific purpose and scope (i.e., the third activity), is the task for the ontology capture activity. The difference between ontology development from scratch and using system taxonomy is that the latter uses search and navigation in the taxonomy hierarchy to find relevant concepts. Once concepts are chosen, an instance of system taxonomy is created that captures only selected concepts, which is T_w and specified by Eq. (6.11). As was mentioned earlier, for the sake of simplicity, thing T_w will be regarded as the object model Eq. (6.6). Relationships R_w are captured automatically in the form of a taxonomy structure that defines how concepts relate to each other.

The knowledge management system conceptualization framework, in addition to the data model (M) identified in the previous section, defines two other components— axioms (A in Eq. (6.18)) and algorithms (H in Eq. (6.19)). Axioms and algorithms capture a process for a search of rules held in the domain of interest for which an ontology is to be built. The theory for axiom representation is based on situation calculus and predicate calculus for representing a dynamically changing supply chain environment. Situation theory (Lesperance et al. 1995) views a domain as having a state (or situation). When the state is changed, there is a necessity for an action. Predicate theory (McCarthy 1958) defines conditions on which specific actions can be taken. Based on these two theories, ontology calculus for a supply chain is planned to be built. It will be based on extending both predicate and situation calculus with new terminology specific to the supply chain domain. The term $do(x,s)$ represents the state after an agent performs an action x in state s. A more supply chain-specific example can be the statement that each product should have demand. This can be formulated as $Exist(demand, \Pr oduct)$. Another example of an axiom is the inventory constraint: Maximum Inventory >= Current Inventory Level, which can be formulated as $Less(MaxInventory, CurrInventory)$.

An example of a portion of an algorithm is the formula according to which order size is calculated as $s = L * AVG + z * STD$; IF IL < s THEN Order = s-IL, where s is the reorder level, L is lead time; AVG, STD are forecasted demand means and standard deviation, respectively, and z is a customer service indicator. If the inventory level (IL) is less than the calculated reorder level, an order is placed (Order), which is equal to the difference of reorder and inventory levels. This axiom can be formulated through situation calculus as $Poss(do((L * AVG + z * STD) = s) > Il) \equiv MakeOrder(s - Il)$.

6.6.2 Assembly

Assembly is an explicit representation in some formal language of the conceptualization captured in the preceding stage. This involves (1) committing to the basic terms that will be used to specify the ontology, (2) choosing a representation language, and (3) writing the code. It simply has to do with writing down, in some language or communicative medium, descriptions or pictures that correspond in some salient way to the world, or a state of the world, of structured data.

For ontology representation, different programming languages and standards have been utilized. Ontolingua (Farquhar et al. 1997) adds primitives to defined classes, functions, and instances. Ontolingua is not a representation system, but rather a mechanism for translating from standard syntax to multiple representation systems. OIL (Ontology Interchange Language) (Fensel et al. 2002) fuses two paradigms— frame-based modeling with semantics based on description logic, and syntax based on web standards, such as extensible markup language (XML) schema and resource description framework (RDF) schema. Both Ontolingua and OIL are frame-based languages that do not provide formalism for first-order logic. With the latter, we intend to represent process logic the same way as frame logic.

XML has become a standard for communication between heterogeneous systems and is widely used on the Internet (Staab et al. 2001). This presents new opportunities for knowledge representation and acquisition and has two aspects. First, XML documents can easily be translated into knowledge representation format and parsed by problem-solving environments or domains. Second, XML can directly connect with data storage repositories (RDBMS or ERP systems), thus enabling database queries to be more expressive, accurate, and powerful. The two objectives can be achieved by enhancing the semantic expressiveness of XML, especially XML data schemas (XSD). We propose a new language, SCML, for presenting knowledge about supply chains. The specification of SCML is formulated as a XSD data schema, depicted in Fig. 6.2. It reflects system representation formalism presented in system taxonomy. At the top level there are seven groupings: input, output, functions, environment, processes, and mechanisms. Each grouping is a container, which consists of subclasses.

A representative sample of SCML is depicted in Fig. 6.3. It defines the entity *Axioms*, any elements it may have, and entities it may contain. An *Axioms* entity class may have one or many *Rules* (*unbounded*) entities, which may have *Attributes* entities (0 or many). An *Argument* entity may have two attributes: *Name* and *Description*. The entity *Rule* may have one and only one *Body* entity and two attributes.

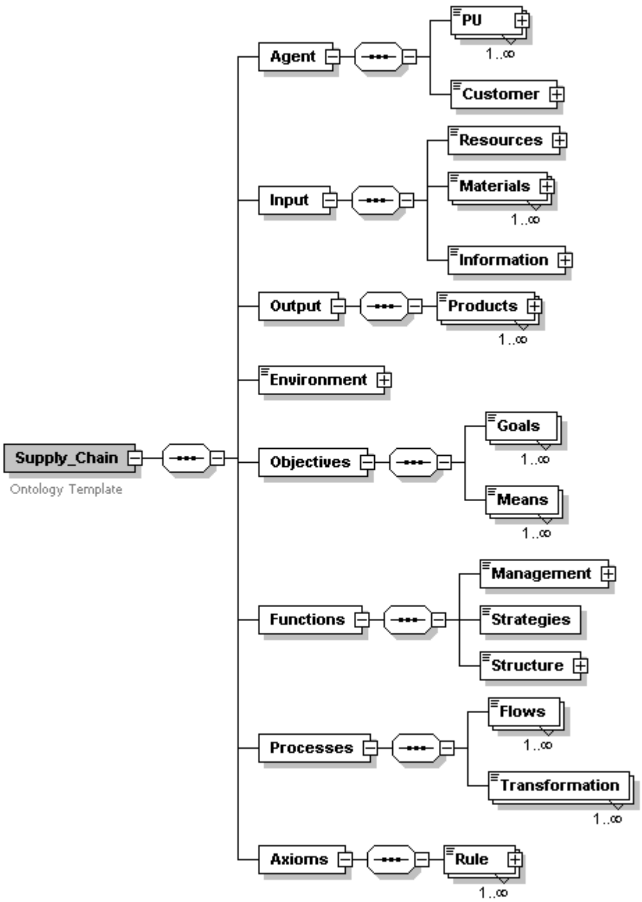

Fig. 6.2 Data schema for supply chain markup language.

The SCML XSD specification defines the format of knowledge representation and can be used for developing ontology models and verifying their correctness.

The assembly process, as viewed in this chapter, is the representation of captured knowledge with XML formalism. Three components of an ontology model can be represented. Data assembly is concerned with developing software programs for connecting to data storage facilities and building XML data files based on schema described earlier. A data model example is represented in Fig. 6.4. Demand for a part (Number 295) produced for Customer Number 21 is demonstrated with four attributes. The *DemandNet* attribute can be used if the demand is stationary. In case it is dynamic, the *DemandMeans* and *DemandDeviation* pair of attributes can be used to present the demand distribution function (it is assumed that demand has a normal distribution). The *numberofRegression* attribute presents the number of observations when calculating its mean and deviation.

Axiom assembly is a manual process consisting of manually entering rules captured with ontology calculus into an XML data file based on SCML schema. An axiom model XML example is represented in Fig. 6.5. The rule demonstrated here is about the relationship between inventory and demand, in case the service level is 100 percent. Ontology calculus for this rule looks like:

$$Poss(ServiceLevel = 100\%) \equiv Less(CurrInventory, Demand)$$

Ontology calculus formalism is transformed into XML formalism as follows. The entity type *Rule* defines the condition *Service level is 100%*. It contains two arguments, *inventory* and *demand*. The entity *Body* defines the relationship between these two arguments according to the condition identified in the parent *Rule* entity's *Name* property.

```
<xs:element name="Axioms">
    <xs:complexType>
        <xs:sequence>
            <xs:element name="Rule" maxOccurs="unbounded">
                <xs:complexType>
                    <xs:sequence>
                        <xs:element name="Body"/>
                        <xs:element name="Attribute" minOccurs="0"maxOccurs="unbounded">
                            <xs:complexType>
                                <xs:attribute name="Name" type="xs:string" use="optional"/>
                                <xs:attribute name="description" type="xs:string" use="optional"/>
                            </xs:complexType>
                        </xs:element>
                    </xs:sequence>
                    <xs:attribute name="Number" type="xs:string" use="optional"/>
                    <xs:attribute name="Name" type="xs:string" use="optional"/>
                </xs:complexType>
            </xs:element>
        </xs:sequence>
        <xs:attribute name="Name" type="xs:string" use="optional"/>
        <xs:attribute name="ID" type="xs:string" use="optional"/>
    </xs:complexType>
</xs:element>
```

Fig. 6.3 Supply chain markup language example axioms.

```
<Demand>
        <Attribute part="295" customer="21"
        DemandNet="5984"
        DemandMeans="6868"
        DemandDeviation="1000"
        numberofRegression="20"
</Demand>
```

Fig. 6.4 Data model XML fragment.

```
<SupplyChain>
    <Axioms>
        <Rule Number="1" Name="Service level is 100%">
            <Argument Name="Inv" Description="Inventory"/>
            <Argument Name="Dm" Description="Demand"/>
            <Body>Inv&gt;=Dm</Body>
   </Axioms>
</SupplyChain>
```

Fig. 6.5 Axiom model XML fragment.

6.6.3 Storage

The purpose of building an ontology server is to enable technology that will facilitate the large-scale reuse of ontologies through Web interfaces for decision-making purposes throughout the complex, extended supply chain enterprise. Fig. 6.6 depicts the ontology server architecture. Data are stored in data storage facilities, which are mainly relational database systems or other carriers of information such as ERP repositories (as a complex system for maintaining data) or files (as a simpler class of data storage facilities).

The main component of the ontology server is the ontology library, which must have an index indicating how each individual item can be found. A problem classification hierarchy, Eq. (6.4), defines this index. Each node in this library corresponds to a problem and is the ontology-specifying description of that problem.

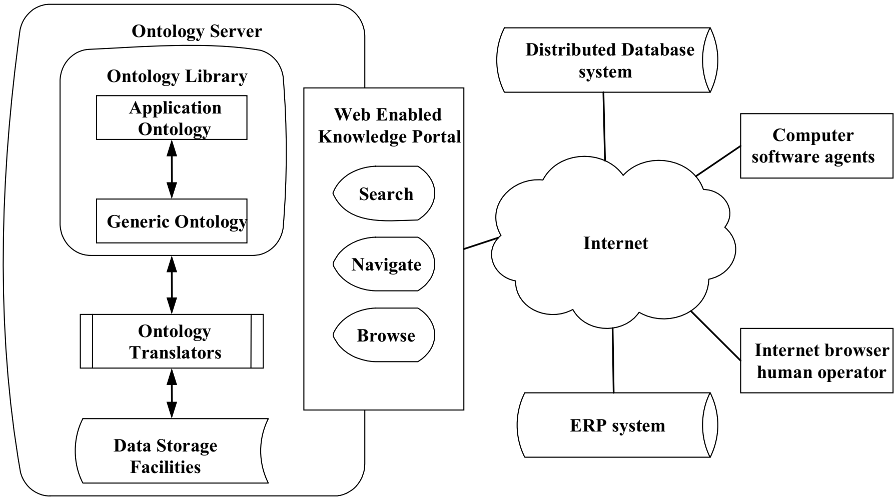

Fig. 6.6 Ontology Server architecture.

6.6.4 Usage

Ontology can be utilized in a variety of ways. It can serve as an explicit medium where knowledge workers share their expertise and skills, it can be used as specifications for software engineers in developing complex software applications, and it can be used by decision makers for understanding the problem and making decisions. But the greatest advantage of having explicit ontologies is in implementing the vision of supply chain management as formulated by Fox et al. (2000). According to Fox, a supply chain is viewed as being managed by a set of intelligent agents, each responsible for one or more tasks in the supply chain, and each interacting with other agents in the planning and execution of their responsibilities.

An ontology server deployed on the Web makes the library available to supply chain members, who share the same perception of problems that they communicate to each other. In the case of agent-based SCM, ontologies provide the members with communication and interoperation. Ontologies inform the system user of the vocabulary for representing domain or problem knowledge.

6.7 Summary

In this chapter, we explore the complexity of the supply chain configuration problem and argue that the best way to solve it is through devising a crosscutting approach that adopts concepts drawn from various disciplines in designing, developing, and implementing efficient and effective solutions. We take the representative information integration problem in the supply chain and argue that any methodology developed for supply chain configuration must explicitly take into account the systemic, reductionist, and analytic approaches available either in the published literature, or designed specifically. These approaches incorporate supply chain configuration problem details at the abstract, activity, and implementation levels, respectively. We have made a case for knowledge design, development, and dissemination using taxonomy and ontology principles to incorporate system integration concepts. We have proposed a theoretical knowledge management system development framework, which acts as a reference model. It is based on problem solving at the above three levels. We also describe a brief implementation scenario of this framework. The utility of this framework rests on the fact that it provides a high level approach to managing the generated supply chain problem-solving knowledge, using various techniques described in Chapter 7 to 11.

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7. Information Modeling Approaches

7.1 Introduction

An understanding of information flows and processing functions is essential for any decision-modeling effort. Traditionally, these information flows are described in terms that are specific to particular decision-modeling techniques. However, in the heterogeneous supply chain environment, that results in largely diverse and often incompatible data definitions. Therefore, a more unified approach to representing information flows and their processing functions is required. Information modeling techniques long-used for information systems development are well-suited for these purposes. Supply chain management is an area where interactions between Decision Sciences and Information Systems Engineering are most profound. Implementation of decisions is not possible without information systems support, and information systems alone without decision-making components are no longer sufficient to maintain a competitive advantage.

Information modeling is a key part of the information systems modeling process, where models undergo different phases of elaboration starting with general requirements for information systems down to semi-executable models directly used in the implementation phase. The main purpose of these models is to simplify development and maintenance complexity of large information systems by describing the system using less abstract concepts. That is especially important for channeling user requirements to system developers.

Similarly, information modeling can be used to describe complex decision-modeling problems. Besides the descriptive capabilities of information modeling techniques helping to understand the problem, developed information models provide a link between decision-modeling and the enterprise-wide information system.

The objective of this chapter is to describe the application of information modeling techniques for supply chain configuration purposes. The general approach is to use well-approbated information modeling techniques that would enable potential model-driven implementation of decision-modeling components.

The following section describes the types of information modeling techniques suitable for supply chain configuration and their application areas. Process modeling, as applied in the supply chain management and particularly for dealing with the configuration problem, is discussed in Section 7.3. Data modeling is described in Section 7.4. Based on data modeling described and the literature survey presented in Chapter 3, a generic supply chain configuration data model is developed in Section 7.5. Section 7.6 offers summary and conclusions for the chapter.

7.2 Information Modeling for Supply Chain Configuration

Information modeling finds multiple applications in supply chain modeling and different modeling techniques can be used. This section introduces these applications and lists main modeling techniques available.

7.2.1 Purpose

One of the main objectives of using information modeling is providing a relatively easily understandable representation of a problem. Several information modeling techniques are usually applied to obtain a comprehensive representation of the problem. The choice of techniques and modeling concepts depends upon objectives of the information modeling application. In the framework of supply chain configuration, several objectives can be identified:

- *General description of the modeling problem*. Information modeling methods are used to attain a better understanding of a particular decision modeling problem. They can be especially useful for describing the decision-making environment. This approach is being used in relation to simulation modeling while it is rarely considered in relation to analytical modeling.
- *Implementation of decision-making components*. If decision making is to be performed routinely, a software application needs to be developed. Information modeling is an essential part of almost any software development project.
- *Definition of links between decision-modeling and other parts of the enterprise-wide information system*. Decision-making models rely on data provided from other parts of the information system and can also use some functions provided by the supply chain information system. In-

formation modeling is used to map data between components and identify available functions.

- *Integration of the decision-making process with the overall information processing system*. This is similar to the second objective, although a decision-making component becomes an integral part of the supply chain information system in this case. The main problem is ensuring that changes made in both decision-making component and supply chain information system are properly represented in related components.

In the case of implementation of decision-making components, information modeling methods are used in a similar manner as in the development of information systems. This approach is mainly applicable if decision-making components are implemented using general purpose programming languages. If a specialized decision-modeling environment and programming languages are used, application of information modeling is not common and the majority of available tools do not support such an approach.

7.2.2 Interactions with Information Systems Development

Modeling of the supply chain configuration problem is considered in the information system development framework (Fig. 7.1) in order to support the integration of decision modeling components and other parts of the information system. High-level problem-domain analysis provides further information systems' development processes with initial input data, such as general supply chain description and modeling objectives. Techniques, such as use case modeling can be used to specify requirements. For the supply chain configuration problem, key requirements for the information system are execution of decision-making processes and incorporation of decision-making results into the overall supply chain information flows. Analysis and design phases elaborate mechanisms for meeting these requirements. Method and tool specific modeling and object-oriented modeling are distinguished. The object-oriented model of the supply chain configuration problem is developed to describe the decision-making problem in relation to the overall supply chain management information system. To achieve that, the model is developed using concepts and models defined in the supply chain repository. That improves consistency, integrity, and development speed of the model. The method and tool specific modeling pertains to specification of the logic of decision-making models. For instance, while data needed for solving an optimization problem are described using object-oriented modeling, the optimization model by itself is described using special purposes mathematical programming languages. If models are properly specified, model generators can be used to implement executable models. The object-oriented models developed support linking the decision-modeling components with the supply chain management information system. Changes made somewhere in the information system in response to variations in the operating environment or other factors would be propagated to associated decision-modeling components.

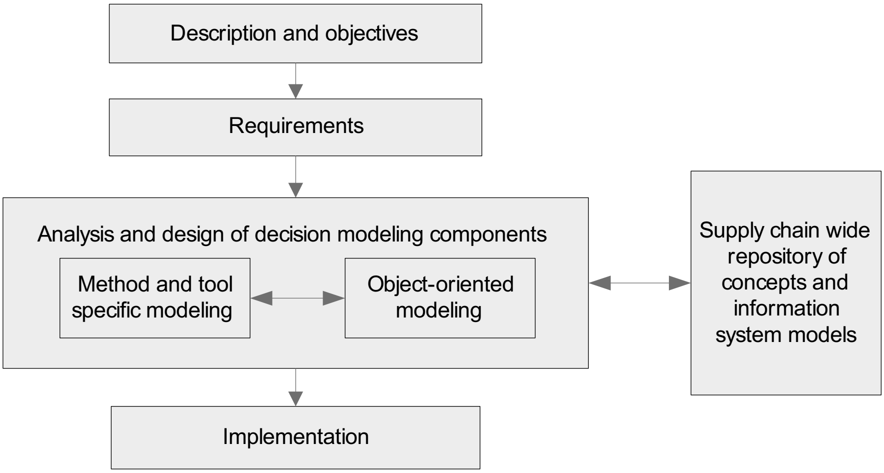

Fig. 7.1 Interactions between information systems development and decision-modeling.

The main difference between the development of enterprise-wide information systems and decision-making components is that the latter are used by a small cadre of skilled professionals. Application of information modeling for decision-modeling purposes is also strongly influenced by interactions between decision-modeling and other modeling efforts at an enterprise. Two cases are distinguished: 1) decision-modeling is performed independently from information system modeling processes in an enterprise; and 2) decision-modeling is based on existing enterprise information system models. We discuss these below.

Independent Decision-Modeling

This is the traditional case when decision models are developed on a case-by-case basis. Model specific modeling concepts are used. Formalization and representation of the modeling problem and data requirements are secondary and developed information models, if any, are not sufficiently elaborated.

If previously developed information models are not available, then independent decision modeling is faster by focusing only on issues directly relevant to the decision-making problem. However, following this approach, no basis will be created to reduce the workload of future decision-modeling activities and implementation of decision-modeling components.

The approach is feasible for pure configuration problems when interactions between the decision-making model and other parts of the information system are negligible. However, the increase in the scope leads to difficulties in incorporating other components and identifying relevant data in the enterprise information system.

Models developed during independent decision modeling do not aid implementation of decision-making components and their integration into the supply chain-wide information system. Additionally, updating of models is complicated as no formalized links between decision-modeling and other parts of the information system are established, and tracing of changes can be automated.

From the information-modeling perspective, decision-modeling on a case-by-case basis does not facilitate the reuse of existing models, compromises consistency of models developed, provides limited traceability, and does not provide implementation aids.

Decision-Modeling Based on Existing Information Models

Information models of decision-making components are developed on the basis of existing supply chain wide information systems models, implying that the same concepts are used in decision-making oriented information models, as in the supply chain-wide information system. Additionally, parts of information models can be composed from existing information models. That allows reducing model development workload and improving modeling consistency. Information models developed for decision-making purposes can be linked with corresponding elements in the supply chain wide-information systems. That allows the tracing of changes occurring in the supply chain information systems and the updating of decision-models. Implementation of decision-modeling components as a part of the supply chain-wide information system can be streamlined.

Difficulties with this approach are increased initial workload, the problem of bringing together information technology and decision-making personnel, representation of specific decision-making aspects, and integration of different (both logically and technically) information models.

7.2.3 Overview of Modeling Techniques

There are a large variety of information-modeling techniques. If one follows the traditional information systems development life-cycle (Pressman

2004), problem-model analysis or requirements engineering is the first step. This step is used not only to define requirements of the projected information systems, but also to attain a more general understanding of an enterprise (or group of enterprises, such as a supply chain) and its business. Process modeling, concept modeling and objectives modeling are often used modeling techniques at this stage. Supply chain configuration objectives are assumed to be given at the beginning of the configuration process. Therefore, objective modeling methods are not considered. Concept modeling is needed if the supply chain is established from scratch or a configuration problem solving is attempted for the first time. Otherwise, more elaborate data modeling approaches could be used. Process modeling is of primary concern and is discussed in detail in Section 7.3.

The problem domain analysis is followed by application domain analysis and design. The Unified Modeling Language (UML) has become one of the major information modeling tools for these stages (Arlow and Neustadt 2005). It includes a number of interrelated models. UML defines modeling syntax while it does not govern the model development process. Therefore, it can be applied for dealing with a diverse range of problems. Not all UML diagrams are equally important for supply chain configuration and decision-making in general. For instance, the use case diagram, which describes functionality from the end user perspective, usually is not important because the number of users for decision-modeling components commonly is small.

The static structure representation is one of the main aspects of object-oriented modeling supported by UML. Similarly, as conceptual models, class diagrams represent subjects characterizing a problem domain. In the supply chain context, the class diagram is mainly applied for data modeling purposes. It can also be used to establish a structure of decision-modeling components although this aspect is beyond the scope of this book.

Entity-Relation diagrams (Hoffer 2006) also can be used for data modeling purposes. These diagrams are especially useful for representing decision-modeling data base and identifying data sources in the supply chain management information system. However, the class diagram can represent more information than ER diagrams. Therefore, the use of class diagrams for data modeling purposes is advocated. Class diagrams are also important for providing process integration capabilities and supporting implementation of decision-modeling components. Automated conversion tools between class and ER diagrams are available. The Integrated Definition (IDEF) language is an information modeling approach encompassing tools for both data and process modeling. It is popular for many manufacturing applications. An advantage of UML over IDEF is its integration with software development processes.

Detailed design and direct implementation aids are provided by such UML diagrams as state, sequence, and deployment diagrams. The state and sequence diagrams show dynamic interactions among objects. The deployment diagram provides a high-level description of interactions among components. These models are required mainly for achieving the fourth objective of using information modeling for supply chain decision-making.

To support integration of decision-components with other part of the information system, decision-modeling components need to be designed following good software engineering practices, with an emphasis on modularity.

Some of the modeling methods have been applied to modeling supply chains or distributed manufacturing systems. Decision-modeling components with simulation-based decision-making capabilities are often developed using the object oriented approach (Alfieri and Brandimarte, 1997; Anglani et al., 2002). However, simulation models generally are decoupled from other parts of the information system. A higher level of integrity has been achieved in the modeling of manufacturing systems. Al-Ahmari and Ridgway (1999) use the GRAI enterprise modeling method for descriptive high-level analysis of the manufacturing system, and IDEF0 for process modeling and as a basis for tool-specific simulation model development. Although their paper focuses on obtaining the simulation model as a system design tool, the process model also could be used for implementation of the manufacturing automation system and other information systems. Gayialis and Tatsiopoulos (2004) also use GRAI, along with the ARIS system architecture to describe the vehicle-scheduling problem. The models obtained are used to select appropriate Geographical Information Systems (GIS) and Enterprise Resource Planning (ERP) systems for implementation of the decision-modeling component. Kang and Kim (1998) develop an integrated modeling framework for a manufacturing system, where representations of physical processes and information systems are integrated. The object-oriented approach is used to describe the static structure of the manufacturing system.

There are also several works on object-oriented modeling in the supply chain configuration framework. Biswas and Narhari (2004) use the UML class diagram to describe a decision-making problem and the UML activity diagram to describe the model solving procedure. These representations are used for automated generation of the executable model. The authors demonstrate the potential benefits of object-oriented modeling for building mathematical programming models in off-line decision-making situations. However, application of the object-oriented modeling and particularly UML is considered on a case-by-case basis and comprehensive guidelines for representing mathematical programming models using UML have not been elaborated. Moreover, modeling of decision-making components is treated as a separate activity without considering further integration of mathematical programming model with the core of the enterprise information system. Kim and Rogers (2005) develop object-oriented supply chain models. These models can be used to incorporate the decision-modeling component into the overall information processing flow. The authors emphasize the supplementary value of various modeling views. The object-oriented model of existing supply chain configuration is developed in Hung et al. (2006) for standalone simulation modeling purposes. Dolk (2000) shows a sample object-oriented model of the manufacturing network.

An important issue to be addressed during information modeling is integration of heterogeneous models developed using different modeling techniques and by different parties involved in collaborative supply-chain planning.

The following section discusses information-modeling techniques most relevant to the supply chain configuration problem. Readers are referred to Pressman (2004) for more detailed description of information modeling techniques and the general information systems development process.

7.3 Process Modeling

Process modeling can be used to achieve all four of the stated information modeling application objectives. However, description and exploration of the decision-making problem is the most classical application objective. There are two important sources of information supporting the supply chain configuration process modeling: 1) the Supply Chain Operations Reference (SCOR) model; and 2) ERP reference models. Reference models are important to achieve a common understanding of supply chain processes.

SCOR Model

The SCOR model (Stephens 2001) was proposed by the Supply Chain Council as a reference model for describing supply chains. The reference model defines typical supply chain management processes, and performance metrics and best practices associated with these processes. It has hierarchical structure consisting of three levels and a fourth implementation level, which is elaborated for particular supply chain management problems. The first level describes generic supply chain management processes, namely *Plan, Source, Make, Deliver* and *Return*. Additionally, the *Enable* process type is included to represent processes of preparing, maintaining, and managing the information or relationships necessary for the execution of other processes. These main processes are further decomposed in process categories, which in turn are decomposed into process elements. A description of each process element includes a short definition, metrics for each of the standard performance attributes (the SCOR model defines reliability, responsiveness, flexibility, cost and assets as standard performance attributes), best practices characterized by their features, process inputs, and process outputs. Processes providing inputs and consuming outputs are identified. The SCOR model mainly focuses on practices suitable for supply chain implementation and execution while decision-making techniques are not covered. The SCOR model, again, can be used for two purposes: 1) to describe the supply chain under consideration; and 2) to understand processes relevant to supply chain configuration.

If the SCOR model is used to describe supply chain configuration, SCOR processes are used as building blocks to develop a descriptive model. Such an approach has been taken by Huang et al. (2005) who composed a supply chain from processes defined in the SCOR model using a custom-built configuration tool. This descriptive model shows either the current supply chain or an envisioned supply chain structure. The configuration model benefits from using widely accepted supply chain modeling concepts. However, it lacks in the level of detail needed for further modeling and implementation purposes. Therefore, another modeling layer is required. Supply chain-wide usage and compatibility of this layer would be greatly improved by using a widely accepted process modeling technique, such as IDEF or Event-Process Chains (EPC).

As noted before, the SCOR model also can be used to improve understanding of supply chain configuration problems. Analysis of the SCOR model summarized in Table 7.1 shows processes perceived as most pertinent to the supply chain configuration problem. The comments column of the table emphasizes only main points characteristic of these processes, but complete descriptions of the processes can be found in the SCOR model documentation. These processes mainly help in identification of issues to be addressed during supply chain configuration decision-making and in identification of appropriate policies such as collaborative planning, exchange of information, outsourcing, and third-party services. Use of SCOR metrics substantially facilitates definition of the supply chain configuration scope. For instance, a broker can identify relevant cost parameters. Additionally, a broker can attempt to structure the overall supply chain planning process according to the SCOR guidelines, and define location of configuration decision-making in this process.

Table 7.1 includes a few execution processes because these are more relevant to operational planning and daily supply chain execution. However, many of these processes can be used if a supply chain configuration simulation model is constructed.

Table 7.1 SCOR Processes Directly Attributable to Supply Chain Configuration

Number	Type	Name	Comments
P1	Plan	Plan supply chain	The second-level process category representing the development and establishment of courses of action over specified time periods that represent a projected appropriation of supply chain resources to meet supply chain requirements. Best practices emphasize importance of integrated supply chain management information systems and calls for the use of reconfigurable business processes.
P1.1	Plan	Identify, prioritize, and aggregate supply chain requirements	Deals with demand planning and sales forecasting. Collaboration among supply chain partners is essential.
P1.2	Plan	Identify, prioritize and aggregate supply chain resources	Defines supply chain resources. Uses sourcing, production, delivery, and outsourcing plans as inputs. Collaboration among supply chain partners is emphasized.
P2.4 P3.4 P4.4	Plan	Establish sourcing, production, delivery plans (respectively)	Three similar processes establishing course of action representing appropriation of supply chain resources.
P1.4	Plan	Establish and communicate supply Chain plans	The establishment and communication of courses of action over the appropriate time-defined (long-term, annual, monthly, weekly) planning horizon and interval, representing a projected appropriation of supply-chain resources to meet supply-chain requirements.
ES.9	Enable	Manage supplier agreements	The management of existing or supplier contracts.
(continues on the next page)			
D1.7	Deliver	Select carriers and rate shipments	Specific carriers are selected by lowest cost per route and shipments are rated and tendered assuming that main delivery modes are identified during supply chain configuration decision making.
EP.5	Enable	Manage integrated supply chain capital assets	The process of defining capacity strategy (i.e., internal versus contract manufacturing or internal versus 3rd Party Logistics) and then acquiring, maintaining, and dispositioning an organization's capital assets to operate the integrated supply

Number	Type	Name	Comments
			chain. Outputs of the process include projected internal and external capacity and outsourcing plans.
EP.6	Enable	Manage integrated supply chain transportation	Defines the transportation strategy across the supply chain, including information systems support.
ES.7	Enable	Manage supplier network	Defines and maintains supply network. Metrics for assessment of supply network are provided (important for Step 11 of supply chain configuration methodology). Supplier management practices, such as Internet exchanges, vendor managed inventory, consignment inventory, Kanban, concurrent engineering, and supplier certification are identified. The process also includes ranking of suppliers.
EM.7	Enable	Manage production network	Defines and maintains manufacturing network.
ED.6	Enable	Manage transportation	Defines and maintains information about transportation modes and routes
ED.7	Enable	Manage product life-cycle	Defines and maintains distribution network for specified products.
ER.7	Enable	Manage return network configuration	Defines and maintains product return information.

ERP systems have major impact on the supply chain information processing environment. Many supply chain members store their data and implement their processes using ERP systems. Process models constitute a key part of ERP systems reference models (Curran and Ladd 2000), which describe the company's business processes and data.

ERP Reference Models

Reference models of ERP systems represented as process models help integration of configuration decisions into the overall decision-making and process execution-process. Interactions between configuration decisions and other enterprise activities can be identified. The EPC process modeling approach (Curran and Ladd 2000) has been adopted by the largest enterprise software developer, SAP, as their standard process modeling language.

Problem Specific Process Modeling

The process-modeling approaches discussed above are intended for gaining a general understanding of the decision-making environment. However, they provide insufficient information about particular decision-making problems. To achieve that, some of the existing process modeling techniques can be used to describe a particular supply chain configuration problem. The decision-making-oriented process model describes main functions performed by supply chain partners as well as interactions among the partners. Fig. 7.2 shows a process-modeling example for the supply chain configuration problem. In the upper panel, supply chain tiers are encapsulated under supply, manufacturing or distribution processes functions. This general function for the supply tier is further decomposed in the lower panel of the figure. The decomposed view shows all individual suppliers. Each supplier has at least one function (in this example, a quite general function is used although further decomposition is possible). A particular supplier performing the function is indicated by an associated organizational unit (light ellipses). Materials supplied by suppliers are shown using squares. Relationships between suppliers and particular manufacturers or manufacturing facilities are indicated using the process path symbol. Some of the principles employed in this model are

- Given that representing units in the configuration framework is often more important than representing functions, which are shown in association with organizational units. That is often omitted in common process models
- Representing materials and products at each tier in association with supply chain units is also important. Therefore, material representation is used
- If decision-modeling scope is kept narrow, then functions used in the process model can have a high level of abstraction
- Events can be used to describe constraints, such as capacity and transportation mode selection constraints

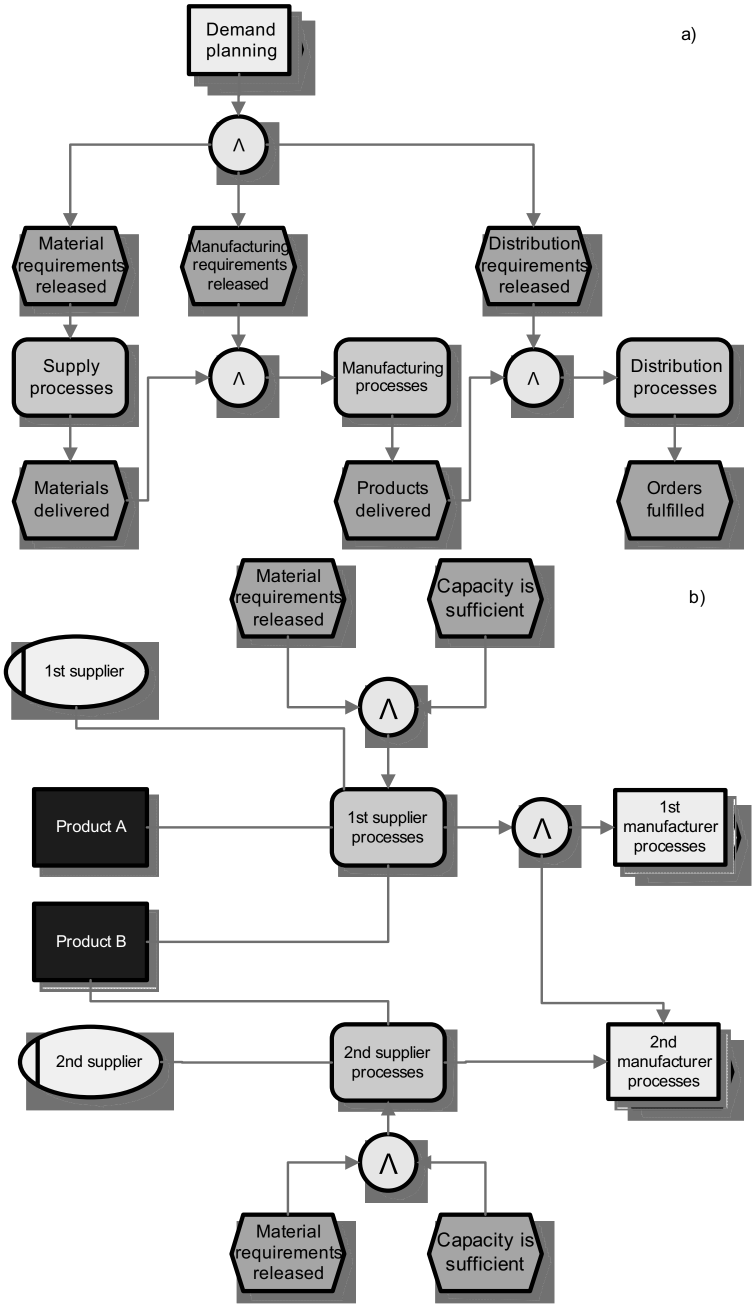

Fig. 7.2 Supply chain configuration problem described by a process model: a) the overall process; and b) elaboration of the supply processes function.

There are some limitations concerning process modeling of the supply chain configuration problem. Particularly, simultaneous representation of structural and dynamic properties is difficult, a correct process model can be overly complicated, and possibilities to represent alternative policies are limited. Given the growing importance of the SCOR model and executable business process models discussed below, it can be expected that specific supply chain business process modeling tools will be developed. The modeling framework by Dong and Chen (2004) is a step in this direction. Activities (i.e., processes) are grouped together in sites. Each site also has stores for keeping work-in-progress materials and finished products. Raw material suppliers and customers are designated as special concepts, serving as supply chain endpoints.

Executable business processes (Thatte et al. 2003) is an important development in information technology with a predictably major impact on enabling dynamic supply chain configuration. They differ from traditional business processes by not only naming processes but also formalizing business logics and data requirements behind these processes. The business logics and data requirements can be described in a standardized manner so that a developed business process model can be readily executed. The technology used to implement executable business processes is based on web services, which are described in Chapter 11 of this book. Executable business processes also stress the importance of linking supply chain information processing with decision-making components through well-structured information models.

7.4 Data Modeling

Data modeling can be applied to describe data relevant to the modeling problem, or to support direct implementation of the decision-modeling component. Process models facilitate development of data models.

Two types of data models are distinguished: 1) general data models; and 2) modeling technique specific data models (this distinction roughly corresponds to logical and physical data models used in the database management area). General data models describe the supply chain configuration problem independently of the model implementation environment. They are used for descriptive purposes. Modeling technique specific data models describe the whole problem or its subset in terms of specific decision-modeling tools to be used. They are used for execution purposes.

The modeling technique specific models are developed on the basis of the general data model. Utilization of the general model is useful if multiple specific models need to be constructed. It is also important to enable data mapping between source information systems and decision-modeling components

7.4.1 General Data Model

The supply chain configuration scope definition developed in Chapter 2 identifies main concepts relevant to the supply chain configuration problem. It included supply chain units, products, objectives, variables, parameters, and others. If UML is selected as the data modeling language then stereotyping can be used to define specialized elements for describing generally used concepts. Stereotypes and other concepts used can be defined in a meta-model for building supply chain configuration object models (see Kleppe et al. (2003) for more information on meta-modeling). The meta-model defines concepts used for further development of models for particular problems. They facilitate development of consistent data models. Using modeling concepts defined in the meta-model, a supply chain configuration class diagram is developed. The class diagram describes general supply chain subjects. An object diagram showing particular supply chain units with specific values assigned to parameters is developed by instantiating the supply chain configuration classes.

The supply chain configuration meta-model is shown in Fig. 7.3. A representation of the supply chain configuration problem is built starting with definition of supply chain units and other physical objects relevant to a particular decision making problem. These are all commonly referred to as subjects. Each subject has a specified dimension defining the number of instances in a system. For instance, there are 10 different products in the system. Subjects are represented as a class using the UML syntax. Several parameters and decision variables can be associated with a subject. They describe characteristics of corresponding subjects. For instance, a plant is described by a parameter *capacity*. Subjects in the system typically interact among themselves. These interactions are defined as *SubjectRelation* in the meta-model and are represented as an association class using the UML syntax. An example of such subject relationships between subjects *Product* and *Plant* is production of the specified product at the specific plant. Relationships also can be characterized by decision variables and parameters. Parameters and decision variables characterize subjects and their relationships. They are represented as attributes in UML. Parameters and decision variables associated with subjects and subject relationships are one-dimensional and multi-dimensional arrays, respectively. All subjects together form a supply chain.

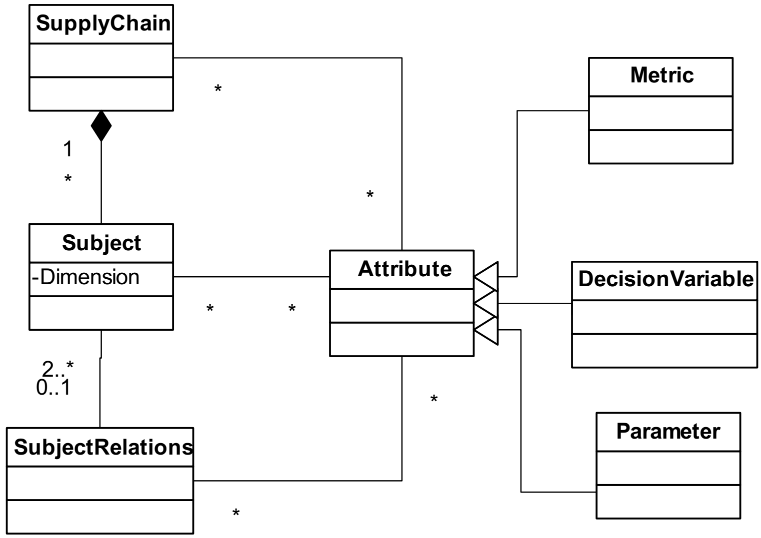

Fig. 7.3 The supply chain configuration UML meta-model.

An example of the supply chain configuration class diagram was given in Chapter 5. A generic supply chain configuration class diagram, which attempts to incorporate major features of the supply chain configuration problem, is developed in Section 7.5. It is intended as a reference point for development of problem-specific supply chain configuration data models.

An object diagram can be developed as instantiation of the class diagram. It contains objects identified for a particular supply chain configuration problem. However, this diagram has limited practical value because the graphical representation for a complex supply chain is too large, and the actual values of parameters can be represented in a more efficient manner.

7.4.2 Modeling Technique Specific Data Model

The UML-based data models provide a descriptive model of the decision-making problem. However, not all data necessary for decision-making can be efficiently represented using UML diagrams. Therefore, modeling technique specific data models are also needed, especially at the model-implementation level. Distinction between general and modeling technique specific models is similar to differences between logical and physical data base models in database design.

Modeling technique specific data models can assume a large number of different formats ranging from flat files to multi-dimensional databases. Sample modeling technique specific models are described in Chapters 8 and 13. Subsequently, in chapters describing various quantitative supply chain configuration models, general data models are more often used to develop the structure of decision-making models while modeling technique specific data models are used to describe data structures used directly during the modeling process.

7.4.3 Data Mapping

Data models serve as the basis to establish mappings between data sources and the decision-making system, and to actually implement a data exchange mechanism. Implementation of data exchange mechanisms is mainly a technological problem (Chapter 11 describes different information technology solutions available for technological implementation of data exchange mechanisms using the enterprise application integration (EAI) approach) while establishing data mappings is a complex logical problem because various systems (and their information models) use different data definitions, formats, and so on.

Kühn et al. (2003) discusses the importance of model integration. The authors identify model integration patterns and describe an example of integrating custom-built software with the ERP system at the modeling and implementation levels. UML is used as the centerpiece of integration efforts in the majority of the papers surveyed above.

The following steps are integration of the UML model into the model of enterprise-wide information system and establishing mappings to additional data sources. In the case of integration of class diagrams, integration guidelines presented in Blaha and Premerlani (1998) and McBrien and Poulovassilis (1998) can be followed. The integration involves primitive, complex, and knowledge-based transformation. In many cases, data from transactional data sources need to be processed and aggregated. Additional data sources are needed for data not readily available in the information system — for instance, various cost estimates.

7.5 Generic Supply Chain Configuration Data Model

Chapter 3 surveyed the state of the art of supply chain configuration research and practice. It identified the most important issues regarding the supply chain configuration. Similarly, an analysis of existing work can be used to develop a general representation of the supply chain configuration problem. Data modeling can be used to describe entities and attributes most commonly characterizing the supply chain configuration problem. The obtained data model can be used as a common basis for developing problem specific data models and for integrating decision-making processes across the supply chain. It provides a formalized definition of the scope of the supply chain configuration problem viewed from the perspective of static data structure.

The UML class diagram is used to describe the general data model. This generic model is constructed using definitions provided in the supply chain configuration meta-model (see Fig. 7.3). Classes are used to represent entities involved in the supply chain configuration and attributes of the classes are used to describe data items. Decision variables and parameters are two main types of data items. The parameters also can be perceived as data received from the enterprise-wide information system and the decision variables can be perceived as data sent back to the enterprise-wide information system.

In order to construct the common data model, literature sources classified as presenting quantitative configuration models in the state of art survey in Chapter 3 are selected. Entities, decision variables, and parameters from all models are extracted. These are analyzed to identify most commonly used terms (Chandra and Grabis 2006). As a result, the following data model is obtained (see Fig. 7.4).

The data model contains supply chain units representing all supply chain tiers. These units are represented by *Supplier, Plant, DistributionCenter*, and *Customer* classes. *Material* and *Product* classes are also included as these entities are usually involved in configuration problem solving. The most common parameters and decision variables are defined for each class and association among these classes. For instance, common attributes of the *Plant* class are *capacity, fixedCost* and *isOpenIndicator*. This class has associations with *Supplier, DistributionCenter, Product,* and *Material* classes. For instance, association class *MaterialSupplierPlant* with attribute *transportationCost*. This attribute describes material transportation costs from supplier to plant.

This data model represents only the most common terms reported in the literature. It can be expanded to include additional classes and their attributes by adding either new classes or child classes through inheritance relationships.

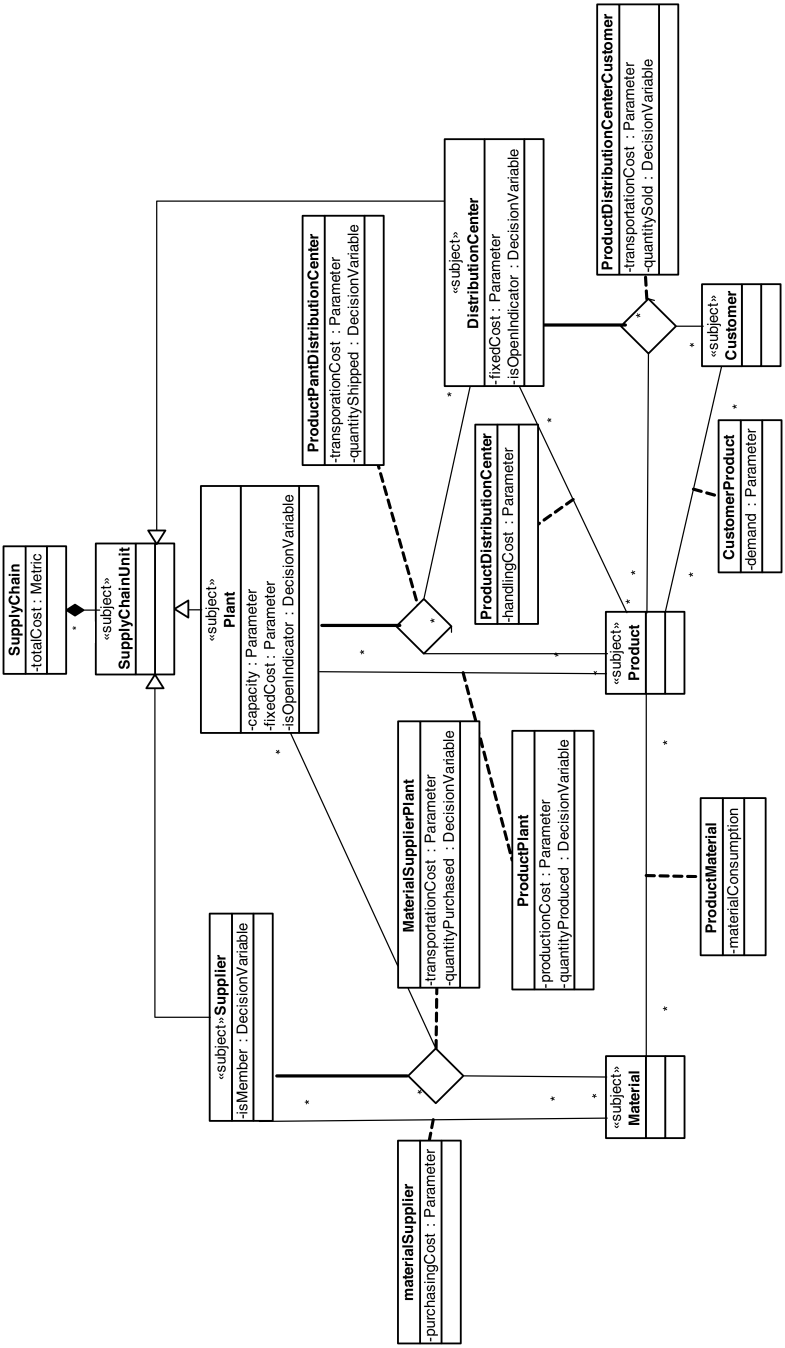

Fig. 7.4 The generic supply chain configuration data model.

7.6 Summary

Information models have a crucial role if decision-modeling capabilities need to be integrated into an enterprise wide-information system. If these models are sufficiently elaborated, they can be used to support automated implementation of the decision-making components and their integration with the enterprise-wide information system. This chapter has presented several possibilities for using well-known information modeling techniques for descriptive supply chain modeling.

Development of information models can be time-consuming, and is not appropriate for one-of-a-kind studies. However, if supply chain configuration decisions are evaluated relatively frequently (e.g., in the case of reconfigurable supply chains) and there are re-use opportunities across other supply chain modeling activities, then application of information modeling techniques can offer significant advantages in the form of reduced modeling efforts (e.g., easier data gathering) and improved model integrity and consistency.

The majority of information modeling techniques are general purpose modeling techniques and do not contain constructs specific to supply chain modeling. It appears that the supply chain specific modeling constructs would be useful in process modeling to represent spatial aspects of supply chain representation. The same applies to representation of multiple alternatives.

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8. Mathematical Programming Approaches

8.1 Introduction

Mathematical programming is one of the most important techniques available for quantitative decision making. The general purpose of mathematical programming is finding an optimal solution for allocation of limited resources to perform competing activities. The optimality is defined with respect to important performance evaluation criteria, such as cost, time, and profit. Mathematical programming uses a compact mathematical model for describing the problem of concern. The solution is searched among all feasible alternatives. The search is executed in an intelligent manner, allowing the evaluation of problems with a large number of feasible solutions.

Mathematical programming finds many applications in supply chain management, at all decision-making levels. It is also widely used for supply chain configuration purposes. Out of several classes of mathematical programming models, mixed-integer programming models are used most frequently. Other types of models, such as stochastic and multi-objective programming models, are also emerging to handle more complex supply chain configuration problems. Although these models are often more appropriate, computational complexity remains an important issue in the application of mathematical programming models for supply chain configuration.

This chapter is aimed to describe application of mathematical programming for supply chain configuration. The general overview is given in Section 8.2. It is followed by a description of generic supply chain configuration mixed-integer programming model in Section 8.3. This model is based on the data model presented in Chapter 7. Computational approaches for solving problems of large size are also discussed along with typical modifications of the generic model, especially, concerning global factors. Section 8.4 outlines the application of other classes of mathematical programming models. In Section 8.5, an illustrative application of the generic supply chain configuration optimization model is presented. Section 8.6

details a model integration procedure whereby optimization models for supply chain configuration problems can be built on the basis of pertinent information models.

8.2 Fundamentals

Mathematical programming models are used to optimize decisions concerning execution of certain activities subject to resource constraints. Mathematical programming models have a well-defined structure. They consist of mathematical expressions representing objective function and constraints. The expressions involve parameters and decision variables. The parameters are input data, while the decision variables represent the optimization outcome. The objective function represents modeling objectives and makes some decisions more preferable than others. The constraints limit the values that decision variables can assume.

The main advantages of mathematical programming models are that they provide a relatively simple and compact approximation of complex decision-making problems, an ability to efficiently find an optimal set of decisions among a large number of alternatives, and supporting analysis of decisions made. Specifically, in the supply chain configuration problem context, mathematical programming models are excellent for modeling its special aspects.

There are also some important limitations. Mathematical programming models have a lower level of validity compared to some other types of models — particularly, simulation. In the supply chain configuration context, mathematical programming models have difficulties representing the dynamic and stochastic aspects of the problem. Additionally, solving of many supply chain configuration problems is computationally challenging.

Following the supply chain configuration scope, mathematical programming models are suited to answer the following supply chain configuration questions:

1. Which partners to choose?
2. Where to locate supply chain facilities?
3. How to allocate production and capacity?
4. Which transportation mode to choose?
5. How do specific parameters influence supply chain performance?

The most common type of mathematical programming models is linear programming models. These models have all constraints and the objective function expressed as a linear function in variables. However, many real-life problems cannot be represented as linear functions. A typical example is representation of decisions concerning the opening of supply chain facilities. These decisions assume values equal either to 0 or 1. Integer programming models are used to model such problems. Their computational tractability is lower than that of linear programming models. Non-linear expressions are often required to represent inventory and transportation-related issues of supply chain. That results in nonlinear programming models, which have high computational complexity.

Given the heterogeneous nature of supply chains, optimization often cannot be performed with respect to a single objective. Multi-objective programming models seek an optimal solution with regard to multiple objectives. These models rely on judgmental assessment of the relative importance of each objective.

Generally, as one moves from linear programming to more complex mathematical programming models, the validity of representing real-world problems is improved at the expense of model development and solving simplicity. Specialized model-solving algorithms are often required to solve complex problems.

Mathematical programming modeling systems (Greenberg 1993) have been developed for elaboration, solving, and analysis of mathematical programming models. These include GAMS, ILOG, and LINGO, to mention a few. These systems provide a means for data handling, model composition using special-purpose mathematical programming languages, and model solving. From the perspective of integrated decision modeling frameworks, these systems can be easily integrated into the decision support system to provide optimization functionality. The integration is achieved by using some types of application programming interfaces (Chapter 11 provides more detailed discussion on this topic). Data structures used, generally, are system specific. Therefore, these need to be mapped to data sources using information modeling.

The role of mathematical programming systems in the overall strategic decision-making system has been described by Shapiro (2000). The described optimization modeling system includes links from the mathematical programming system to a decision-making database and other data sources, as well as advanced tools for conducting analysis. Generation of optimization models from data stored in the decision-making database is considered.

8.3 Mixed-Integer Programming Models

Traditional supply chain configuration models are mixed integer programming models. This section starts with presenting a generic model formulation which includes only the most frequently used decision variables, parameters, and constraints, as identified during construction of the generic supply chain configuration data model. The presentation of the generic model is followed by an overview of most frequently used modifications.

8.3.1 Generic Formulation

The following sub-sections define notation used to specify the generic supply chain configuration optimization model, and present the object function and constraints of this model.

Notations

Notation	Definition
Indices	
I	Products, i=1,…, I
j	Materials, j=1,…, J
k	Plants, k=1,…, K
s	Suppliers, s=1,…, S
m	Distribution centers, m=1,…, M
n	Customers, n=1,…, N
Parameters	
d_{in}	Demand
h_k	Plant capacity
γ_i	Capacity requirements for product
δ_{ij}	Material consumption per product
ω_{js}	Material purchasing cost from supplier per unit
λ_{ik}	Production cost at plant per unit
r_{im}	Handling cost at distribution center per unit
t_{1jsk}	Transportation cost from supplier to plant per material unit
t_{2ikm}	Transportation cost from plant to distribution center per product unit
t_{3mn}	Transportation cost from distribution center to customer per product unit
f_{1k}	Plant fixed opening/operating cost per time period
f_{2k}	Distribution center fixed opening/operating cost per time period
P	A large constant number
Decision variables	
X_{imn}	Quantity of products sold from distribution center to customer
Q_{ik}	Quantity of products produced at plant
Y_{ikm}	Quantity of products shipped from plant to distribution center

V_{jsk}	Quantity of materials purchased and shipped from supplier to plant
W_k	Plant open indicator equals 1 if plant is open and 0 otherwise
U_m	Distribution center open indicator equals 1 if distribution center is open and 0 otherwise

Objective Function

The objective function minimizes the total cost (*TC*). As indicated in the previous chapter, minimization of the total cost is considered more often than profit maximization. The total cost consists of production cost, materials purchasing and transportation cost, products transportation cost from plants to distribution centers, product handling and transportation cost from distribution centers to customers, and fixed costs for opening and operating plants and distribution centers.

$$\begin{aligned} TC = {} & \sum_{i=1}^{I}\sum_{k=1}^{K}\lambda_{ik}Q_{ik} + \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{k=1}^{K}\left(\omega_{js} + t_{1jsk}\right)V_{jsk} \\ & + \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{m=1}^{M} t_{2ikm}Y_{ikm} + \sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{n=1}^{N}\left(r_{im} + t_{3imn}\right)X_{imn} \\ & + \sum_{k=1}^{K} f_{1k}W_k + \sum_{m=1}^{M} f_{1m}W_m \end{aligned} \tag{8.1}$$

Constraints

$$\sum_{m=1}^{M} X_{imn} \le d_i, \forall i,n \tag{8.2}$$

$$\sum_{n=1}^{N} X_{inm} \le \sum_{k=1}^{K} Y_{ikm}, \forall i,m \tag{8.3}$$

$$\sum_{m=1}^{M} Y_{ikm} \le Q_{ik}, \forall i,k \tag{8.4}$$

$$\sum_{i=1}^{I} \gamma_i Q_{ik} \le h_k W_k, \forall k \tag{8.5}$$

$$\sum_{i=1}^{I} \delta_{ij} Q_{ik} \le \sum_{s=1}^{S} V_{jsk}, \forall j,k \tag{8.6}$$

$$\sum_{i=1}^{I}\sum_{n=1}^{N} X_{imn} < PU_m, \forall m \tag{8.7}$$

$$W_k, U_m \in \{0,1\}, \forall k,m \tag{8.8}$$

Eq. (8.2) enforces the balance between products sold and demand. The balance between incoming and outgoing flows at distribution centers is defined by Eq. (8.3). The balance between products produced and products shipped to distribution centers is enforced by Eq. (8.4). Eq. (8.5) restricts capacity availability. Availability of materials to produce products is checked by Eq. (8.6) and Eq. (8.7) states that product flows are allowed only through open distribution centers.

Comments

The model does not explicitly include parameters characterizing a spatial location of supply chain units. Alternative locations for a particular supply chain unit are evaluated by allowing for several units with equal characteristics but different transportation costs, which characterize the location of the unit.

There are two factors affecting the model composition: 1) the broker and power structure; and 2) the initial state of the network. Depending upon the organizational and power structure of the supply chain and a decision maker's point of view (i.e., interests of the whole supply chain vs. interests of the dominant member), some of the cost parameters are set to zero because the total cost the broker is concerned about is not affected by these cost parameters, even if these are relevant to the overall supply chain modeling (e.g., a final assembler pays only purchasing costs for components and is not concerned about processing costs at the supply level). The initial state of the network determines whether some of the decision variables already do not have a fixed value. For instance, the location of several assembly plants is already fixed and cannot be changed. Similarly, long-term purchasing contracts with some suppliers can set definite limits on purchasing volume from these suppliers.

8.3.2. Modifications

The generic formulation obviously needs to be adjusted to include factors relevant to a particular decision-making problem. The literature analysis suggests that the most frequently considered factors are international factors, inventory, capacity treatment, transportation, and supply chain management policies. We discuss these below.

International Factors

Given that many supply chains involve partners from different countries, international factors need to be addressed in supply chain configuration. This problem is of particular importance for large multi-national companies manufacturing and selling their products world-wide. Mathematical programming models consider quantitative factors, while there are also numerous qualitative factors influencing international decision making.

Table 8.1 lists selected decision variables, parameters, and constraints used in some international supply chain configuration models. Goetschalckx et al. (2002) provide a summary table on works considering international factors. This summary indicates that taxes and duties are the most often considered international factors. In a similar work by Meixell and Gargeya (2005), the most frequently considered international factors besides tariffs and duties are currency exchange rates and corporate income taxes. However, many of the models surveyed use already fixed supply chain configuration. Kouvelis et al. (2004) presents an extensive sensitivity analysis of the impact of international factors on supply chain configuration.

Table 8.1 Selected International Factors Considered in Literature

Source	International factor
Arntzen et al. (1995)	Duty charge for shipping product on a link
	Tax on product at facility
	Duty drawback credit for a product imported into a nation-group from another nation-group and re-exported in the same condition/different condition
Bhutta et al.(2003)	Exchange rate
	Tariff rate for a product from a facility to market
Nagurney et al. (2005)	Exchange rate
Kouvelis et al. (2004)	Income tax rate
	Depreciation rate
	Discount rate of after-tax cash flows

Inventory

The literature survey of complexity of quantitative models in Chapter 3 identified seven papers considering multiple planning periods. Accounting for inventory-related issues is one of the main reasons behind considering multiple periods. Inventory holding costs per unit held are included in models by Viswanadham and Gaonkar (2003) and Bhutta et al. (2003). Viswanadham and Gaonkar (2003) also include ordering costs. Arntzen et al. (1995) and Dogan and Goetschalckx (1999) account for inventory costs associated with products held at supply chain units, as well as with products in transit between supply chain units. The former author also imposes a lower limit of quantity held in inventory.

Capacity Treatment

A majority of models have some sort of flow intensity and transformation capacity limits as a parameter. A parameter characterizing capacity consumption per unit processed or handled is also widely used (e.g., Pirkul and Jayaraman (1998) and Sabri and Beamon (2000)). Sabri and Beamon (2000) and Yan et al. (2003) use product specific capacity, while Pirkul and Jayaraman (1998) the flexible capacity. Bhutta et al. (2003) is one of the few papers using capacity as a decision variable. This paper allows either increasing or decreasing capacity at the facility.

Transportation

The most common way of representing transportation is considering just one mode and including variable costs per unit shipped between supply chain units. However, transportation-related issues generally are much more complex and several models attempt to account for this complexity. Non-linear dependence of transportation costs according to quantity shipped is modeled by Tsiakis et al. (2001). This dependence is represented by a piece-wise linear function. Transportation costs are not calculated for individual products but for families of similar products, thus reducing the model complexity. Syam (2002) and Viswanadham and Gaonkar (2003) include a fixed charge per unit using a particular link to transfer products between units. Arntzen et al. (1995), Dogan and Goetschalckx (1999), and Viswanadham and Gaonkar (2003) also include the transportation time parameter. Ross et al. (1998) has transportation as one of the key specific problems of supply chain configuration decision making and the model represents individual vehicles with their characteristics. Vidal and Goetschalckx (2001) split transportation costs between supplier and manufacturer to take advantage of lower taxes.

Capacity limits are also frequently used for links between units. Arntzen et al. (1995) and Syam (2002) represent transportation capacity by limiting the total weight of products shipped. The shipment weight-based representation of shipments costs and transportation capacity is often used in applied studies.

Detailed representation of transportation is a feature of many commercial supply chain network design models. These are based on detailed databases of distance and freight rates. These data as well as transportation cost structure and shipment planning are described by Bowersox et al. (2002).

Supply Chain Management Policies

Configuration decisions concerning use of particular supply chain facilities are often tightly interrelated with strategic-level decisions in relation to the particular managerial policies used. Two cases of representing management policies are distinguished:

- policies are represented structurally;
- policies are represented through values of parameters.

An example of structurally represented policies is a decision between using direct shipments and using a centralized warehouse. Evaluation of such alternatives effectively implies development of two separate models, which share common features. However, it is also possible to construct a single model with binary variables used for switching between different structures.

An example of policies represented through values of parameters is a decision between using Electronic Data Interchange (EDI) or the Internet as a communication mode among supply chain units. In this case, a binary variable can be used to represent the decision between policies, and values of parameters representing fixed costs for establishing links among units and variable costs for transferring products are specified for each of the two policies.

A combined example, where policies are represented both structurally and through values of parameters, is a decision variable between using flexible manufacturing facilities or specialized manufacturing facilities. Structurally different product-to-facility assignments are given as inputs (i.e., multiple flexibility scenarios are evaluated). At the same time, representing flexible manufacturing facilities influences the value of the fixed cost parameter.

The literature on including policy-related variables in the quantitative supply chain configuration models is scarce. Truong and Azadivar (2005) include a decision variable representing a choice between using push and pull manufacturing policies.

Analyzing many different policies might lead to explosive growth of the computational time needed to solve the model. Therefore, many policy related decisions are already made at earlier steps of the supply chain configuration.

8.3.3 Computational Issues

Model solving is an important part of supply chain configuration problem solving because the direct use of commercially available solvers might not be sufficient. Geoffrion and Powers (1995), in their discussion of developments in design of integrated production-distribution networks, indicate that corresponding large-scale models are difficult to solve in reasonable time because it is an NP-hard problem. Small to medium problems can be solved using standard software on personal computers (Kouvelis et al. 2004). However, that depends on the structure of a particular model and values of parameters. Specialized model-solving algorithms are generally required to solve large-scale problems.

There are two major approaches to elaboration of computationally efficient algorithms. These are based on Lagrangian relaxation and Bender's decomposition. A short overview of these methods is provided here. Readers are referred to Avriel and Golany (2001) for a detailed coverage of mathematical programming.

Lagrangian Relaxation

The Lagrangian relaxation schema assumes that problem solving is complicated by a few *difficult* constraints. It attempts to simplify the problem by dualizing the difficult constraints (i.e., the constraints are introduced into the objective function with a penalty function). As a result, a relaxed problem of the original problem is obtained. The relaxed problem is solved to obtain an upper bound (for maximization problems) of the original problem. Any feasible solution of the original problem provides a lower bound. Iterative heuristic algorithms are used in searching for the optimal solution of the original problem in this narrowed range. The upper and lower bounds are continuously updated. A good overview of the general theory on the Lagrangian relaxation is provided by Magee and Glover (1996).

Pirkul and Jayaraman (1998) successfully applied the Lagrangian relaxation problem for the supply chain configuration problem. Similar results have been obtained by Jang et al. (2002) and Amiri (2006). The supply chain configuration model by Pirkul and Jayaraman (1998) locates a specified number of manufacturing facilities and warehouses to minimize fixed and transformation costs subject to customer demand satisfaction and capacity constraints.

The mathematical representation of their model is as follows. Parameters of the model are:

C_{cjl} - the variable cost to distribute a unit of product *l* from warehouse *j* to customer zone *i*;

T_{jkl} - a unit cost to transport product *l* from plant *k* to warehouse *j*;

f_k and g_j - fixed cost to open and operate plant *k* and warehouse *j*, respectively;

a_{il} - demand for product l at customer zone i;
D_k - capacity of plant k;
W_j - throughput limit at warehouse l;
q_l - plant capacity consumption by product l;
s_l - is warehouse throughput capacity consumption by product l;
W and P – upper limit on the number of warehouses and plants that can be opened, respectively.

Variables X_{ijl} and Y_{jkl} denote the total number of units of product l distributed through warehouse j to customer zone i and the total number of units of product l shipped from plant k to warehouse j, respectively. P_k and Z_j are binary variables denoting whether plant k is open and whether warehouse j is open, respectively.

The objective function and constraints are given below.

$$\min Z = \sum_i \sum_j \sum_l C_{ijl} X_{ijl} + \sum_j \sum_k \sum_l T_{jkl} X_{jkl} + \sum_k f_k P_k + \sum_j g_j Z_j \quad (8.9)$$

subject to

$$\sum_j X_{ijl} = a_{il}, \forall i, l \quad (8.10)$$

$$\sum_i \sum_l s_l X_{ijl} \le Z_j W_j, \forall j \quad (8.11)$$

$$\sum_j Z_j \le W \quad (8.12)$$

$$\sum_i X_{ijl} \le \sum_k Y_{jkl}, \forall j, l \quad (8.13)$$

$$\sum_i \sum q_l Y_{jkl} \le D_k P_k, \forall k \quad (8.14)$$

$$\sum_k P_k \le P, \forall k \quad (8.15)$$

After relaxing constraints Eq. (8.10) and Eq. (8.13), the Lagrangian relaxation of the problem is

$$\min Z_{LR} = \sum_i \sum_j \sum_l C_{ijl} X_{ijl} + \sum_j \sum_k \sum_l T_{jkl} X_{jkl} + \sum_k f_k P_k + \sum_j g_j Z_j \tag{8.16}$$
$$+ \sum_i \sum_l \gamma_{il} \left(\sum_j X_{ijl} - a_{il} \right) + \sum_j \sum_l \beta_{jl} \left(\sum_i X_{ijl} - \sum_k Y_{jkl} \right)$$

where γ_{il} and β_{jl} are Lagrangian multipliers (dual prices). The relaxed problem is further decomposed into a subproblem representing manufacturing plants and a subproblem representing warehouses. An iterative model-solving procedure is used to solve the configuration problem. The Lagrangian subproblems are used to narrow the gap between lower and upper bounds until the difference is less than one percent or 500 iterations have been executed. Computational efficiency of the procedure has been tested for different numbers of products, potential plants and warehouses, and customer zones, as well as for different levels of capacity load. For instance, the problem-solving time for a problem with 100 customer zones, 20 warehouses, 10 plants and 3 products is about 60 seconds. The Lagrangian relaxation is also used as a part of the unified optimization methodology described by Shapiro (2000).

Bender's Decomposition

The main idea behind the Bender's decomposition approach is partitioning the original mixed-integer problem into its linear and integer parts (Salkin 1975). The steps of the problem-solving algorithm are as follows:

1. Fix values of integer variables and determine upper and lower bounds.
2. Solve a dual problem of the linear programming model obtained by fixing the integer variables and update the upper bound (for minimization problems).
3. Solve an integer problem obtained from the original problem by fixing the continuous part of the problem and update lower bound.
4. Iterate until the gap between the upper and lower bound is sufficiently small.
5. Upon convergence, compute optimal values of continuous decision variables.

At the first step, not only integer variables can be fixed but also any variables deemed as complicated. The Benders decomposition for solving supply chain configuration problems has been used by Geoffrion and Graves (1974), and Dogan and Goetschalckx (1999). In both cases, it has allowed solving large industrial-scale problems within a reasonable time.

The former authors additionally develop a specialized acceleration technique, which has been shown to decrease computational time substantially.

8.4. Other Mathematical Programming Models

Multi-objective, stochastic, and non-linear mathematical programming models are other models that find application in supply chain configuration.

8.4.1 Multi-Objective Programming Models

A multi-objective evaluation is needed to represent various aspects of supply chain performance and customers' requirements satisfaction, as well as to balance the performance of individual supply chain units. Two main technical approaches to representing multi-objective situations are: 1) assigning weights to each objective, characterizing relative importance; and 2) preemptive optimization starting with the most important objective. Choice of appropriate weights and prioritization of objectives relies on the decision maker's judgment and substantially affects modeling results.

Sabri and Beamon (2000) have developed one of the most elaborate multi-objective programming models. The supply chain configuration is established according to total cost and volume flexibility criteria (the customer service criterion is accounted for through operational level submodels). The objective function is expressed as

$$\begin{aligned} \min Z = & \sum_{rvj}\left(a_{rvj}+\lambda_{rv}\right)A_{rvj}+\sum_{j} f_{2j}q_{2j}+\sum_{ij}U_{2ij}X_{ij} \\ & +\sum_{k} f_{3k}q_{3k}+\sum_{ikm}U_{3ik}D_{im}y_{km} \\ & +\sum_{ijk} c_{ijk}C_{ijk}+\sum_{ikm} d_{ikm}D_{im}y_{km} \end{aligned} \quad . \tag{8.17}$$

The following notation is used in this model. Parameters a_{rvj} is unit transportation cost from vendor v to plant j for raw material r, λ_{rv} is unit cost of raw material r for vendor v, f_{2j} is fixed charges for plant j, U_{2ij} is unit production cost for product i at plant j, f_{3k} is fixed charges for distribution center (DC) k, U_{3ik} is unit cost of throughput (handling and inventory) for product i at DC k, D_{im} is average demand for product i at customer zone (CZ) m, c_{ijk} is unit transportation cost from plant j to DC k for product i, and d_{ikm} is unit transportation cost from DC k to CZ m for product i. Decision variables A_{rvj} is quantity of raw material *r* shipped from vendor *v* to plant *j*, q_{2j} is 1, if plant *j* is open and 0 otherwise, X_{ij} is quantity of product *i* produced at plant *j*, q_{3k} is 1, if DC *k* is open and 0 otherwise, y_{km} is 1, if DC *k* serves CZ m and 0 otherwise, C_{ijk} and y_{km} are 1, if DC *k* serves CZ *m* and 0 otherwise.

The objective function is minimized subject to

$$W = \left[\sum_j \left(q_{2j}\Phi_j - \sum_i \delta_{2ij} X_{ij} \right)\right] w_2 + \left[\sum_k \left(q_{3k}\beta_k - \sum_{im} \delta_{3ik} D_{im} y_{km} \right)\right] w_3 \quad (8.18)$$

$$W \geq \varepsilon \,, \quad (8.19)$$

where Φ_j is production capacity for each plant, δ_{2ij} is capacity consumption for product *i* at plant *j*, β_j is maximum throughput at DC *k*, δ_{3ik} is DC capacity consumption by product *i* and w_2, w_3 are weight factors for capacity utilization.

Z represents minimization of total costs defined as Eq. (8.17). Eq. (8.18) represents the second objective — volume flexibility. This objective is incorporated in the model by requiring its value to be larger that a certain threshold ε, which is set by the decision maker. The complete model description is given in the original paper (Sabri and Beamon 2000).

Li and O'Brien (1999) optimize supply chain configuration according to profit, lead-time performance, delivery promptness, and waste elimination criteria. The customer specifies requirements for each criterion and the importance of each criterion is assessed using weighting. The objective function for the whole supply chain measures how well the established supply chain structure satisfies these requirements.

Multi-objective optimization is often considered for the supplier selection problem. Weber et al. (2000) select suppliers according to purchasing cost, on-time deliveries, and materials quality criteria. Weights characterizing their relative importance are assigned to all criteria. Dependence of results upon chosen weight values is illustrated. Wang et al. (2004) use multi-objective optimization as a final stage of more complex supplier selection methodology. The final decision on supplier selection is obtained by using goal programming, where the first preemptive priority is maximization of the total value of purchasing (a composite measure of suppliers' characteristics) and the second priority is minimization of the total cost of purchasing.

Optimization according to multiple objectives can also be implemented using different multi-staged network design techniques, such as those presented by Talluri and Baker (2002). These techniques encompass preselection and selection steps in the supply chain configuration methodology.

8.4.2 Stochastic Programming Models

The models discussed above assume that all parameters are known with certainty, which is not the case in real-life situations. To obtain robust results, the impact of uncertainty needs to be assessed. Stochastic programming is one of the techniques allowing accounting for stochastic parameters.

Many of the stochastic programming models developed for supply chain configuration have demand as a stochastic parameter. Demand uncertainty usually is represented by multiple demand scenarios (Mirhassani et al. 2000; Tsiakis et al. 2001). In this case, a prototype objective function can be expressed as

$$Z = \max_{\mathbf{Q},\mathbf{Y}} E\left[F(\mathbf{c},\mathbf{D},\mathbf{Q},\mathbf{Y})\right] = \max_{\mathbf{Q},\mathbf{Y}} \sum_{s=1}^{S} F(\mathbf{c},\mathbf{D}_s,\mathbf{Q},\mathbf{Y}) , \tag{8.20}$$

where $\mathbf{c}$ represents all parameters of the supply chain configuration problem, $\mathbf{D}$ represents demand, $\mathbf{Q}$ represents continuous decision variables and $\mathbf{Y}$ represents binary decision variables (e.g., inclusion of units in the supply chain). F is an abstract function, E is the expected profit, and s=1,…,S are evaluated demand scenarios.

Other stochastic parameters can also be represented by evaluation of multiple scenarios (e.g., Gutierrez et al. 1996). The obvious limitation of this approach is a limited number of considered scenarios and there is little assurance that the coverage of uncertainty has been adequate.

Kim et al. (2002) develop a model for determining ordering quantities from suppliers for a fixed supply chain network subject to demand uncertainty. The demand uncertainty is represented using demand probability density function and an iterative model-solving procedure is developed without relying on using scenarios.

Santoso et al. (2005) develop a stochastic programming model for a typical supply chain configuration problem. The model minimizes total investment and operating costs by deciding which facilities to build and routing products from suppliers to customers. It allows for uncertainty in processing/transportation costs, demand, supplies, and capacities and for limited, but a very large number of scenarios representing uncertainty in demand, as well as in other parameters. The main constraints enforce capacity limits, flow conversion limits, and facility opening requirements (i.e., facility is operational only if open). The model is a two-stage stochastic program that minimizes the current investment cost and expected operational costs.

A specialized model-solving algorithm is developed. It uses an accelerated Benders decomposition to solve the facility opening problem and the sample average approximation scheme to solve the stochastic part of the model. The model is tested by its application in designing a supply chain in the packaging industry. The authors show that the developed model-solving algorithm allows solving large scale problems (13 products and 142 facilities) in less than two hours for one scenario and, more importantly, growth of computational time as the number of scenarios increases is slow. The stochastic approach to supply chain design allowed savings of up to 6 percent compared to the mean value problem solution for the considered supply chain design problem. The stochastic programming solution also exhibits substantially lower variability over testing scenarios, which is a desirable property during the results approbation phase of the supply chain configuration methodology.

8.4.3 Non-Linear Programming Models

Due to major computational difficulties, non-linear configuration models have not been frequently encountered in the supply chain configuration literature (see Wu and O'Grady (2004) for a brief discussion of non-linear programming models in supply chain configuration). The main non-linear factors relevant to supply chain configuration, such as inventory and transportation costs, are usually represented using piece-wise linear functions (e.g., Tsiakis et al. 2001).

Explicitly, non-linear constraints have been used in models solved using simulation-based optimization and other nonparametric optimization methods, which will be discussed in Chapter 10.

8.5 Sample Application

To illustrate application of the generic mixed-integer programming model presented in Section 8.3.1, a simple supply chain configuration problem is investigated. The objective of this illustrative problem is to minimize the total costs by choosing among four alternative locations of assembly plants and allocating steel purchases among five alternative suppliers. Other materials are sourced either locally or internationally from fixed locations. The supply chain delivers just a single product. The total demand is 20,000 units. All materials (i.e., steel, domestic supplies and international supplies) are delivered to the manufacturing facilities where assembly operations are performed. Initially, manufacturing was split into two tiers between preprocessing and assembly. However, a simple analysis showed that it is never beneficial to open manufacturing facilities at different locations. Therefore, both manufacturing tiers are merged for configuration problem-solving purposes.

The fixed cost for opening and operating assembly plants is the same for all alternative locations. The production cost is given in Table 8.2. The generic model formulation (Eqs. 8.1-8.8) is modified to include capacity restrictions for suppliers. These restrictions and the material cost are given in Table 8.3. Distribution costs present in the generic formulation are omitted because orders are place directly to the manufacturer. Configuration results are also substantially affected by transportation costs. The matrix of transportation costs for steel is given in Table 8.4.

Table 8.2 The Production Cost at Alternative Locations of the Assembly Plant

Assembly Plant Locations	Production Cost ($/unit)
Assembly location 1	1050
Assembly location 2	1150
Assembly location 3	1150
Assembly location 4	1250

Table 8.3 Characteristics of Alternative Suppliers

	Material Cost ($/unit*)	Capacity (units*)
Steel supplier 1	300	40000
Steel supplier 2	350	30000
Steel supplier 3	250	15000
Steel supplier 4	300	15000
Steel supplier 5	280	15000

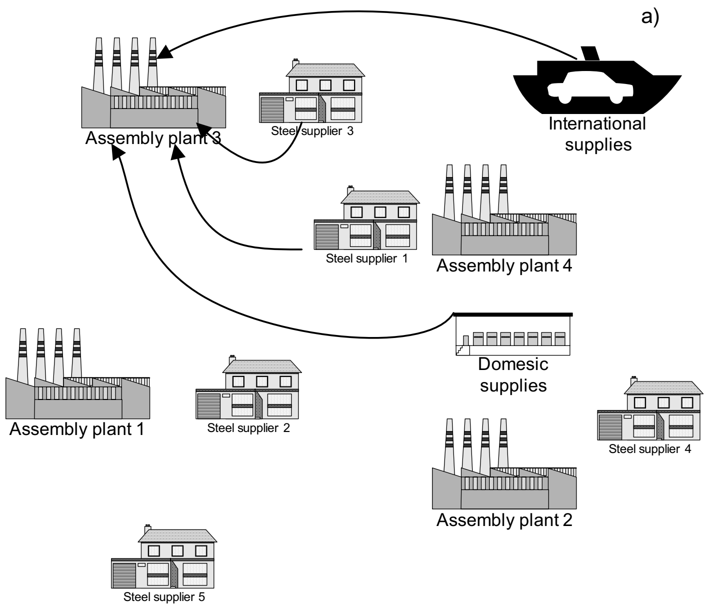
NOTE: * equivalent product unit

Table 8.4 The Matrix of Transportation Costs for Steel in $ per Equivalent Product Unit

	SS 1	SS 2	SS 3	SS 4	SS 5
Assembly plant location 1	127	28	165	165	141
Assembly plant location 2	142	181	226	57	316
Assembly plant location 3	142	181	57	226	316
Assembly plant location 4	42	141	89	89	311

NOTE: SS – steel supplier

Two optimization scenarios are compared. In the first scenario, the production cost at the third candidate assembly plant location, $\lambda_3 = 1150$. In the second scenario, the production cost is increased up to 1500. The configuration results obtained are shown in Fig. 8.1. The position of candidate and selected unit is shown to approximately indicate their geographical location. In the first case, the third alternative location for the assembly plant is selected, and two suppliers are allocated to supply the necessary quantity of steel. Notably, the location selected does not offer the lowest cost. The third supplier is selected because it provides the lowest purchasing cost and is located in close proximity. However, not all purchases are allocated to this supplier because of insufficient capacity. In the second case, the location offering the lowest production cost and its closest steel supplier are selected. The relative cost difference between two configurations is 1 percent.



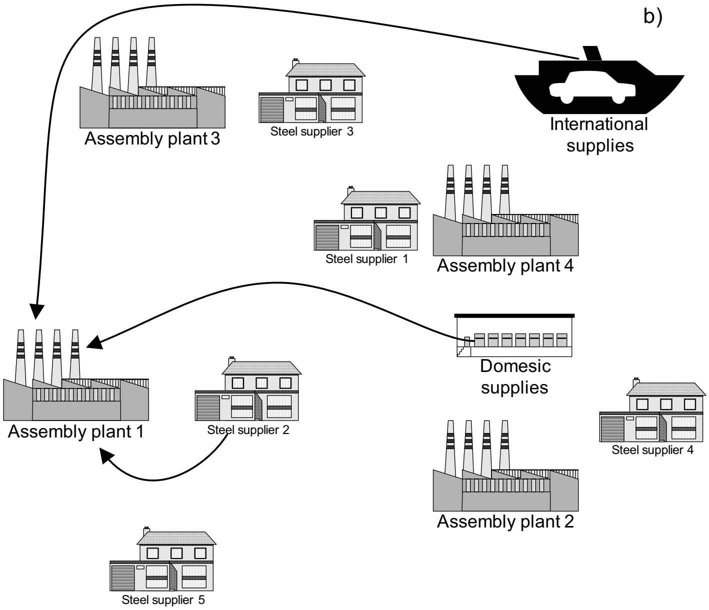


Fig. 8.1 Schematic representation of the supply chain-optimized supply chain configuration with arrows indicating links among units selected for inclusion in the supply chain, (a) $\lambda_3 = 1150$ and (b) $\lambda_3 = 1500$.

8.6 Model Integration

The supply chain configuration methodology emphasizes the integration of decision-making models with information models. Therefore, the supply chain configuration model's data model is used to develop the supply chain optimization model. Fig. 8.2 elaborates the transition from information modeling to quantitative modeling. This figure represents implementation of the optimization-related functionality of the integrated decision support system presented in Chapter 5. The commercially available LINGO (*www.lindo.com*) mathematical programming system is used in this case, although the approach is similar to several other mathematical programming languages. The figure shows only one-way interactions for simplicity. Obviously, modeling outcomes can be sent back to the supply chain management information system in a similar manner.

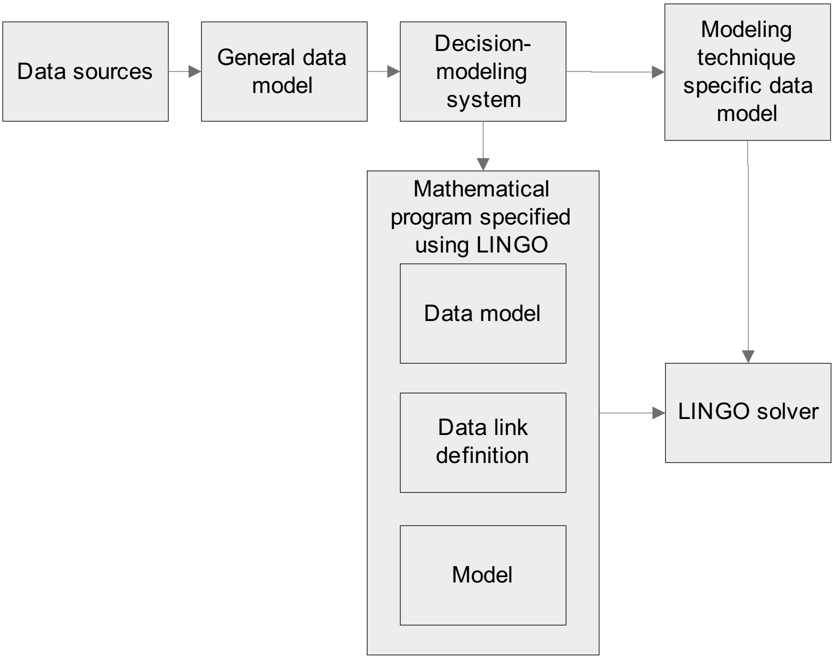


Fig. 8.2 Development of optimization models on the basis of information models.

The general data model discussed previously is developed using a general modeling method such as UML, while the mathematical model is implemented using a special-purpose modeling language, LINGO. The LINGO model includes data definitions in the form of data sets, data link definitions providing link to data sources, and a formalized representation of the mathematical program. Data definitions and data links are generated automatically using data provided in the general data model (Fig. 8.3). Transformations are informally listed as follows (numbers in the list correspond to the numbering of arrows in Fig. 8.3):

1. A data set declaration instruction is generated for each class in the diagram. All attributes except *dimension* are also included in the instruction line to declare parameters and variables of the mathematical programming model.
2. A variable declaration instruction is generated for the *dimension* attribute of each class (in the example, the variable is named *PD*). The generated instruction also defines data reading from the data source (using the @POINTER function of the special purpose programming language).
3. An instruction for reading values of the declared parameters is generated for each attribute of the *Parameter* type in the class diagram.

4. Attributes of type *DecisionVariable* are only included in the data set declaration instruction line (see Transformation 1 above) and this arrow only signifies the representation of decision variables.

The mathematical program is composed in a semiautomated manner by a decision maker who indicates which constraints to include from the decision-modeling knowledge base. The modeling technique specific data model contains actual data to be passed from the decision-modeling system to the LINGO solver during the problem-solving process. LINGO supports two main data transfer mechanisms:

- *Open Database Connectivity (ODBC) based data transfer*. In this case, the separate modeling technique specific data model is not necessary because LINGO can directly request data from database tables using the standard database access protocol.
- *Remote Procedure Call (RPC) based data transfer*. This mode is necessary if LINGO is part of a more complex decision-making system and is invoked programmatically. In this case, LINGO receives two specially structured data arrays from the decision-modeling system. The first array contains meta-data about data being transferred. The second array contains actual values. The decision-modeling system is responsible for merging data from the general data model into these two arrays.

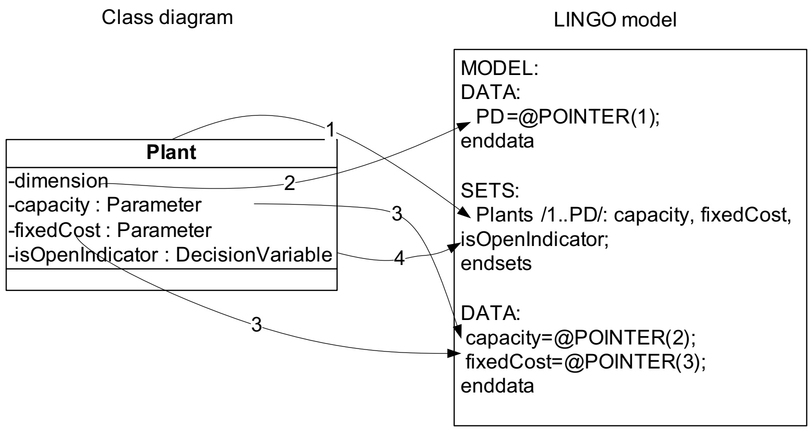


Fig. 8.3 Generation of the LINGO data definition from the general data model.

8.7 Summary

This chapter has described the generic supply chain configuration model, modifications of this model, and the integration of the mathematical programming model into the overall decision-modeling process.

Computational limitations still remain an important factor when considering practical application of mathematical programming for the supply chain configuration problem solving. Solving configuration models using computational approaches described in this chapter requires substantial expertise in mathematical programming, and algorithms are developed on a case-by-case basis. Therefore, commercial applications often rely on pure computational power or heuristic approaches. The former is not always sufficient for medium-size problems, while the latter cannot guarantee the quality of obtained solutions. Computational feasibility also restricts the development of non-linear mathematical programming models.

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9. Simulation Modeling Approaches

9.1 Introduction

Mathematical programming models were described in Chapter 8 as the primary type of models used in supply chain configuration. However, these models have several limitations. Therefore, the integrated supply chain reconfiguration framework and the supply chain configuration methodology consider simulation modeling as an approach to address decision-making issues not covered by mathematical programming models. It is widely recognized that simulation can describe complex systems in a highly realistic manner and is used to explore the properties of such systems.

Simulation is perceived as an essential part of the supply chain configuration process. It complements findings made using mathematical programming and other modeling approaches. In view of the high costs associated with the implementation of configuration decisions, simulation provides a means for detailed evaluation of these decisions before their physical implementation.

A majority of simulation models available in the literature are not aimed at solving the supply chain configuration problem explicitly. These models are developed as a general descriptive representation of the supply chain, or for purposes of more detailed supply chain design activities, for example, scheduling and layout planning. The overview of available simulation models includes those simulation models that consider several supply chain tiers and attempt to mimic the network structure. However, efficient application of simulation for supply chain configuration problem calls for providing some specialized solutions. This chapter aims to provide some guidelines for simulation model building in the context of supply chain configuration.

The rest of the chapter is organized as follows. Section 9.2 discusses the general aspects of simulation modeling and its application in supply chain modeling. An overview of selected existing works on supply chain simulation is given in Section 9.3, which also summarizes the main characteristics of supply chain simulation models. Section 9.4 describes the development of supply chain simulation models as a part of the supply chain configuration methodology. Section 9.5 provides summary of discussion on the efficacy of the proposed simulation modeling approach for supply chain configuration.

9.2 Background

Simulation is used along with mathematical programming in the selection step of the supply chain configuration methodology. Generally, it is assumed that mathematical programming is used to establish supply chain configuration while simulation is used to evaluate this configuration. The main reason why simulation is used to evaluate decisions made by mathematical programming models is its ability to represent supply chain in a more realistic manner. Simulation can be perceived as a test-bed for implementing configuration decisions. It enables supply chain evaluation with respect to various factors; particularly those representing supply chain dynamic, stochastic factors and interactions among supply chain units. Simulation also allows obtaining multiple performance measures characterizing both cost and time related characteristics of the supply chain.

Referring back to the definition of the supply chain configuration scope (Chapter 2), simulation is particularly well suited to address managerial concerns, such as:

- customer service and delivery reliability
- quantification of risk factors
- what-if analysis

Some important performance measures provided by simulation are:

- product cycle time
- customer service level
- probability distributions of cost and time estimates
- supply chain robustness

The last measure is of particular importance in the case of reconfigurable supply chains because it also characterizes processes during transition from one supply chain configuration to another.

Despite the powerful capabilities provided by simulation it is rarely used as a standalone tool for solving configuration problems. This is due to the several shortcomings of simulation modeling. The main limitation in the supply chain configuration context is that simulation is primarily a descriptive tool, which requires a human decision maker to identify alternative configurations that he or she wishes to explore. While it is possible to identify such alternatives in some situations, that is not possible in the general case because the number of alternatives is large. Some other disadvantages of simulation modeling are expensive model development and usage, and interpretation of stochastic modeling results.

Simulation modeling can be performed at various levels of abstraction, which is one of the main options to balance model development cost and usability against model validity. Supply chain configuration is a strategic decision-making problem. Therefore, the level of abstraction generally could be kept quite high. Multiple supply chain simulation approaches discussed later in this chapter attempt to generalize supply chain units representing them as abstract nodes in the simulation model. The level of abstraction is likely to vary according to the broker's perspective because sufficient information is likely to be available only about an organization represented by the broker. In the context of the integrated supply chain configuration framework (see Chapter 4), each potential supply chain partner could maintain its simulation model, which can be linked together, if necessary. However, current experiences in executing such inter-enterprise simulation models are limited. Hibino et al. (2002) and Mertins et al. (2005) describe High Level Architecture (AHL) based approaches to inter-enterprise simulations. However, the computational time needed to execute such simulations, general feasibility, and organizational issues remain the limiting factors.

Simulation model development and execution forms a subprocess in the selection step of the supply chain configuration methodology. This subprocess begins with problem formulation, data collection, and definition of a conceptual simulation model. That is accomplished by using data provided by the supply chain configuration information models. The subprocess proceeds with the development of an executable simulation model. The executable model is mainly constructed using either general purpose programming languages or specific simulation modeling languages and software packages. The developed model is validated. Upon successful validation, experimental design is constructed and simulation modeling is performed according to this experimental design.

The validation of simulation models is an important, although difficult, step of the simulation modeling process. In the case of supply chain configuration, it is complicated by lack of historical records and a long feedback loop between implementation and observation of results, which are often obscured by other supply chain management decisions. Law and Kelton (2000) list the following approaches to validation of simulation models:

- structured walkthrough
- expert evaluation
- comparison against performance of the existing system

- comparison against the existing theory
- sensitivity analysis

Comparison with results obtained using other supply chain configuration models is an additional validation technique. Expert evaluation, comparison with manual computations, comparison of simulation with real-life situation, and pilot implementation of simulation results are named as validation methods used by Van der Vorst et al. (2000) in their supply chain redesign model. However, the pilot implementation was possible only for operational level decisions. Bowersox (1972) uses the stability of output data, sensitivity analysis, and comparison of simulated output to historical data as his model validation methods.

9.3. Overview of Existing Simulation Models

Existing simulation models representing configuration, related issues are grouped according to the simulation-modeling approach used — namely, process-oriented simulation, object-oriented simulation, and agent-oriented simulation. We discuss these below.

Process-Oriented Models

A simulation model is described by a sequence of processes initiated by events occurring in the system. This approach is attractive from the model-integration point of view. Supply chain process models can be transformed into simulation models.

Bowersox (1972) presents an early study on application of simulation for long-term distribution planning. The model consists of standardized nodes representing manufacturing plants with adjacent warehouses, distribution centers, consolidated shipping points, and demand units. In the case studies reported, simulation is used to evaluate several preconfigured supply chain design alternatives. Decisions to be made include capacity expansion and location of new facilities. The author indicates that data availability and complex model building are major obstacles for widespread use of simulation in supply chain management.

The business process orientation is adopted by Van der Vorst et al. (2000). The supply chain is defined as consisting of multiple business processes governed by design variables, defined as configuration level and operational level. Thus, a simulation model is used for decision-making in both strategic and operational decisions. The business process modeling formalism used is Petri-nets, which are often considered over other process and network modeling methods because they are based on sound theoretical principles and enable some analytical evaluation. Strategic and operational supply chain design decisions to be made are identified following the principle that supply chain performance can be improved by reducing the impact of various sources of uncertainty. Configuration-related decisions are implementation of real-time inventory management information systems and reallocation of some of the supply chain management functions. The supply chain performance is evaluated for numerous scenarios, where each scenario is characterized by a set of design variables with specified values. It is reported that the adoption of decisions made on the basis of simulation modeling has resulted in major performance improvements. Petri-nets also have been used for simulation of the manufacturing supply chain by Dong and Chen (2001).

Ganeshan et al. (2001) simulate the performance of a retailing supply chain. The simulation model takes the supply chain network structure as an input parameter. Inventory cycle time, return-on-investment (ROI), and service levels are measured for several scenarios characterized by forecasting accuracy, information exchange mechanism used, and planning cycle length. Simulation results show that all three factors have significant impact on supply chain performance.

Process-oriented simulation of existing systems and envisioned systems for a logistics services provider is explored by Jain et al. (2001). The modeling objective is to evaluate the possible benefits of replacing legacy IT systems and business processes. Performance measures are service level, inventory turns, and order-to-delivery lead time. Processes represented in the model are order fulfillment, procurement, and demand-and-supply planning. The authors emphasize the importance of providing an adequate level of abstraction, which should correspond to modeling objectives. Bagchi et al. (1998) describe a supply chain simulator developed at IBM. This simulator defines seven typical supply chain processes available for model composition: customer, manufacturing, distribution, transportation, inventory planning, forecasting, and supply planning processes. Performance measures characterizing customer service, inventory, resources, and returns are collected during simulation. Similarly, Ingalls and Kasales (1999) present a simulation model used for supply chain analysis at Compaq. The model is used to answer managerial questions concerning customer service and profitability of the entire supply chain, as well as that of individual units. It includes eight standardized structures, such as customer, company, inventory site, manufacturing site, geo (i.e., sales component where revenue and costs are accounted for), and country. Thus, the model emphasizes global aspects of the supply chain. The model uses 59 input data tables and provides 112 output data tables. Schunk and Plott (2000) describe a tool, Supply Solver, which incorporates various specific features for specifying supply chains. For instance, an interface for inputting distances between supply chain units is provided.

Persson and Hager (2002) apply simulation to select among three alternative configurations of a manufacturing supply chain. Simulation can be perceived similar to the scenario-based approach, where a scenario is defined by a particular supply chain configuration under evaluation.

Object-Oriented Models

As discussed in Chapter 7, object orientation has found many applications in describing complex systems because of its ability to decompose a problem. The object-oriented approach allows the designing of modular simulation models. In the case of supply chain configuration, that implies compilation of the supply chain network from a set of standardized objects. The object-oriented approach also makes easier the transition between model development and executable software.

Several existing works on object-oriented supply chain simulation attempt to identify main classes characterizing supply chains in general. Alfieri and Brandimarte (1997) define key classes for representing demand points, factories, stocking points, and routing. The authors show the use of generalization and inheritance to describe specific management policies. For instance, the general stock point class has two child classes representing (R, Q) and (s, S) inventory management policies, respectively. A simulation workbench for analyzing information-sharing policies at the operational level is developed by Ng et al. (2002). It contains several classes used to represent a supply chain that include decision-making classes for forecasting and inventory planning, and classes for structural supply chain elements.

Van der Zee and van der Vorst (2005) use object-oriented simulation model development to improve separation of concerns with particular emphasis on better representation of control elements, which tend to be dispersed anywhere in the simulation model.

An object-oriented supply chain simulation system named SISCO has been developed by Chatfield et al. (2006). The system allows users to specify supply chain structure and management policies using a user friendly graphical interface. Users' inputs are saved in an XML-based Supply Chain Modeling Language (SCML) format. The XML document obtained is used to generate an executable supply chain simulation model by mapping its elements to specific classes in the supply chain simulation library. The library contains the implementation of classes representing order, supply chain arcs, and nodes, and several manager and actor classes, which are implemented using a general purpose programming language called Java.

Hung et al. (2006) develop a supply chain simulation model for production scheduling purposes. The supply chain network is composed of generic nodes. Each node has three components: 1) inbound material management, 2) material conversion, and 3) outbound material management. The class diagram is used to design the model structure of each node. It describes various mechanisms available for material handling and processing.

Agent-Based Models

Agent-based approaches attempt to capture collaborative and implicit aspects of supply chain behavior. Swaminathan et al. (1998) propose an agent-based architecture for building and executing networked supply chain models. Developed models allow describing issues related to network structure evaluation according to lead time, transportation cost, currency fluctuations, inventory control, information exchange, supplier reliability, flexibility, and others. The architecture is based on employing a generic agent, which can be specialized to perform various supply chain activities. Agents communicate with each other by sending messages. The processing of each message is governed by a set of rules (for example, rules defining an inventory replenishment policy). Types of agents and available control polices are structured into the supply chain library. Reduction of model development workload is identified as the key advantage of this architecture, which is achieved by supporting modular model structure and the reuse of existing components (agents and control policies).

A supply chain simulation framework proposed by Van der Zee and Van der Vorst (2005) also advocates use of the agent-based approach. Agents are used to represent infrastructural elements of the supply chain as well as managers of these elements. External agents represent suppliers and customers. Internal agents operate according to allocated jobs and their local intelligence. They transform available flow items (i.e., products, information). The agent-based approach is implemented using ARENA. The authors also list several key requirements for an efficient supply chain simulation modeling tool. These include an appropriate user interface, which facilitates trust building in collaborative decision making, and ease of handling modeling scenarios.

Efficiency of agent-based modeling largely depends upon developed agent capabilities, which are often limited to most basic behavior.

Observations

The above overview of selected works on supply chain management allows us to draw the following conclusions about the common characteristics of supply chain simulation:

- The level of abstraction used varies substantially, although it is agreed that a relatively high level of abstraction is sufficient for strategic decision-making purposes. The level of abstraction should be decreased if the operational level problems need to be evaluated
- Model development complexity is a major issue in supply chain simulation
- In response to the previous point, there are attempts to define generic supply chain units and the typical elements to be used in a simulation model
- Supply chain configuration is considered as a fixed input parameter. Configurations are evaluated under numerous scenarios describing supply chain external and internal characteristics
- A large number of performance measures are used to evaluate supply chain performance. These include those characterizing customer service, inventory management, and other dynamic aspects. Variability of obtained results is assessed
- Model development is highly case specific, and few attempts exist to build upon methodologies reported in the literature

9.4 Development of Supply Chain Configuration Simulation Models

Development of simulation models is a complex process. General simulation modeling methodologies have been developed (see Law and Kelton (2000)). However, simulation models tend to be rather case specific, thus requiring a major development effort. Therefore, specific modeling templates, methods, and tools for a particular problem domain are useful. In the case of supply chain configuration, development of simulation models can be facilitated by exploring several specific characteristics including 1) a high level of abstraction, 2) representing two main elements, namely, supply chain nodes and arcs connecting nodes, and 3) interactions with other supply chain configuration models.

Commercially available simulation packages have attained a high level of maturity. Therefore, using these packages for development of supply chain configuration models and specific utilities facilitating the development process is advisable, instead of relying on custom tools. The benefits of using Commercial-Of-The-Shelf (COTS) software in the framework of optimization and simulation are also identified by Vamanan et al. (2004).

9.4.1 Approach

The proposed simulation model building approach utilizes two main concepts: 1) separation between data and the model; and 2) a generic representation of supply chain units. The main stages of the model building approach are shown in Fig. 9.1.

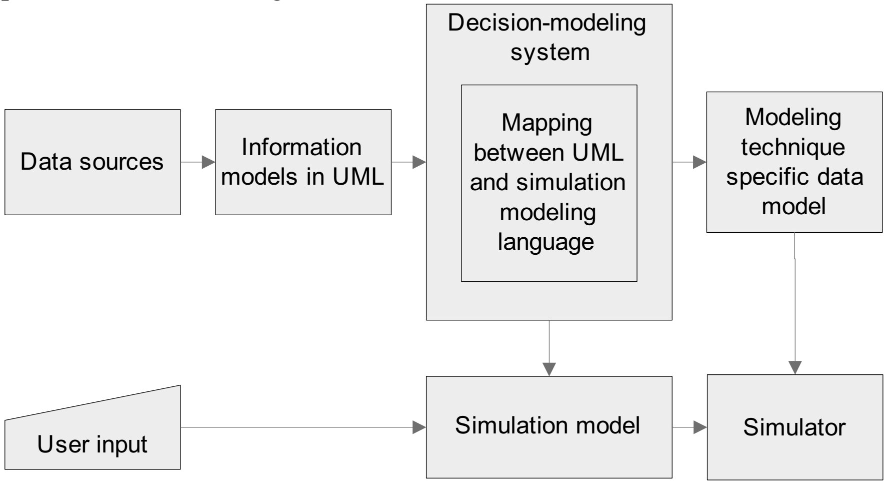

Fig. 9.1 Integrated simulation model building.

A supply chain simulation model is developed using data from the supply chain management information system, and is initially specified using UML. If simulation is used to evaluate supply chain configuration optimization results, then optimization results are an important data source. The decision-modeling system generates the simulation model by transforming information models into a specific simulation modeling language, which is generated on the basis of a predefined template. The template does not contain any simulation objects. It only contains procedures for executing control of the generic functions and data declarations. The procedures have a uniform design. Different procedures can be developed to perform the same activity. Thus, different management policies can be analyzed. The generated simulation model can also be manually edited by a user to incorporate features not represented in the information models or not supported by the model generation mechanism.

The decision-modeling system also transforms input data in a format suitable for efficient execution of the simulation model. This format is referred to as the modeling techniques' specific data model.

The generated simulation model is executed by a commercially available simulator.

9.4.2 Representation of Supply Chain Entities

The main task is to transform information models into an executable simulation model. To achieve this, the main entities of the supply chain configuration simulation model are defined. There are three main types of supply chain entities in the proposed supply chain simulation model — supply chain units, customers, and products. Links among supply chain units are represented by transportation functions of supply chain units. Several authors have indicated that a supply chain units or a node in the supply chain can be represented in a generic form (Chandra et al. 2000; Pontrandolfo and Okogbaa 1999; Hung et al. 2006). Fig. 9.2 shows one representation of the generic supply chain unit. The concept of the generic unit essentially corresponds to supply chain representation in the Supply Chain Operations Reference (SCOR) model. The important aspect of the SCOR model is the presence of both global and local control (i.e., planning processes).

The data model described in Chapter 7 is expanded to include information necessary for describing generic units and supply chain simulation. Therefore, the *SupplyChainUnit* class is shown to be an aggregation of *IncomingFlows, FlowTransformation,* and *OutgoingFlows* classes, which represent generic functionality of supply chain units (Fig. 9.3). The generic functionality is specified by using classes representing particular activities. For instance, products received at a supply chain unit are stored in inventory, described by the *Inventory* class. Classes representing supply chain unit level and supply chain wide control mechanisms are also included. The *Inventory* class describes inventory handling at a particular supply chain unit, while the control classes provide communications among supply chain units and coordinate activities with the unit.

Given that the simulation model is generally used to evaluate fixed supply chain configuration, it is developed on the basis of the object model containing objects, which are instances of classes defined in the class diagram of the generic supply chain unit.

Fig. 9.3 also shows classes for representing products and customers. Classes representing global and local control mechanisms are abstract classes and their elaboration is case specific.

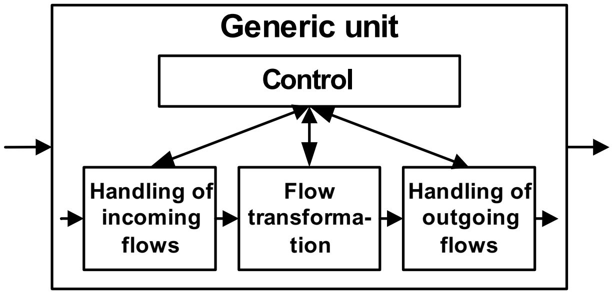

Fig. 9.2 A generic representation of supply chain unit.

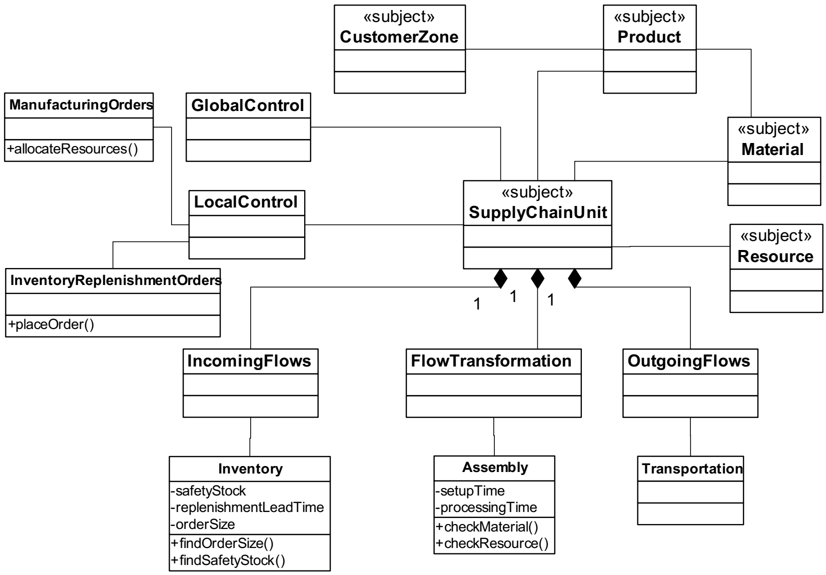

Fig. 9.3 A class diagram of the generic supply chain unit.

9.4.3 Model Generation

The simulation model is generated on the basis of the object diagram. The object diagram contains realizations of classes shown in Fig. 9.3. Realizations are created according to optimization outcomes (for instance, optimization yields that three out of five manufacturing units are to be opened at selected locations; objects representing these three manufacturing units are created) or for a given fixed supply chain configuration to be evaluated.

Different mechanisms are used to represent various entities from the supply chain object model. In the case of using ARENA (Rockwell, 2001) as a simulation modeling tool, a supply chain unit object is represented as a standardized sequence of simulation modeling blocks, customer zones are represented using a differently structured sequence of simulation modeling blocks, products and materials are represented using simulation modeling entities, and resources are represented using the resource module.

An ARENA submodel is generated for every supply chain unit included in the configuration (i.e., for every *SupplyChainUnit* object). Such a submodel for one of the supply chains units is shown in Fig. 9.4. The *FlowTransformation* object is transformed into a sequence of processes realizing manufacturing order for processing, setting up resources, requesting materials from the stock, and finally assembling the product. The object diagram prescribes that flow transformation is needed and allows the setting of variables in the ARENA model (for instance, the *setupTime* attribute is used to generate a corresponding variable in the ARENA simulation model). At the same time, the object diagram does not specify the flow transformation process. That is perceived as model method and modeling tool specific data, which determine transformation of the object in ARENA blocks. Products and materials are represented by ARENA entities. Arrays are used to deal with multiple products and resources. The model generator in the decision support system is implemented using Visual Basic (VB). It creates ARENA objects using the ActiveX technology (actually, the same data model can be used to create a simulation model in other simulation modeling environments supporting the ActiveX technology).

A separate submodel is used to represent *CustomerZone* objects. This sub-model is used to generate customer demand and to serve as a final destination for finished products.

The main model generation transformations are summarized as follows:

1. A sequence of simulation modeling blocks is generated for each object of the *CustomerZone* type. This sequence represents generation and queuing of demand orders and receiving.
2. The ARENA resource table is populated by generating an entry for each object of the *Resource* type.

3. An ARENA entity is generated for each object of the *Product* type.
4. An ARENA submodel is generated for each *SupplyChainUnit* object. It consists of four sets of simulation modeling blocks corresponding to objects that compose the *SupplyChainUnit* object. The local control set is generated from the appropriate object of the *LocalControl* type (the object is named *lc_Unit1* in Fig. 9.4). Other sets of blocks are generated in a similar manner.

Global control, and some other local control mechanisms not shown in Fig. 9.4, are included in the supply chain modeling template or manually developed. They are implemented using VB code.

The modeling method specific data model is also generated and populated during the model generation process. The data model organizes data in a manner suitable for execution of the simulation model. This ensures quick access of necessary data items. The data model consists of multiple spreadsheets containing information about structure and operational characteristics of the system. At the beginning of simulation, modeling data from the data model are loaded in the simulation model. Before loading, intermediate data have been created by converting the data model tables from the Excel format into the text format because ARENA reads text files much faster than Microsoft Excel files. Some of the data tables are loaded into ARENA arrays for access by ARENA objects, while some others are loaded in VB arrays for access by control functions.

A more detailed description of functions performed by individual blocks of the simulation model, and structuring of the modeling technique specific data model for a specific industrial case study, can be found in Chandra and Grabis (2003) and in Chapter 13 of this book.

The generated simulation model is subsequently used to evaluate the given supply chain configuration. The automated generation enables rapid development of simulation models representing various alternative supply chain configurations.

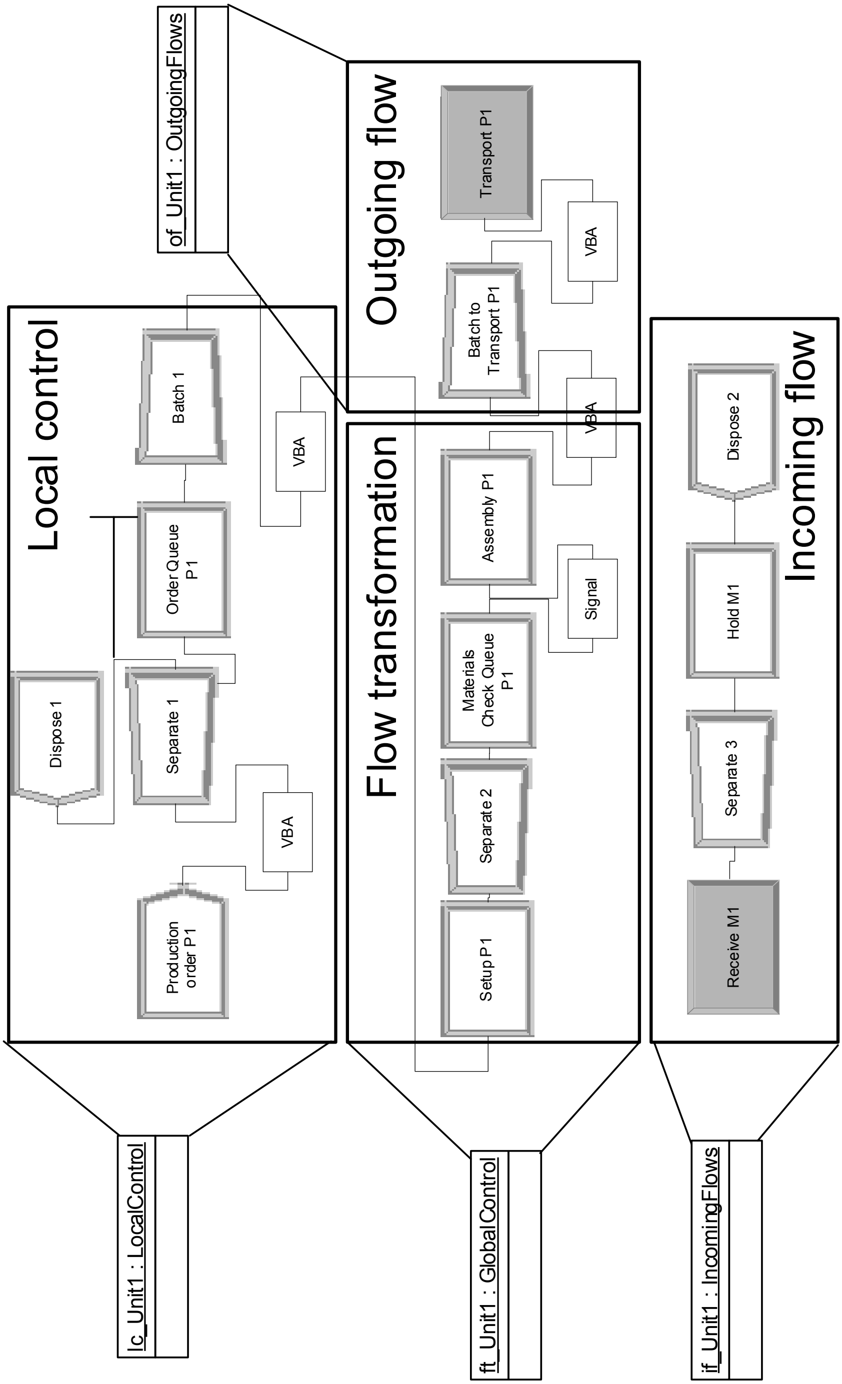

Fig. 9.4 Generation of the ARENA model from the object diagram.

9.4.4 Sample Simulation Results

As indicated earlier in the chapter, simulation modeling is used to evaluate temporal aspects of supply chain configuration. Sample simulation results illustrate evaluation of the robustness of supply chain configuration in the case of disruptive events (the sample is adopted from the case study of establishing an automotive supply chain in emerging markets (Chandra and Grabis (2002)).

Simulation is used to compare two alternative supply chain configurations differing by the number of suppliers. The first configuration (D1) uses MS1 as a single steel supplier while the second configuration (D2) uses MS3 and MS5. Among other performance measures, the configurations are compared according to the ability to maintain high delivery time reliability in the case of disruptive events. Fig. 9.5 shows delivery time changes in the case of a large-scale distortion, which causes a loss of supplies from some of the second tier suppliers for several periods.

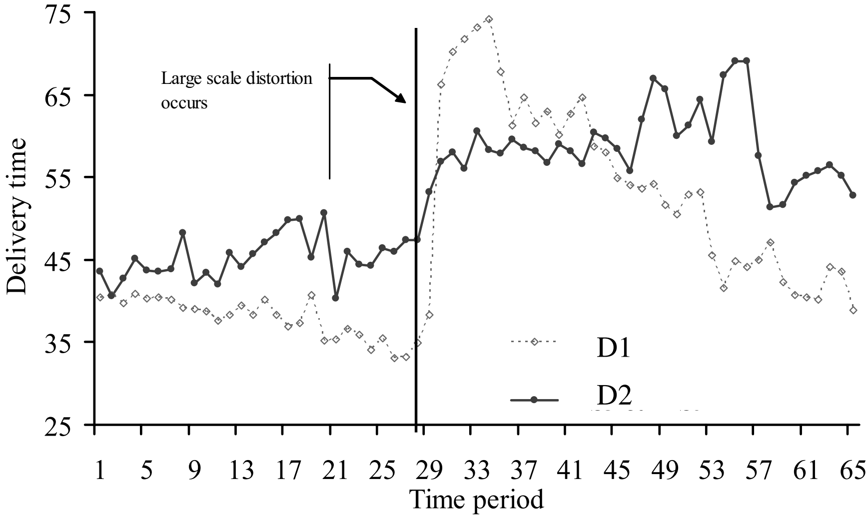

Fig. 9.5 Average delivery time for alternative designs D1 and D2.

During that time, lost suppliers are replaced by new suppliers. Reported results are obtained over 20 replications, and each replication is 75 periods long. The configuration including only MS1 suffers more intense immediate effect, but further on, it is capable of recovering. The configuration including MS3 and MS5 has difficulties reestablishing previous delivery promptness mainly due to high capacity utilization, which prevents quick replenishing of lost deliveries. Other performance measures, such as inventory costs and total costs, do not change significantly in both cases.

9.5 Summary

Simulation modeling is a well-established tool for evaluation of fixed supply chain configurations. This chapter has focused on making simulation an integral part of the supply chain configuration methodology. This is achieved by proposing the automated model development approach, which advocates generation of simulation models on the basis of information models and optimization outcomes. Automated model development is beneficial because the simulation model does not need to be manually redeveloped for every new configuration.

There are several limitations that need to be addressed. The proposed approach allows for automated development of structure of simulation models while information models driven development of control mechanisms is supported to a limited extent. Improving implementation of control mechanisms is a direction of further research. The approach can only be efficient if high reusability is achieved. Therefore, a precise specification of model transformation and generation mechanisms is required.

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10. Hybrid Approaches

10.1 Introduction

Mathematical programming and simulation are the main modeling approaches used for supply chain configuration. Previous chapters dedicated to discussing these approaches have identified both their strengths and weaknesses. Obviously, a modeling approach capitalizing on the strengths while avoiding the weaknesses is desirable for a comprehensive evaluation of supply chain configuration. Hybrid models combining optimization and simulation models have long been identified as an opportunity to exploit the benefits of different modeling techniques. This approach has been strengthened by the increasing computational power available to decision-makers.

In this chapter, the discussion on hybrid modeling is not limited to combining only optimization and simulation models, which remain a cornerstone of hybrid modeling for supply chain configuration, but also includes other models such as analytical hierarchical process and statistical models.

Section 10.2 discusses the motivation behind using hybrid modeling. Section 10.3 describes the general aspects of using hybrid models for supply chain configuration, such as flow of the hybrid modeling process and types of hybrid models. Given that a large variety of hybrid models can be constructed, Section 10.4 discusses some particular hybrid models.

10.2 Background

A comprehensive evaluation of supply chain configuration decisions requires utilization of multiple models as described in previous chapters. There are two alternatives in employing these models: 1) independent models exchanging input-output data, and 2) fully integrated models where selected functions of one model are implemented by another. Application of independent models and interpretation of their often seemingly contradicting results cause difficulties for decision modelers. Therefore, the area of hybrid modeling that can be perceived as the development of a model consisting of two or more highly integrated models is appealing. Such hybrid models exploit the strengths of multiple models to provide a single answer to decision modelers.

Hybrid modeling usually considers a combination of analytical and simulation models. In the case of supply chain configuration, analytical modeling is typically implemented using mathematical programming optimization models. However, in general, hybrid modeling is not limited to combining just two models or combining just mathematical programming and simulation models.

Hybrid mathematical programming simulation models are aimed at combining the strengths of mathematical programming and simulation models and reducing the impact of limitations characteristic of these models. Strengths and limitations of such models are summarized in Table 10.1. Mathematical programming models are generally well suited to dealing with spatial issues, while simulation models are more appropriate for dealing with temporal issues. Although the cost of model development and usage can be substantial for mathematical programming models, it is generally lower than for similar simulation models.

Table 10.1 Summary of Strengths and Limitations of Mathematical Programming and Simulation Models

	Mathematical Programming	Simulation
Strengths	Evaluation of large number of alternative configurations Exact results Capabilities for efficient analysis	Realistic representation of the problem Accounting for dynamic and stochastic factors Availability of different performance measures
Limitations	Quickly increasing model complexity if dynamic, stochastic and nonlinear factors are added	Expensive development and usage Interpretation of results

Similar discussion on differences between mathematical models and simulation models can be found in Nolan and Sovereign (1972) and Shanthikumar and Sargent (1983). Ingalls (1998) points out that there are not only technical differences between these two types of models, but the choice between them has major implications from a managerial perspective. Managers are often concerned with finding good workable solutions rather than pursuing more elusive optimal solutions.

If viewed from the supply chain configuration perspective, differences between mathematical programming and simulation are particularly noticeable. Mathematical programming models can be perceived as providing the base decision-making functionality. Their main advantage is an ability to quickly evaluate a large number of alternative configurations. Simulation models, on the other hand, provide the functionality needed to cover the entire scope of the supply chain configuration, especially dynamic and stochastic factors. Given that these factors are very important for reconfigurable supply chains, hybrid models are particularly appropriate for decision making in this case. Simulation alone can be rarely applied for establishing supply chain configuration because evaluation of a large number of alternative configurations is not computationally feasible.

The application of combined mathematical programming and simulation models has become relatively widespread. Simchi-Levi et al. (2003) describe using an optimization model to establish supply chain configuration and subsequent utilization of simulation to evaluate the established configuration. The procedure is executed in an iterative manner until a sufficiently robust supply chain configuration is found. However, developing a feedback mechanism between optimization and simulation is a challenging theoretical and practical issue, which has limited exposure in the supply chain configuration context. Such feedback mechanisms have been more successfully developed for some other related supply chain management problems. For instance, a production planning hybrid model (Byrne and Bakir 1999) uses a capacity adjustment coefficient to incorporate simulation results in subsequent optimization runs. A formalized feedback mechanism is essential for the success of hybrid modeling, otherwise it downgrades to model combination.

Obviously, fully integrated models also have their own shortcomings, the most significant of which is more complex model development and lower flexibility in model modification and application.

10.3 Hybrid Modeling For Supply Chain Configuration

Hybrid modeling for supply chain configuration is primarily used for establishing supply chain configuration. Additionally, it can be used in the preselection and results analysis phases of the supply chain configuration methodology. Mathematical programming simulation hybrid models are generally used for the selection phase, while statistical models can be brought into the preselection and evaluation phases. Thus, a single hybrid model can potentially cover multiple configuration phases.

A large number of different hybrid models can be designed. The following subsections describe common principles used in the development of hybrid models and introduce main classes of hybrid models.

10.3.1 General Approach

A hybrid model is part of the integrated supply chain decision-modeling framework. It represents a tightly coupled subset of decision-making models. Hybrid modeling starts with semiautomated generation of appropriate optimization and simulation models (Fig. 10.1). These models are generated on the basis of information models, which also provide a means for information exchange between the hybrid model and information sources. The optimization model is used to obtain a tentative supply chain configuration. The simulation model is modified according to the obtained optimization results. Modifications may range from simple updating of parameters to modification of the supply chain network structure in the simulation model. For instance, if the optimization model suggests opening new warehouses, these should be included in the simulation model. To make such modifications, the automated simulation model development capabilities described in Chapter 9 are essential, otherwise model development and usage becomes too expensive. After simulation modeling is performed, selected criteria are tested for convergence. If convergence has not been achieved, feedback from simulation to optimization is provided and the next optimization iteration is started after feedback information is incorporated into the optimization model. Feedback mechanisms are discussed later in this chapter.

10.3.2 Types of Hybrid Models

Shanthikumar and Sargent (1983) classify hybrid models by identifying the model that is most important in a pair of simulation and optimization models. There are four classes of hybrid models:

1. Hybrid models whose behavior over time is obtained by alternating between using independent simulation and analytic models.
2. Hybrid models in which a simulation model and an analytical model operate in parallel over time, with interactions through their solution procedure.
3. Hybrid models in which a simulation model is used in a subordinate way for an analytic model of the total system.
4. Hybrid models in which a simulation model is used as an overall model of the total system and requires values from the solution procedure of an analytical model representing a proportion of the system for some or all of its input parameters.

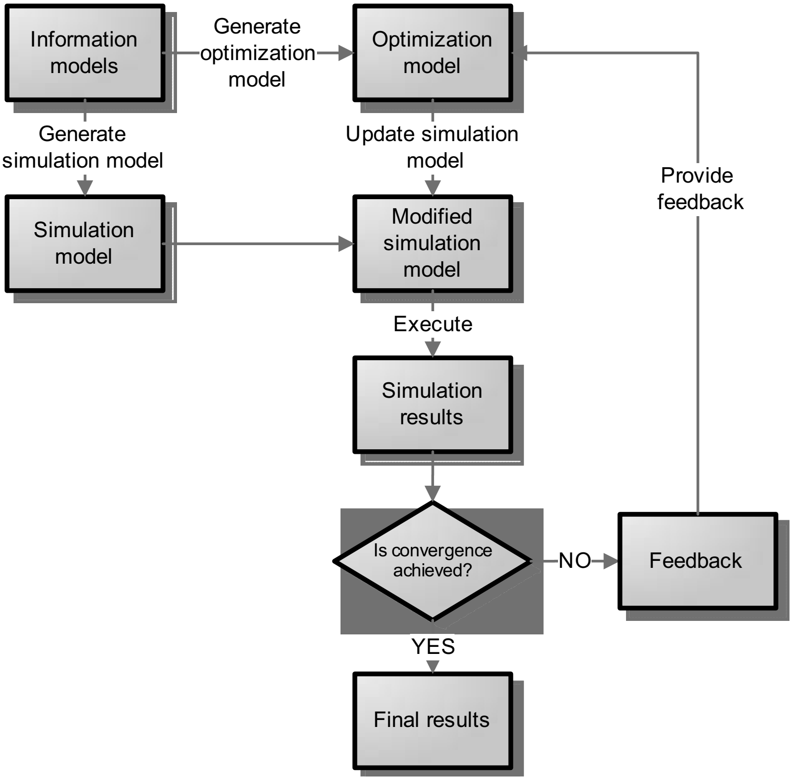

Fig. 10.1 Hybrid models and the supply chain decision-making framework.

In this chapter, two primary types of hybrid modeling are distinguished in the supply chain modeling context:

1. Sequential hybrid modeling – integration between simulation and optimization is implemented by updating parameters of simulation and optimization models. For instance, a supply chain configuration is optimized using a given processing cost parameter. A simulation model for the configuration established by optimization is executed and the processing cost parameter is updated. The next optimization iteration uses updated values of the parameter. This updated value represents some aspects of supply chain behavior previously not accounted for. One can say that all optimization trials are performed before calling simulation.
2. Simultaneous hybrid modeling – integration between simulation and optimization is implemented by evaluation of objective function. In this case, objective function of the optimization model is not available as a closed form expression (or its analytical evaluation is too com-

plex). An optimization model sets values of decision variables. Simulation modeling results obtained using these decision variables as input parameters are used to find a value of the optimization objective function. The value found is passed back to the optimization model. One can say that simulation is called on each optimization trial. Simulation based optimization (Carson and Maria 1997) also can be perceived as a type of simultaneous hybrid modeling. Breadth and scope of the simulation model distinguishes these two approaches.

Simulation models often include analytical models for run-time decision making. For instance, an inventory management algorithm is implemented to make inventory replenishment decisions. Such models closely resemble the fourth type of hybrid model according to the classification by Shanthikumar and Sargent (1983). However, this practice has become so widespread that incorporation of analytical models for performing some specific functions during simulation can be perceived as one of the base simulation modeling capabilities.

10.4 Sample Hybrid Models

This section discusses sequential and simultaneous hybrid modeling approaches. An alternative approach using a regression based meta-model as a feedback mechanism between simulation and optimization is also presented.

10.4.1 Sequential Hybrid Modeling

Sequential hybrid modeling executes a sequence of optimization and simulation at each iteration (Fig. 10.2). At the beginning of the modeling process, a fixed set of parameters are given and optimization problems can be expressed as $Z = \max_{\mathbf{V}} F(\mathbf{V}, \mathbf{p})$, where $F(\mathbf{V}, \mathbf{p})$ is a function of decision variables $\mathbf{V}$ and $\mathbf{p}$ representing the initial set of parameters. Supply chain configuration is optimized for these initial set of parameters. The simulation model is developed according to optimization results. It resembles the network structure established during optimization. The simulation model also includes additional factors, which have not been accounted for during optimization. Examples of such factors are short-term demand pattern, lead-time uncertainty, down time, and materials quality. Generally, these could be any factors relevant to the supply chain configuration problem and which can be better represented using simulation modeling as discussed in Chapter 9. The simulation model is executed following the same execution guidelines as in the execution of standalone simulation models. The main attention is devoted to determination of simulation run length and number of replications. These two simulation modeling parameters greatly influence overall execution time of hybrid modeling. During simulation, performance measures characterizing parameters used in the optimization model are accumulated. These performance measures are used to update values of the parameters. That can be formally expressed as $\hat{\mathbf{p}} = G(\mathbf{R})$, where $G(\mathbf{R})$ is a function of simulation results $\mathbf{R}$. Values are updated only for some selected parameters because simulation does not necessarily cover all the parameters included in the optimization model and fewer updates should lead to faster convergence of hybrid modeling. The updated parameters are sent back to start the next iteration. Optimization is now performed using the updated parameters $Z = \max_{\mathbf{V}} F(\mathbf{V}, \hat{\mathbf{p}})$. Iterations are executed until changes become sufficiently small.

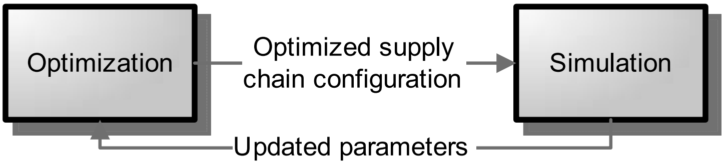

Fig. 10.2 Interactions between optimization and simulation models in the case of sequential hybrid modeling.

Several sequential hybrid models have been developed for problems related to supply chain configuration. Byrne and Bakir (1999) propose a hybrid production planning model. Production quantities are planned over multiple periods with carry-over inventory from period to period. The linear-programming model is used to elaborate the production plan. The simulation model is used to evaluate this plan under realistic conditions. If capacity is found insufficient to implement the production plan, a capacity adjustment coefficient is computed and used in the following optimization iteration. The convergence is achieved after seven iterations in the case study presented. Hybrid modeling has enabled elaboration of more realistic production plans. A modification of the model described above is presented by Kim and Kim (2001). Lee et al. (2002) apply similar principles to solve a production-distribution planning problem. Capacity is the parameter of the optimization model updated according to simulation results. The simulation model accounts for factors such as machine and vehicle breakdowns, repair times, queuing, and transportation delays.

Production planning using hybrid modeling in the supply context is also used by Gnoni et al. (2003). The model distinguishes between local and global planning. Besides other factors, the optimization model considers production setup times. Demand and reliability of manufacturing machinery are stochastic factors represented in the simulation model. Feedback between optimization and simulation models is implemented by updating capacity availability and average setup time parameters. The model is applied to studying the manufacturing of breaking equipment.

The major difficulty in using hybrid models in supply chain configuration is the treatment of location and facility-opening decisions. For instance, the optimization model makes decisions concerning supplier selection, and manufacturing cost is an updatable parameter. However, according to simulation results, this parameter may depend upon a particular supplier. On the first iteration, one supplier is selected, and the processing cost is updated. Another supplier is selected on the second iteration, and the processing cost is again updated, leading to non-converging fluctuations. These can be avoided by including supplier specific manufacturing costs already in the optimization model (causing increased modeling complexity and data requirements). However, in this case some of the manufacturing cost parameters might never get updated. Therefore, a decision modeler should pay special attention to possible interdependences among parameters in the supply chain.

Another major difficulty associated with hybrid modeling is the interpretation of strategic decisions at the operational level. For instance, the optimization model has a decision variable representing manufacturing capacity expressed as units annually, the while simulation model uses measures such as processing time and number of work stations, and throughput which greatly depends upon proper scheduling. Similarly, strategic level models use annual demand forecasts, while operational level simulation models need at least monthly demand forecasts and their performance substantially depends upon demand pattern (e.g., uniform, seasonal).

10.4.2 Simultaneous Hybrid Modeling

In the case of simultaneous hybrid modeling, the optimization model invokes simulation on each trial to evaluate the objective function as shown in Fig. 10.3. The optimization problem can be formulated as $Z = \max_{\mathbf{D}} F(\mathbf{D})$.

Values of decision variables are set at the beginning of each optimization trial. These values are set in an intelligent manner by an optimization algorithm. The trial decision variables are passed to the simulation model (structure of the simulation model may change because of values assumed by the decision variables). Multiple replications of sufficiently long simulation runs are executed to determine the value of the objective function expressed as $F(\mathbf{D}) = G(\mathbf{R}, r)$, where r is the number of replications. This value is not necessarily an average over all replications, therefore, other aggregated measures also can be used. The optimization model receives the value of the optimization function, which is used to appropriately select values of the decision variables for the next optimization trial. The process is executed until a convergence criterion is satisfied.

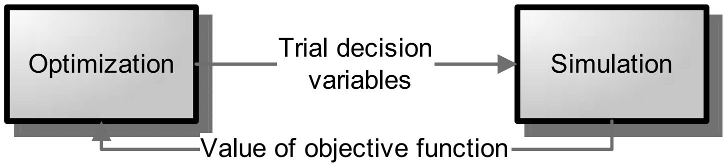

Fig. 10.3 Interactions between optimization and simulation models in the case of simultaneous hybrid modeling.

The example of simultaneous hybrid modeling is optimization of supply and manufacturing capacity of the flexible automotive supply chain under demand uncertainty (Chandra et al. 2005). The supply chain consists of multiple manufacturing plants and parts suppliers. Parts suppliers provide a set of components for each product. Manufacturing plants have limited flexibility to process more than one, but not all, products. The objective function of this optimization problem maximizes expected profit as a function of income from product sales, investments in build-up of supply and manufacturing capacity, capacity maintenance costs, and non-linear marketing costs. The optimization problem is solved subject to demand satisfaction, assembly capacity restrictions, supply capacity restrictions, and legislative constraints. Mathematically, the profit $E[P]$ maximization is expressed as

$$Z = \max_{\boldsymbol{\delta} \in \boldsymbol{\Delta}, \lambda \in \boldsymbol{\Lambda}, \nu \in \boldsymbol{\Omega}, \mathbf{Q}} E[P]. \tag{10.1}$$

Capacity adjustment coefficients $\boldsymbol{\delta} = \{\delta_1, ..., \delta_M\}$ and ν are used to change supply capacity, and λ is used to change manufacturing capacity. M is the number of products. Adjustment coefficients are used in the optimization, instead of directly altering the capacity in order to limit the size of the optimization space. Multiplication of capacity adjustment coefficients and initial capacity yields the optimized capacity requirements. Matrices $\boldsymbol{\Delta}$, $\boldsymbol{\Omega}$ and $\boldsymbol{\Lambda}$ represent sets of predefined values for the coefficients. The matrix $\mathbf{Q} = \{Q_{it}\}, i = 1,...M, t = 1,...,T$ represents the quantity of the ith product produced and sold in the tth time period, where T is the planning horizon. Some of the produced products are assembled during overtime. The fixed product-to-assembly plant assignments are input data to the model. Demand D_{it} for ith product at tth time period is given by its distribution

$$D_{it} \sim I_t G(\bar{D}_{it}, \sigma_{it}), \tag{10.2}$$

where $I_t \sim G(1, \varpi_t)$ is an indicator describing total industry demand, G is a probability distribution, $\bar{D}_{it}$ is average demand for ith product at tth time period, σ_{it} is standard deviation of product demand aside from that part due to total industry demand, and ϖ_t is the standard deviation of the total industry demand indicator (the average value of the indicator is 1). More detailed discussion of this problem is given in Chapter 13.

The development and solution of a standalone optimization model is complicated by the presence of non-linear and stochastic factors as well as complex interactions within the supply chain. Therefore, a hybrid model is developed where the optimization part is used to select the capacity adjustment coefficients and the simulation part is used to evaluate the value of the objective function. The capacity adjustment coefficients are selected using a genetic algorithm. The simulation model performs the following activities:

1. Generates demand scenarios.
2. Accounts for nonlinear marketing costs.
3. Allocates manufacturing quantities by using an embedded linear programming model.
4. Enforces legislative constraints.
5. Computes total operational profit.

The hybrid model is used to evaluate alternative product-to-plant allocation schemas characterized by varying the degree of manufacturing flexibility. Table 10.2 presents results obtained for one of the multiple scenarios analyzed. Profit is obtained as the result of optimization. Other performance measures are made available by using simulation. The results indicate that increased manufacturing flexibility improves the performance of the manufacturing supply chain. These gains are substantially smaller if stochastic factors are not accounted for during optimization (Chandra et al. 2005). A more detailed analysis of these and other results on the evaluation of flexible manufacturing is presented in Chapter 13.

Table 10.2 Optimized Expected Profit of the Flexible Manufacturing Supply Chain According to Degree of Manufacturing Flexibility

Performance Measure	Low Flexibility	Medium Flexibility	High Flexibility
Profit ($M)	8815	9185	9450
Sales/Demand ratio	0.85	0.87	0.88
Capacity utilization	0.87	0.89	0.90

A general overview of simultaneous hybrid modeling is given by Law and Kelton (2000) in the context of simulation-based optimization. It includes references to papers investigating this problem and a description of software packages supporting simulation-based optimization. The software description includes a schematic view of interactions between optimization and simulation models. Main nonparametric algorithms used in optimization are named.

10.4.3 Meta-Model Based Feedback

The hybrid models discussed above inherit several drawbacks from their simulation component:

- Computational time substantially depends upon complexity of simulation models
- Stochastic outcomes complicate feedback to optimization and interpretation of results

In some special cases, the impact of these limitations can be further reduced by using a hybrid modeling approach proposed by Chandra and Grabis (2005). This approach allows only one-way interactions between simulation and optimization (i.e., simulation results do not depend upon optimization results while optimization uses information obtained using simulation). It uses simulation to estimate the performance of the fixed part of the supply chain subject to dynamic and stochastic factors. Potential supply chain partners are modeled by a set of input parameters characterizing their aggregated properties. A regression based meta-model relating these parameters to their impact on supply chain performance is developed according to simulation results. This meta-model is incorporated as a constraint into a final optimization model, which is used to finalize supply chain configuration. The meta-model is used because simulation yields the performance estimates needed for optimization at only a few discrete points, while the meta-model is a continuous function. Further presentation of this approach is based on a supplier selection case study.

Case Description

The supplier selection problem is adopted from Weber and Current (1993) and Weber et al. (2000). It concerns procurement of one major raw material. Suppliers are selected for the length of a relatively long planning horizon. The number of suppliers to be selected is predefined, and suppliers have restricted supply capacity. There are three supplier selection criteria: 1) material price, 2) delivery reliability measured by percentage of late items, and 3) quality measured by the percentage of rejected items. Supplier data characterizing the selection criteria are given for candidate suppliers. Materials are delivered to the manufacturer in just-in-time mode.

The multi-objective optimization problem is formulated as

$$\min Z = (Z_1, Z_2, Z_3) \tag{10.3}$$

subject to

$$\sum_{j=1}^{N} x_j \geq D \tag{10.4}$$

$$Z_1 = \sum_{j=1}^{N} \rho_j x_j \tag{10.5}$$

$$\sum_{j=1}^{N} v_j = P \tag{10.6}$$

$$x_j \leq v_j w_j^{\max} \tag{10.7}$$

$$x_j \geq v_j w_j^{\min} \tag{10.8}$$

$$Z_2 = \sum_{j=1}^{N} \lambda_j x_j \tag{10.9}$$

$$Z_3 = \sum_{j=1}^{N} \beta_j x_j \tag{10.10}$$

$$v_j = \begin{cases} 0, \text{if } x_j = 0 \\ 1, \text{if } x_j > 0 \end{cases}, j = 1, \ldots, N \tag{10.11}$$

Z_1 represents the material price criterion, Z_2 represents the delivery reliability criterion, and Z_3 represents the quality criterion. x_j is the quantity to be purchased from the *j*th supplier. N denotes the number of candidate suppliers. v_j indicates whether the *j*th supplier is included in the supply network. $w_j^{\min}$ and $w_j^{\max}$ limits minimum and maximum total order quantities for the *j*th supplier, respectively. ρ_j is the net purchase price per unit for *j*th supplier, λ_j is the percentage of late items for the *j*th supplier, β_j is the percentage of items rejected for the *j*th supplier.

General Approach

The standalone optimization of this supplier selection problem is complicated by different dimensions of supplier selection criteria. The simulation model is used for evaluating the impact of delivery performance and quality of materials on manufacturing costs. It represents the actual manufacturing system at an appropriate level of abstraction. If all selection criteria are expressed in terms of the manufacturing costs incurred, then the multi-criteria problem is transformed into a single objective optimization problem, which selects suppliers in such a way that minimizes the costs associated with sourcing from these particular suppliers. To perform simulation without knowing specific suppliers, these specific suppliers are abstracted by an aggregated supplier.

Alternatively, the optimization of a supply network could be performed using the simulation model directly or using a hybrid optimization-simulation model, which invokes the simulation model on each optimization trial, and is computationally challenging.

The hybrid modeling process, using the meta-model as a feedback mechanism, involves the following steps:

1. Identify supplier selection criteria and a plausible range of values for these criteria.
2. Develop the simulation model of the manufacturing system and experimental design.
3. Run simulations.
4. Construct the meta-model relating suppliers' characteristics and manufacturing costs.
5. Integrate the meta-model into the optimization model.
6. Optimize the supply network.

During Step 1 of the modeling process, a list of supplier selection criteria is compiled. Plausible ranges of criteria are also identified. For instance, the percentage of defective materials varies from 1 to 5 percents. A simulation model of the manufacturing system is developed at Step 2. Manufacturing operations are simulated without specifying suppliers, and an abstract aggregated supplier is used instead. The importance of experimental design is stressed because simulation experiments need to cover the entire range of plausible values in the supplier selection criteria. During the simulation, manufacturing costs are evaluated subject to the suppliers' characteristics corresponding to the chosen criteria. Simulation modeling results are used to construct a regression-based meta-model. This meta-model takes the suppliers' characteristics as input parameters and returns the total manufacturing cost. The meta-model can be readily integrated into the supplier selection optimization model. The optimization models select suppliers and determine order quantities from each supplier by minimizing the calculated manufacturing costs using the meta-model and purchasing costs, such as material prices included only in the optimization model.

Specific Models

The supplier selection problem description defines the list of supplier selection criteria. The minimum and maximum values of supplier data that characterize the selection criteria constitute lower and upper bounds on the range of plausible values, respectively.

Simulation model: Development of the manufacturing system's simulation model is the next step of the modeling process. Simulation modeling of the manufacturing system generally requires more information than needed just for mathematical programming purposes. Therefore, the following assumptions about the system are made:

1. Procured materials are used to manufacture a single end product.
2. The planning horizon is one year, divided into 8-hour normal work days.
3. Demand for the end product is uniformly distributed across the planning horizon (this assumption is consistent with the just-in-time system condition).
4. The manufacturing system has the fixed and relatively high capacity utilization level.
5. Materials are supplied at the beginning of each day in a single batch.
6. Each day, a percentage of all items is delivered late. This percentage is distributed according to the logarithmical normal distribution with mean λ^* and standard deviation $g\lambda^*$. Processing of items delivered late can be started only after all on-time deliveries are processed.
7. Each day a percentage of all items are rejected because of poor quality. This percentage is distributed according to the logarithmical normal distribution with mean β^* and standard deviation $h\beta^*$. The rejected items can be processed on the next day, after all on-time deliveries are processed. Processing of these items takes ~2.5 times

longer than processing of standard items. This increase in processing time depends upon the quantity of late deliveries on a particular day.
8. Items delivered on time can be processed within normal working hours. However, processing of late deliveries and rework can extend to overtime. The premium charge B \$/item is imposed for overtime processing (rework counts with respect to increased processing time).
9. Overtime cannot exceed two hours. If more work is left, it is carried over to the next day.

For selection purposes, only suppliers' characteristics dependent manufacturing costs MC need to be accounted for. In this case, these are only overtime costs, which are computed as overtime cost B times the number of items processed in overtime.

The experimental design is created by varying values of the aggregated suppliers' characteristics λ^* and β^* within specified ranges. Multiple replications of simulation modeling are executed for each experimental cell.

Meta-model: The manufacturing cost MC is the output variable of simulation modeling. λ^* and β^* are input variables of simulation modeling. The results of simulation modeling are used to develop a regression-based meta-model relating manufacturing costs to suppliers' characteristics. In this case, a linear meta-model is used

$$MC = a_0 + a_1\lambda^* + a_2\beta^* \tag{10.12}$$

where $a_k, k = 0,..,2$ are estimated coefficients of the meta model (see Kleijnen (2005) for more details on creating meta-models from simulation results).

Optimization model: After developing the meta-model, the supply network is established using mathematical programming. The meta-model yields suppliers' characteristics dependent manufacturing costs. The mathematical programming model also includes other strategic purchasing costs. In this case, these are net purchasing costs per item. Because the simulation model expresses the delivery performance and quality criteria in terms of manufacturing costs, the single objective mathematical program corresponding to the multi-criteria supplier selection problem described earlier is formulated.

The objective function of this mathematical program is

$$\min TC_m = Z_1 + C \tag{10.13}$$

where TC_m are total costs, with accounting for costs due to the impact of delivery performance and quality.

It is evaluated subject to constraints in Eqs. (10.4-10.8) and Eq. (10.11). The additional constraint representing the manufacturing costs is introduced per Eq. (10.14).

$$C = \sum_{j=1}^{N} \left[(a_0 + a_1\lambda_j + a_2\beta_j) x_j D^{-1} \right] \quad (10.14)$$

This constraint is derived from the meta-model. The simulation model, and consequently the meta-model, uses a single aggregated supplier. To account for the individual contributions of each supplier, the manufacturing cost is weighted by a proportion of items purchased from a particular supplier.

Results

Experimental studies are conducted to demonstrate the proposed supplier selection approach. These compare the supplier selection results obtained using the proposed multi-objective approach, and the single-objective optimization with respect to purchasing price only.

To assess the impact of assumptions, different sets of experiments are conducted as per the criteria defined in Table 10.3. The overtime processing cost comparative to the material purchasing price is chosen. g characterizes the level of uncertainty about how many items are delivered late each day. h characterizes the level of uncertainty about how many items are rejected each day. The total demand is 40,000 items per day. The capacity utilization rate is 95 percent.

The supplier selection problem is solved for each set of parameters of the manufacturing system. The full factorial experimental design needed to develop the meta-model is created for each set. It is developed by pairing the upper and lower values of λ^* and β^* identified in Table 10.4. Fifty replications are executed for each experimental cell, and a meta-model for each set is fitted. The R-squared values for all meta-models exceed 0.85.

Table 10.3 Sets of Parameters of the Manufacturing System Considered

	G	*h*	*B*
1st set	1	1	0.2
2nd set	0.2	0.2	0.2
3rd set	1	1	2
4th set	0.2	0.2	2

Table 10.4 Values of Aggregated Suppliers' Characteristics Used

	λ^*	β^*
Upper level	1	0.2
Lower level	7	2.3

The fitted meta-models for each set of parameters are incorporated separately into the optimization model to make the supplier selection decisions. The optimization model uses values of net purchase price per unit ρ_j, percentage of items late λ_j, and percentage of items rejected β_j, as given in Weber et al. (2000, Table 1). The number of candidate suppliers is six. The number of suppliers to be selected is five. The quantity of raw materials allocated to each supplier is reported in Table 10.5. The table also compares the total cost TC_m as estimated using optimization model, the total cost TC_m^* obtained by simulating the optimized supply network, and the total cost TC_1^* obtained by simulating the optimized supply network, if $a_k = 0, k = 0,..,2$ (i.e., only the price criterion is used). In the case of $a_k = 0, k = 0,..,2$, the optimization model yields $x_j = \{36.9, 107.9, 0, 0.4, 0.4, 0.4\}$. The results show that differences between supplier selection results for the 1st and 2nd sets are not statistically significant. Additionally, the multi-objective problem-solving approach and the single-objective approach yield statistically identical results. The overtime driven manufacturing cost is too low to substantially affect supplier selection decisions. The majority of items are ordered from the supplier offering the lowest unit price, despite its poor on-time delivery performance. However, if the overtime cost factor B is set at a high level (3rd and 4th sets), the manufacturing cost substantially influences supplier selection decisions. The majority of items are ordered from the supplier offering the highest price and proving the good on-time delivery performance and quality. TC_1^* is substantially worse than TC_m^* for the 3rd and 4th sets, highlighting the importance of accounting for not only the purchasing price factor but for other factors as well.

The described approach can be expanded to other supply chain configuration problems in addition to the supplier selection problem. However, it is more suitable, if the supply chain structure is partially fixed.

Table 10.5 Supplier Selection Results in '00000

	Multi-Objective								Single Objective
	TC_m	x_1	x_2	x_3	x_4	x_5	x_6	TC_m^*	TC_1^*
1st set	29.0 (±0.02)	36.9	107.9	0.4	0.4	0	0.4	28.8 (±0.02)	28.9 (±0.02)

2ed set	28.8 (±0.02)	36.9	107.9	0.4	0.4	0	0.4	28.7 (±0.0)	28.7 (±0.00)
3rd set	31.1 (±0.02)	0.4	30.3	107.9	7.0	0	0.4	31.3 (±0.02)	38.5 (±0.13)
4th set	30.7 (±0.01)	0.4	46.7	98.1	0.4	0	0.4	30.7 (±0.00)	36.6 (±0.05)

NOTE: 95% confidence intervals are provided in parenthesis

10.5 Summary

Hybrid modeling is a powerful technique proving additional opportunities for comprehensive supply chain configuration modeling. It implements the principle of the model synergies. However, there are several major issues to be addressed. There are the development of a theoretically sound feedback mechanism, accumulation of general knowledge on application of hybrid modeling, and expansion beyond joining simulation and optimization modeling.

Ad hoc feedback mechanisms for the sequential approach are available for problems like production planning with continuous variables. However, there are profound difficulties in implementing the feedback mechanism for the supply chain configuration problems involving binary variables. Additionally, convergence properties of algorithms used for solving hybrid models are sparsely investigated. That leads to uncertainty concerning the quality of solutions.

Hybrid models tend to be developed on a case-by-case basis. Therefore, little guidance for developing hybrid models is available. The problem is also important for simulation-based optimization models. Despite the availability of advanced computational tools, empirical evidence of application of these tools in combination with complex discrete event simulation models is limited.

Hybrid modeling originally applied to the integration of simulation and optimization models. However, integration with other quantitative models is also possible. This direction is particularly relevant for the supply chain configuration problem because statistical models are frequently used at the preselection stages. Currently available models consider a linear chain of statistical models used for preselection, and optimization models used for selection (and simulation models used for evaluation). Alternatively, a sequential hybrid model could be constructed for iterative evaluation. For instance, a statistical preselection model captures suppliers' commitment strengths, which is influenced by a purchasing quantity determined using optimization.

Finally, this chapter emphasizes that the common information basis, and the automated development and modification of hybrid models, are essential for efficient application of these models.

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11. Information Technology Support for Configuration Problem Solving

11.1 Introduction

Supply chain management and information technology are tightly coupled. Implementation of supply chain strategies would be very difficult without the support of information technology. At the same time, many developments in information technology have arisen from requirements set by enterprises seeking collaboration with their partners in the supply chain environment. For instance, the development of web services has been driven by a need for flexibility and more open information systems interfaces to support reconfigurability.

This chapter describes the information technologies used to support supply chain configuration, both from the decision-making and decision-implementation perspectives. Information technologies include hardware, communications, and software. Here, the focus is on software. Hardware and communications are described only at the conceptual level in relation to the general architectures of information technology solutions in the supply chain management framework.

The chapter starts with outlining the major aspects of information technology usage in supply chain management, and supply chain configuration in particular. The classification of applications used is provided. Section 11.3 describes applications used for decision-making purposes. Section 11.4 discusses the supply chain management information system, with emphasis on the use of flexible, service-oriented architecture. A prototype of the supply chain configuration decision-making system is described in Section 11.5.

11.2 Information Technology for Supply Chain Configuration

Information technology is irreplaceable, primarily because of the amount and complexity of information processing and the physical distribution engaged by each supply chain member.

To describe information technology support for supply chain management, and configuration in particular, it is important to distinguish between information technology support for decision-making needs and information technology support for decision-implementation needs. In the former case, applications of information technology include providing input data to decision models, solving decision-making models, and presentation of results. In the latter case, applications of information technology include communicating data among supply chain units, processing of transactions, online decision-making and monitoring of supply chain efficiency.

Several key requirements for the information technology solutions used to support supply chain management include the following:

- Horizontal and vertical integration. Supply chain management processes are executed across functional domains within individual units, as well as across enterprises involved in the supply chain network. Sharing of data and processes should be supported at a level desirable for a particular decision-making problem. Its implementation should enable relatively simple replacement of components comprising the architecture of the supply chain information system
- Security. Effective supply chain management depends upon a level of trust between partners, especially in the case of rapidly evolving supply chain structures. Clearly defined and strictly enforced security policy has an important role in trust building. Obviously, information technology solutions should also support all common data security requirements
- Reliability. A high level of information systems availability is required to support collaborative decision making and implementation of decisions
- Scalability. The intensity of product and information flows can change quickly, along with changes made in the supply chain configuration. Information technology solutions should be able to accommodate these changes

Functional requirements for supply chain information systems depend upon a particular supply chain configuration problem (some of the common functional requirements are identified throughout the book). These requirements, along with the earlier defined key requirements, determine the design of the supply chain information system. Several common features of such a design can be identified. Information technology solutions are made up by pairing hardware, communications, and software. Typical characteristics of such solutions in the supply chain environment include:

- Heterogeneity. Information technology solutions are heterogeneous, both within an enterprise and throughout the supply chain. The internal heterogeneity is caused by using different applications for solving various supply chain management problems. For instance, decision making is performed using an advanced planning system while decisions are implemented using the Enterprise Resource Planning (ERP) system of another supplier because an enterprise attempts to use best-of-breed solutions. The external supply chain heterogeneity is caused by supply chain members using different information technology architectures, which are still strongly influenced by local tradition. It is important to note that heterogeneity is characteristic to all levels of information technology solutions. At the logical level, different data models and process representations are used (see Chapter 7). Different software packages are used at the implementation level and different platforms and a means of communication are used at the infrastructural level.
- Distributed system. This characteristic mainly owes to the spatially distributed nature of supply chains. Supply chain partners are physically distributed around the world, and the design of the supply chain information system accounts for this problem. An additional important feature is the lack of centralization that complicates management of the supply chain information system. For instance, one supply chain partner generally is not able to use its system to enforce the security policy in the system owned by another partner.
- Use of public communication channels. Reconfigurable supply chain management information systems use public communication channels and the Internet, in particular, extensively. These communication channels offer a substantially higher degree of flexibility and lower costs while modern technologies can provide an adequate level of security.
- Web access. Web-based access to supply chain management information systems provides a high level of accessibility. In the case of supply chain configuration problems, this feature supports collaborative decision making.

Different types of information systems are used in supply chain management. Information systems involved in supply chain configuration decision-making support and implementation can be classified as follows:

- Standalone general-purpose decision modeling packages. These packages are used to develop and solve different types of decision-making problems, including the supply chain configuration problem. Typical representatives include the optimization package LINGO and the simulation package ARENA.
- Standalone problem-oriented decision modeling software packages. These packages include specific solutions for particular decision-making problems – in this case supply chain configuration. Examples of such packages are LORD and modules of i2.
- Integrated modeling environments. Decision-modeling applications are supplemented with different service modules, primarily for data handling, management of experiments, and presentation of results.
- Advanced planning systems. Integrated enterprise-level planning systems supporting hierarchical decision-making.
- Data warehousing systems. Special purpose data storage and presentation systems integrating data from various sources to support decision making.
- Legacy systems. Mainly custom-built systems supporting specific functional areas of enterprises. Legacy systems are developed on the basis of outdated computing platforms.
- ERP systems. Integrated information systems supporting transactions processing for the majority of functional domains in enterprises.
- Workflow management systems and groupware. These systems are used to support collaborative decision making and implement decisions made.
- Specialist information systems. While enterprise resource planning systems are designed to cover many functional domains, specialist information systems are aimed at particular functional or process areas. For instance, customer relations management systems provide an interface between a supply chain and its customers. Manufacturing automation systems generally form a separate class of information systems. They are also important for addressing product and process-related issues of reconfiguration.
- Web-based information systems and e-business systems. These systems can be perceived as a subclass of specialized information systems. They provide web-based access to enterprise computing resources for both customers and suppliers.
- Information modeling packages and integrated development environments. These systems are used for information systems development purposes, supporting both information systems modeling and actual implementation. Systems integration applications also can be attributed to this class.

The list of information systems does not include software packages used at the infrastructural level, such as server management systems and network routing systems.

Bowersox et al. (2002) present a representation of components of the integrated supply chain management information system, with an emphasis on transaction processing and communication technologies used to link various parts of the information system. These technologies include Electronic Data Interchange (EDI), Internet, Radio Frequency Data Capture (RFDC), Point-Of-Sales (POS) scanners, bar code scanners, and pagers. Communication technologies, which have become widespread more recently, are Global Positioning System (GPS) and General Packet Radio Service (GPRS) (and other mobile data exchange technologies). These, as well as the earlier mentioned real-time data capture and transmission technologies are of major importance to support operations in reconfigurable supply chains.

Helo and Szekely (2005) list supply chain execution applications and their functionality. The list details the class of specialist applications. The identified specialist applications are transportation management systems, warehouse management systems, and supply chain management systems (dealing with inventory and materials flow management). ERP systems, advanced planning systems and Enterprise Application Integration (EAI) tools are also mentioned as important components of the overall supply chain information system. The authors indicate that the division between different types of specialist information systems becomes fuzzy. Hassan (2006) attributes information technology solutions to the technological branch of the supply chain system hierarchy. The author names the main types of functional supply chain applications and hardware used for communication and identification purposes.

11.3 Analytical Systems

Analytical systems (i.e., systems used for problem-analysis) are used for decision-making purposes by a limited number of skilled professionals. Their usage is characterized by the high degree of creativity needed to solve each unique decision-making problem. We discuss some of these below.

11.3.1 Standalone Packages

Optimization Package. Optimization software is a key part of many supply chain configuration information technology solutions, as it is used for solving mathematical programming models of supply chain configuration. Its purpose is to establish a supply chain configuration by solving specified mathematical programming models. Optimization packages are characterized by available model solving-algorithms, model development and testing functionality, and data input/output capabilities. They also often provide a spreadsheet-based user interface. From the supply chain integration perspective, optimization packages should support some of the enterprise application integration technologies. Some of the main vendors of optimization software are LINGO (*www.lindo.com*) and ILOG (*www.ilog.com*). Availability of non-parametric optimization software such as @Risk Evolver (*www.palisade.com*) is becoming more wide-spread.

Simulation Packages. Simulation software is used to evaluate configuration decisions. It involves a simulation modeling language and a simulator and is often supplemented by tools for input and output data processing. Selection of appropriate simulation modeling software is discussed by Nikoukaran and Paul (1999) and Hlupic (1999). The main requirements for software include ease of use, data storage capabilities, availability of debugging and testing functions, efficiency of model execution, and animation capabilities. ARENA (*www.arenasimulation.com*), ProModel (*www.promodel.com*), SIMUL8 (*www.simula8.com*) and Extend (*www.imaginethatinc.com*) can be mentioned as typical representatives of available simulation modeling tools. Simulation tools with modules and templates specific for conducting supply chain analysis are also available (see Chapter 14).

Statistical Analysis. Statistical analysis software is used to process input and output data. Direct application of statistical models for supply chain configuration decision making is less common. However, as shown in Chapter 10, there are many situations when statistical models, maintained by statistical analysis software, are combined with other configuration models. Statistical software is used to perform data cleansing and transformation, development of statistical models for preselection purposes, and a whole range of statistical methods for processing of output results, including visualization capabilities. Well-known statistical software tools are STATISTICA (*www.statsoft.com*), MatLAB (*www.mathworks.com*), MiniTAB (*www.minitab.com*), and SAS (*www.sas.com*).

Geographical Information Systems (GIS). Given that the supply chain configuration problem has explicitly spatial character, geographical information support systems are an important part of supply chain configuration information technology solutions. Camm et al. (1997) use GIS to provide a user interface for the supply chain configuration system. This enabled achieving greater acceptance of analytical results by users as well as discovering data errors through visualization. The ArcGIS product family by ESRI (*www.esri.com*) is one of the leading GIS products. It is characterized by user-friendly features and support for component-based integration with other parts of the supply chain information system. Various on line geographical information providers, such as MapQuest (*www.mapquest.com*) and Google (*www.google.com*), are simpler alternatives to expensive geographical information systems for acquiring spatial input data and visualization of configuration results.

11.3.2 Data Warehouses

The data warehouse is an integrated data storage and analysis system built to provide decision modelers with data gathered from multiple data sources. This technology has become popular for conducting analysis on the basis of large data sets, as well as providing data to decision-modeling applications. Fig. 11.1 shows typical data warehouse architecture (according to Kimball et al. (1998)). The data-staging component is responsible for channeling data from heterogeneous data sources to the data warehouse server, where data are arranged according to the dimensional data model. Various general and special purpose database management systems can be used to store dimensional data. Online Analytical Processing (OLAP) tools are used for data presentation purposes. They can be used in the preselection stage of supply chain configuration. Modeling modules and the supply chain configuration decision-making system, in particular, can tap into the data warehouse through the data presentation layer to obtain input data.

The main advantages of using data warehouses are ensuring data availability and quality. However, data warehouse development is a highly resource-consuming process. It is not likely that a data warehouse is developed solely for supply chain configuration purposes, although using existing data warehouses to provide data to supply chain configuration models is a highly efficient approach. Another limitation is that data warehouses depend upon the availability of historical data that complicates its applicability, if many new supply chain structures are required. However, as data are accumulated during the decision-monitoring process, data warehouses become efficient for identification of opportunities for improvement.

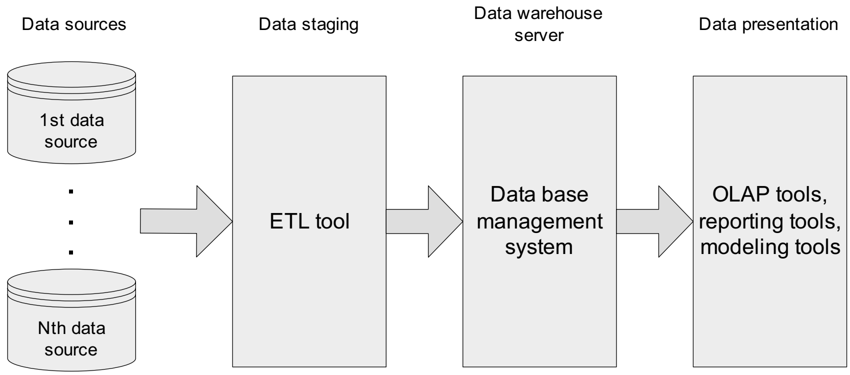

Fig. 11.1 Data warehouse architecture.

Data warehousing solutions can be developed by relying on a single vendor, or by choosing the best-of-breed approach. The main vendors of such solutions are Oracle (*www.oracle.com*), Microsoft (*www.microsoft.com*), Cognos (*www.cognos.com*) and others.

11.3.3 Advanced Planning Systems

Advanced planning systems are used to plan supply chain execution at all decision-making levels, spanning from the strategic level to the operational level. Stadtler (2005) and Stadtler and Kliger (2005) provide a comprehensive description of advanced planning systems. Strategic network planning, or supply chain configuration, is the starting point of the advanced planning process. It provides input to all other planning processes. Advanced planning systems are often tightly integrated with ERP systems. The main vendors are SAP (*www.sap.com*), i2 (*www.i2.com*) and others.

11.3.4 Integrated Decision-Making Environments

This class of analytical systems includes both model development environments, as well as integrated decision support systems, which often invoke other standalone software packages. Integrated decision-making environments provide model development productivity tools, data management functions and functions for executing experiments and presenting decision-making results. Integrated decision-making environments often are developed as a set of utilities supplementing existing decision-modeling applications. For instance, ILOG provides OPL Development Studio for developing ILOG CPLEX optimization models.

Dolk (2000) describes an integrated modeling environment that uses data warehousing principles to provide the data required for decision-modeling purposes. Dotoli et al. (2003) develop a decision support system specifically for supply chain configuration. This system includes modules for data analysis, network design and the evaluation and validation of results. Worley et al. (2002) describe the development of decision support systems from reusable components. Application of this approach at the central unit could lead to quick assembly of the executable decision models for new supply chain configurations.

11.4 Supply Chain Management Information Systems

The supply chain management information system is used for supply chain execution. Given that this book focuses on supply chain decision-making problems, individual components of the supply chain management information system are not discussed in detail (readers are referred to Bowersox et al. (2002) and Gunasekaran and Ngai (2004) for overview of such systems). The supply chain management information system is described from the perspective of its support for decision-making and implementation processes.

11.4.1 Usage

In the context of the supply chain configuration problem, the supply chain management information system is used to maintain information needed for development and execution of decision-making models, to provide appropriate data sources, and to implement on-line decision-making components. The maintenance of the information needed for development and execution of decision-making models primarily concerns maintenance of repository and models of information systems. Decision-making models use information from various sources in the supply chain management system, which is required to provide mechanisms to channel the required data from their sources to decision-making models. While decision-making results are often represented in the supply chain information system in an offline manner, on a case-by-case basis, some of the decision-making results are implemented as online decision-making components, such as, a supplier selection component. In this case, the supply chain management information system facilitates the implementation of this decision-making component and ensures its execution on a daily basis. This way, there are closed-loop interactions between transaction processing and supply chain configuration decision making, as illustrated in Fig. 11.2.

The right-side of the loop in Fig. 11.2 describes the inventory replenishment processes. In this case, suppliers are dynamically selected on case-by-case basis. Suppliers are selected according to decision-making rules elaborated during the supply chain configuration studies and implemented in the integrated manner. The left-side loop describes the supplier selection processes within the decision-making component of the supply chain information system. Demand planning and inventory tracking are also involved in some other transaction processing or decision-making processes. The supply chain information system is required to support this kind of interactions.

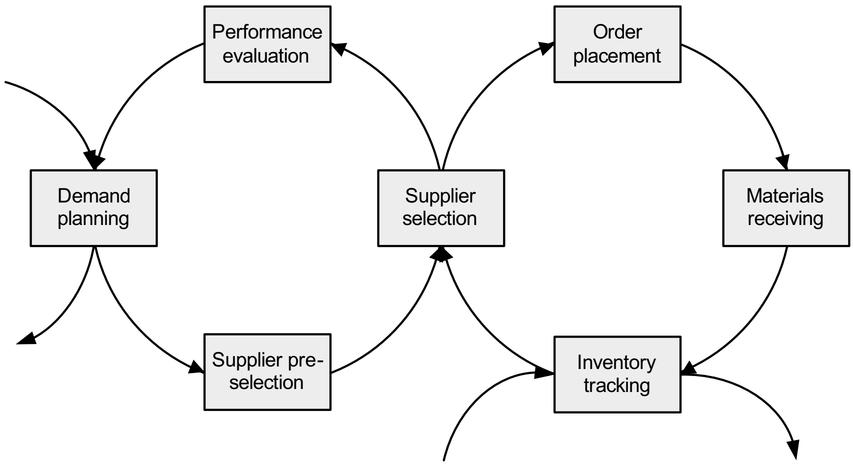

Fig. 11.2 The closed loop interactions between transaction processing and decision making.

From the perspective of operating reconfigurable supply chains, the supply chain management information system is responsible for processing transactions within individual supply chain units, as well as among these units. It also must support the integration of new supply chain units.

11.4.2 Architecture

The architecture of supply chain management information systems shows the main components of this system. It draws upon the service-oriented architecture reference model (see Erl 2005). This type of architecture is built to anticipate changes in the system, which is crucial to support supply chain reconfigurability. The architecture presented emphasizes aspects of the service-oriented architecture important to supply chain management with a focus on decision-making requirements.

The central components of the architecture (Fig. 11.3) are business processes and the decision-making system. The decision-making system consists of various analytical applications. It, along with the business intelligence component, provides tools for decision-making purposes. The business process component enables incorporation of decision-making components into the overall supply chain management information system. It provides a means for assembling business processes. Components and applications of the supply chain information system can be invoked during execution of the business processes. Information flows among components and applications are also defined by means of an exchange of messages. It complies with the web services business process execution language (Thatte et al. 2003; *www.oasis-open.org*). The business integration component provides real-time information exchange among components and applications. It essentially executes cross-functional and cross-enterprise business processes.

The data-integration component links the decision-modeling system with other parts of the supply chain information system to provide links to appropriate data sources and destinations. It is also responsible for ensuring data consistency across enterprise applications. Extraction-Transformation-Loading (ETL) tools are primarily used to provide data exchange capabilities. Technologies such as data hubs are used to maintain and update master data across enterprises and supply chains.

The end-user access to business processes and to the decision-making system is provided by the supply chain management portal, which can be composed from existing modules and provide an individualized user interface. In the case of reconfigurable supply chains, the supply chain management portal can be relatively easily modified to represent information and processes pertinent to the current state of the supply chain configuration.

ERP, legacy systems, specialist applications, and other enterprise applications mainly serve as data sources in the case of supply chain configuration problems. These applications can also be invoked from business processes composed to integrate online decision-making components. Service and components are shown separately. All main vendors of ERP systems have modules for supply chain transaction processing, and these systems are being restructured to comply with the requirements of the service-oriented approach to enterprise computing.

In the context of supply chain configuration, the main application of development tools is elaboration and maintenance of models of the supply chain information system. These models are used to facilitate development of decision-making models (see Chapter 5).

The architecture of the supply chain information system, and the architecture of the supply chain configuration decision support system (see Chapter 5) share several components. For instance, ETL tools are used in both cases.

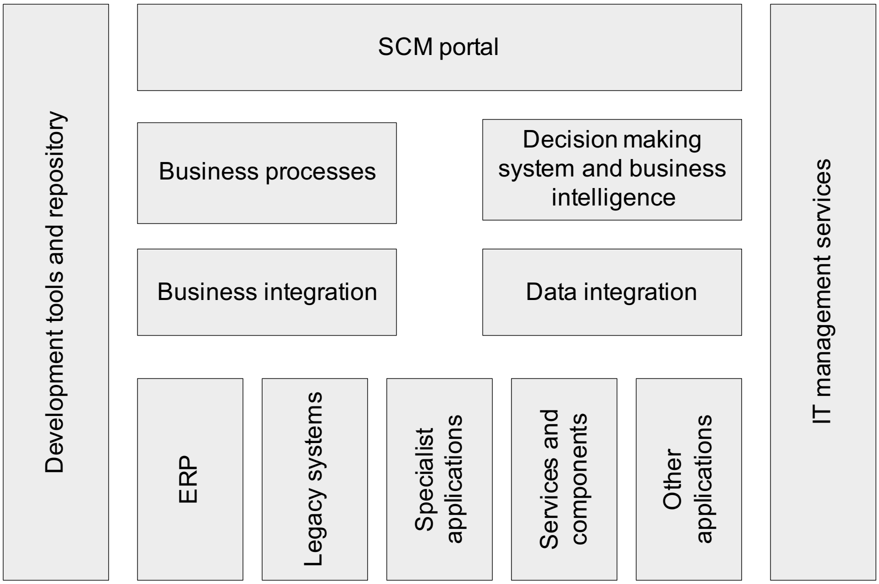

Fig. 11.3 Architecture of the supply chain management information system.

Several other architectures of supply chain management information systems have been proposed in the literature. Verwijmeren (2004) proposes a software component architecture for supply chain management aimed at supporting collaboration and dynamic change. The component layer is put on top of intra-enterprise applications to support integration among supply chain partners. Specific component-level technologies, such as Common Object Request Broker Architecture (CORBA), Remote Method Invocation (RMI), and web services, are used to implement the architecture. Kobayashi et al. (2003) develop a business process and workflow-based approach to linking various supply chain management applications. Helo and Szekely (2005) identify database, business logics, and communication layers of the supply chain integration architecture.

The architecture described can be implemented on the basis of several existing enterprise integration platforms (Table 11.1). The table lists specific commercially available products to provide functionality in components of the proposed architecture. The platform provided by Oracle (*www.oracle.com*) is distinct in its tight integration with the ERP systems provided by the same vendor. Similarly, Microsoft (*www.microsoft.com*) is also headed in the same direction by capitalizing on its Dynamics product range. Several vendors also offer integration platforms specifically tailored to supply chain management needs. For instance, i2 has developed the i2 Agile Business Process Platform (i2 Technologies 2005), which is packaged with business-oriented capabilities and libraries designed to address supply chain management goals.

Table 11.1 Enterprise Application Integration Implementation Platforms

Vendor	Portal	Business processes	Business integration	Business intelligence	Data integration
BEA	WebLogic Portal	WebLogic Integration	WebLogic Integration	-	-
IBM	WebSphere Portal	WebSphere Business Modeler	WebSphere Business Integration Connect	DB2 Data Warehouse Edition	WebSphere Data Integration Suite
Microsoft	Microsoft SharePoint	Microsoft Biztalk	Microsoft Biztalk	Microsoft SQL Analysis Services	Microsoft SQL Integration Services
Oracle	Oracle Application Server Portal	Oracle BPEL Process Manager	Oracle Business Integration	Oracle Business Intelligence Suite	Oracle Data Warehouse Builder

11.4.3 Integration Technologies

The implementation of the architecture requires use of particular integration technologies. The EAI paradigm governs general principles of systems integration (Linthicum, 2003). Themistocleous et al. (2004) show a high-level model of application of EAI in supply chain integration. This model initially links enterprise applications within a supply chain, unit and another integration level is used to enable collaboration among supply chain partners.

There are multiple integration approaches and technologies available to support EAI solutions. Integration technologies can be classified as integration at data, application, and business-process levels. The data-level integration operates at the database level, and database standards such as Open DataBase Connectivity (ODBC) and Java DataBase Connectivity (JDBC) are used to implement data exchange mechanisms. The application-level integration is achieved by using various component development standards, which govern the development of software components to ensure their compatibility. Applications built in accordance with these standards can be relatively easily integrated among each other. The main component development standards are CORBA, Enterprise Java Beans (EJB), and Component Object Model (COM/DCOM). Web services form a specific class of components characterized by their availability over the Internet and platform independence. They are at the heart of the service-oriented architecture. Siau and Tian (2004) provide an introductory overview of these technologies as used in supply chain management. Themistocleous et al. (2003) evaluate these and a few other technologies from the perspective of supply chain management, according to application elements, integration layer, and type of system criteria.

The business-level integration is achieved by designing cross-functional and cross-enterprise business processes. The Web Services Business Process Execution Language (WSBPEL) and various extensions are used to develop applications integrated at the business level.

Specialized supply chain integration technologies such as ebXML (*www.ebxml.org*) and RosettaNet (*www.rosettanet.org*) are developed on the basis of generic integration technologies, which provide a general framework for implementing collaborative supply chain applications. The main difference between these two is that ebXML is an industry independent framework, while RosettaNet is geared towards high-tech industries.

The technologies described above mainly pertain to the physical aspects of integration. Logical integration, which includes agreement on concepts used and model integration, is also an important issue currently under active investigation. Kühn et al. (2003) discuss the importance of model integration. The authors identify model integration patterns and describe an example of integrating custom-built software with the ERP system at the modeling and implementation levels. One of the key problems in model integration is the combination of models developed using differing concepts. Braun and Marschall (2003) advocate the importance of transformation among models because systems are heterogeneous. They use UML as the common modeling basis. McBrien and Poulovassilis (1998) investigate the integration of various database schemas. Lippe et al. (2005) review existing research of modeling of cross-organizational (cross-application) business processes, and conclude that integration of dynamic models is still an open research problem.

11.5 Prototype of a Decision-Modeling System

The prototype decision-modeling system implements some of the ideas explained above, as well as those represented in the architecture of the decision-modeling system (Chapter 5).

Fig. 11.4 shows components of the prototype of the decision-modeling system. The core part of the decision-modeling system is implemented on the basis of Microsoft Excel, using Visual Basic for Applications. It provides functionality to execute decision modeling processes and maintains data needed for decision-modeling applications. Microsoft SQL Integration Services are used to channel data from data sources to the core part of the decision-modeling system, where these data are arranged in a format suitable for efficient use in decision-modeling applications. ARIS is used to develop a supply chain process model. Data about candidate units are extracted from this process model. The decision-modeling applications are LINGO and ARENA for supply chain configuration optimization and evaluation of the established configuration, respectively. The core part of the decision-modeling system invokes LINGO by using its application programming interface, and ARENA is invoked using its COM interface. Automated generation of optimization and simulation models is supported.

Fig. 11.5 shows a fragment of a user interface of the decision-modeling system. The right side of the figure contains the optimization model automatically generated from the input data on the basis of a predefined template. The main functions of the prototype decision support system are as follows:

- Development of descriptive supply chain configuration process models (Section 5.5.3)
- Extraction of data needed for decision-modeling purposes from the descriptive models, and maintenance of modeling method specific data (Section 5.5.3)
- Generation and execution of supply chain configuration optimization models (Section 5.5.5)
- Generation and execution of supply chain configuration simulation models according to the optimization results (Section 5.5.3)
- Accumulation of decision-modeling results in a format suitable for conducting further analysis (Section 5.5.6)

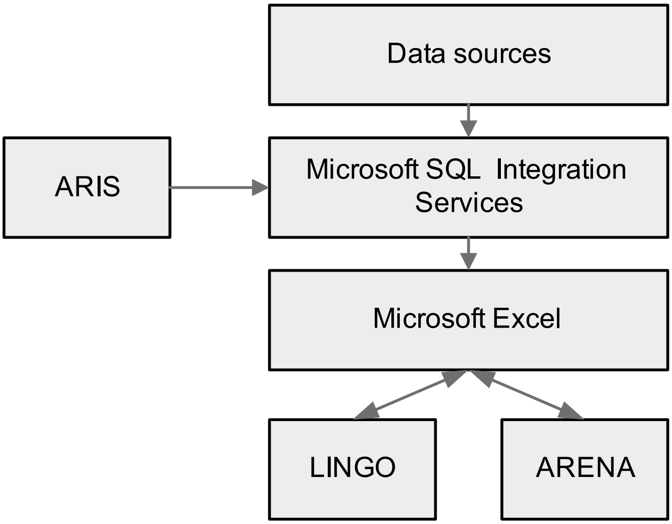

Fig. 11.4 Components of the prototype decision-modeling system.

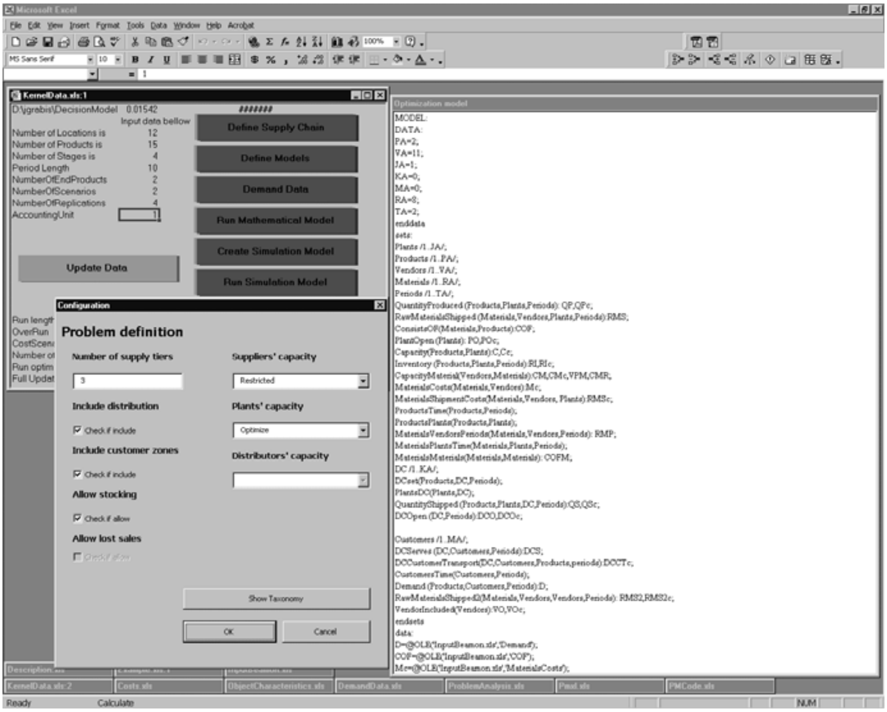

Fig. 11.5 User-interface of the prototype decision-modeling system.

This prototype decision-modeling system has been applied in several supply chain management studies reported in the third part of this book. The main advantages provided by the system include the following:

- The unified data source for supply chain configuration optimization, and simulation models in the form of the supply chain process model, which provides a business user-friendly description of the supply chain
- Reduced model development efforts and improved modeling consistency through automated model generation
- Tight integration between supply chain optimization and simulation models enabling comrehensive appraisal of supply chain configuration decisions
- Integrated environment for conducting supply chain configuration studies

11.6 Summary

The supply chain configuration decision-modeling system and the supply chain management information systems consist of a large number of interrelated components. Modern integration technologies are used to bind these components together in a flexible manner. Obviously, neither the decision-modeling system nor the supply chain management information systems are designed to specifically deal with the supply chain configuration problem. The objective is to design such an information technology solution that decision-modeling and implementation systems can be easily designed on the basis of available information technology infrastructure.

Further evolution of supply chain management information systems strongly depends upon the success of the service-oriented architecture. The service-oriented architecture becomes more influential as more vendors provide functionality of their enterprise and supply chain applications as services.

The evolution of service-oriented architecture enables easier incorporation of decision-modeling components into the supply chain management information system. While many decision-modeling applications already provide an adequate technological support for integration with other parts of the supply chain information system, computational inefficiency remains an obstacle for several complex decision-making problems, including the supply chain configuration problem. From the information technology perspective, this issue is becoming less of a concern as technologies such as grid-computing gain mainstream acceptance.

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Part III Applications

12. Review of Applied Studies

12.1 Introduction

The ultimate goal of the decision-making process in a supply chain is improving the efficiency of individual supply chain units, as well as that of the whole supply chain by implementing decision-making results. Additionally, decision-making efficiency substantially depends upon feedback obtained upon evaluation of implementation results. The supply chain configuration problem presents a major challenge in this regard. The road from decision-making to implementation of decisions made, and further to obtaining the feedback, is often very long. Additionally, decisions made often undergo a process of informal adjustment due to various managerial assumptions. Therefore, observation of results is blurred by many complicating factors. These issues create difficulties in the assessment of configuration decisions and, more generally, in assessing the real value of various decision-making methods and tools. Therefore, applied studies on supply chain configuration pose a high degree of interest.

The papers considering real-life supply chain configuration cases are categorized into two groups. Solving the particular supply chain configuration problem is the primary objective for papers assigned to the first group. These papers explicitly present the motivation behind the supply chain configuration initiative, provide sufficient details on models used and, most importantly, discuss implementation of configuration decisions. The second group of papers primarily explores theoretical aspects of the supply chain configuration problem, and case studies are included for illustrative purposes. This focus of papers on either applications or theory influences the level of details provided about particular case studies. Regardless of the group, a short description of the business problem, models used, and main results achieved are provided for each of the surveyed papers.

The objectives of this review of applied studies are an analysis of correspondence between theoretical aspects of the configuration problem solving and practical concerns, as well as illustration of the consequences of practical implementation of supply chain configuration results.

Section 12.2 reviews several papers, reporting detailed results of applied supply chain configuration studies. Section 12.3 provides a brief overview of other supply chain configuration-related applied studies reported in the literature. Observations drawn from the applied study are listed in Section 12.4.

12.2 Review of Extended Studies

In the literature review in Chapter 3, seven papers focusing explicitly on a particular case study and presenting detailed configuration results are identified. These papers are by Arntzen et al. (1995), Camm et al. (1997), Ross et al. (1998), Sery et al. (2001), Kirkwood et al. (2005), Laval et al. (2005), and Vila et al. (2006). We review below case studies presented in each of these papers.

Digital Equipment Corporation Supply Chain. Arntzen et al. (1995) have published one of the most renowned case studies in supply chain configuration at Digital Equipment Corporation — large multi-national company operating worldwide. The rapid advancement of technologies in the computer industry is identified as the main driver behind the need to reconfigure the company's supply chain. The main factors characterizing the decision-making landscape are:

- A shift towards focusing on core competencies and outsourcing the manufacture of common modules
- A need for accommodating many relatively small orders instead of a moderate number of large orders
- A need for centralized and coordinated supply chain wide decision-making mechanism

The mathematical programming model developed to deal with the configuration problem addresses many typical configuration issues, such as locating plants, selecting suppliers, and allocating products. International factors are deemed as highly important because of the multi-national character of the company. More specialized features of the model include representation of product delivery cycle time, accounting for taxes and duties, and using product weight as a factor limiting throughput capacity of distribution facilities. A specialized model-solving procedure is developed.

The model is used continuously to analyze the introduction of new products, the sourcing of typical components, and the performance of the whole supply chain. Different levels of product aggregations are used to conduct these analyses. More than 20 major configuration projects have been analyzed using the model over the span of six years.

Arntzen et al. (1995) also provide important insights in approbation of modeling results in practice. The model provided an 18-month plan for reconfiguring the network of manufacturing facilities. Implementation of the plan has resulted in the closure of half of the manufacturing facilities and over $360 million annual savings in manufacturing and logistics costs. However, information about costs associated with the implementation of the plan is not provided. Significant savings have been achieved by implementing other recommendations based on modeling results. An increase of production volume and improvement of customer service are also noted as important results of reconfiguration.

Procter & Gamble Supply Chain. Camm et al. (1997) describe a supply chain configuration effort at Procter & Gamble, in the consumer products industry. The company manufactures and sells its products worldwide, while the study presented focused on the North American market. Consolidation of company's global brands to benefit from economies of scale and elimination of nonvalue added processes are identified as two primary drivers of the reconfiguration effort.

The developed model is primarily used to allocate customers to particular distribution centers (DC) and to solve the product-sourcing problem. During the model development process, main attention has been devoted to the most important aspects and relatively minor issues were omitted. For instance, fixed costs for operating DC's were omitted because these are negligible compared to transportation costs. The model development process included phases of preselection of alternative locations for supply chain facilities and validation of results, where visualizations provided by the Geographical Information System (GIS) were of major importance in communicating results. The importance of obtaining good estimates of model parameters is stressed.

The comparison between a configuration built on the basis of existing facilities versus a clean sheet configuration was conducted. The net present value analysis showed that reconfiguring the supply chain is beneficial compared to establishing a new one. After two year of implementing modeling recommendations, 12 sites have been closed and annual savings have reached $250 million per year. The savings occurred in manufacturing costs while transportation costs increased. It is indicated that identification of savings directly attributable to use of quantitative decision-making is problematic.

CountryMark Cooperative Supply Chain. Ross et al. (1998) have developed and applied a supply chain configuration methodology based on identification of best practices. The case study analyzes CountryMark's oil distribution supply chain. The reconfiguration effort was initiated by changing demand patterns for products offered by the company. The supply chain consisted of 4 refineries, 100 bulk-plants and 210 tank-wagon vehicles delivering products to about 8,000 customers. The distribution of products from bulk-plants to customers was a primary focus of the study. The decision-making team started with gathering historical data and evaluating efficiency of bulk-plants and vehicles by using data envelopment analysis. These data were afterwards used in an integer-programming model used for assigning vehicles to bulk-plants. The model suggested closing about 20 percent of bulk-plants resulting in expected savings of 5 to 7 percent of the total cost.

BASF North America's Distribution System. Sery et al. (2001) redesign BASF supply chain in North America. Different chemical products are shipped to customers from 135 locations including plants, distribution centers and other distribution facilities. The shipment volume is 1.6 billion pounds and distribution cost is about $100 million annually. The existing supply chain structure is highly fragmented. The objective of the supply chain configuration effort is reduction of distribution costs and providing a sufficient service by consolidating the existing structure. This objective predefines two main performance indicators: service level and cost. The modeling process starts with data collection and aggregation. As a result, 25,000 SKUs are aggregated into 382 product categories, and 15,000 demand points are aggregated into 287 customer zones. The major emphasis is on compiling accurate transportation rates and timetables. A mathematical programming model is developed. It includes three tiers, starting with manufacturing plants down to customer zones. The first modeling step concerns the exploration of the existing configuration. The next two modeling steps are used to consolidate distribution centers. The model is implemented using a commercially available decision support tool. The duration of the configuration problem solving project is 14 months. Multiple alternative configurations are evaluated to describe the trade-off between costs and customer service. One of the configurations contains only 22 of the 86 initial distribution centers. The cost reduction is about 10 percent and volume delivered within one day increased from 77 to 90 percent. The model is also helpful in negotiating contract warehousing rates.

Hewlett-Packard (HP) Imaging and Printing Group Supply Chain. Laval et al. (2005), in their study of the HP supply chain, emphasize the importance of combining expert knowledge and formal mathematical modeling in making supply chain configuration decisions. The study considers HP's Europe, Middle East, and Africa manufacturing and distribution operations. The aim of the study is to reduce the number of contract manufacturers. Such a reduction leads to the need for restructuring the current network of distribution facilities, where finishing of products also takes place (see Feitzinger and Lee (1997) for a more detailed discussion of postponement in the HP' manufacturing supply chain). A greenfield approach (i.e., without fixing the location of existing facilities) to supply chain development is used to broaden the modeling perspective. The modeling process starts with defining and gathering the necessary data, with a major emphasis on determining the appropriate level of data aggregation and limiting the modeling scope to avoid extensive data requirements and model development costs. A large number of products are grouped into 20 categories and 10 possible locations for distribution facilities. Alternative distribution policies are explored (indirect, replenishment, and direct) for each customer zone. These policies are represented by assigning different values to a freight rate parameter. A modeling approach combining optimization and scenario analysis is used in decision making. The scenario analysis driven by inputs from experts is used to bridge the gap between management and decision analysts. Initially, the optimization model is used to generate scenarios, and subsequently a spreadsheet-based model is used for a detailed exploration of the proposed solution.

The modeling results suggested a configuration with three distribution centers and expected savings of $10 million, without compromising the service level. Understanding between the modeling group and management is identified as a key to successful quantitative decision making and is achieved by providing a high level of transparency of the modeling process.

Supply chain configuration problems at HP are also analyzed by Billington et al. (2004).

IBM Integrated Supply Chain. A multi-objective supply chain configuration decision support system allowing for probabilistic analysis is developed by Kirkwood et al. (2005). IBM supply chain accounts for $39 billion in annual expenses. Broadening geographical basis at all tiers, and increasing complexity, are characteristic features of this supply chain. However, the configuration decision-making objective is the thorough evaluation of separate configuration subproblems instead of an overall change in the supply chain structure. The decision support system is required to support multi-objective decision making and probabilistic analysis. It employs a value-focused approach (Keeney 1992) to evaluation of configuration decisions. A set of considerations (evaluation criteria) is compiled. Using quantitative evaluation scales, considerations are combined into an overall measure characterizing performance of an alternative supply chain configuration. The considerations are identified through interviews with domain experts. Sample considerations are inbound transportation costs, manufacturing-process quality, cycle time, supply chain geopolitical risk, physical infrastructure constraints, and continuity of IT systems and business processes. Importance weights are assigned to each consideration, and a way to measure these considerations is defined. Generally, measurements are made relative to the existing supply chain configuration. Given a specific supply chain configuration problem, an expected value for each consideration is determined using calculated 0.05 percent, median and 0.95 percent fractiles. The expected values are used to calculate the total expected value score for the proposed supply chain configuration. Sample configuration decisions evaluated using the decision support system are outsourcing of manufacturing of a particular product to a contractor, product allocation decisions, and material sourcing decisions. The decision support system is implemented in the spreadsheet environment.

Divergent Supply Chain in the Lumber Industry. A raw materials processing supply chain is analyzed by Vila et al. (2006). It resembles a generic methodology to design the production-distribution network of divergent process industry companies in a multinational context. It is applied in a case study conceived in partnership with three large Canadian lumber companies. The modeling context is defined by limited and regulated availability of raw materials and international factors. The model development process consists of five steps: 1) definition of product markets, sourcing, and planning horizon; 2) definition of product families and supply chain processes; 3) definition of potential resources; 4) definition of cost parameters; and 5) establishing a supply chain network. The planning horizon is up to two years and demand has seasonal pattern. The supply chain process model consists of multiple manufacturing steps and storage points. Potential sites for performing manufacturing operations and storage points are identified. These include both existing and new facilities. Transformation of the existing facilities is also possible. Technologies, which can be used at every site to perform specific activities are defined. A detailed table of costs, depending upon a state of facilities, is developed. For instance, the table shows that, closing of rented facility incurs the lease penalty cost, or transformation of the current layout in a company owned existing facility incurs setup, capital recovery, opportunity, and operating costs. Exchange rate, transfer prices, import duty rates and income tax rates are also considered. The managerial questions regarding supply chain configuration are formulated, and appropriate decision variables are defined. These include decisions on which potential sites to use, which activities to perform at selected sites, and flows among facilities and to customers. Dynamic aspects of the problem are also analyzed by considering temporary capacity shutdowns and inventory build up. Configuration decisions are made using a mathematical programming model. The supply chain configuration problem being studied includes a relatively small number of potential sites for facilities and 138 product families (the model has 227 binary variables) The model is solved using a commercially available solver and fine-tuning of optimization parameters able solver and fine-tuning of optimization parameters is performed to reduce computational time. The model suggested layout transformation at one facility and reassigning of activities at several other facilities. The seasonal inventory build-up for some products is also suggested. The expected increase of after-tax profits is 15.4 percent.

The applied studies surveyed above are summarized in Table 12.1 according to business drivers and objectives, model features, and implementation results.

Table 12.1 Summary of Selected Applied Studies

Source	Business Drivers and Objectives	Model Features	Implementation of Results
Arntzen et al. (1995)	Changing technologies	International factors	Closure of about half of the facilities. Savings up to $2 billions. Increased production volume and customer service.
Sery et al. (2001)	Supply chain consolidation	Data aggregation	Nearly 4 fold reduction of the number of facilities, 10percent cost reduction, improved delivery promptness.
Laval et al. (2005)	Reduction of the number of contract manufacturers	Combination of mathematical modeling and expert judgment	Reduced number of supply chain units and $10 million savings.
Kirkwood et al. (2005)	Broadening geographical basis at all tiers and increasing complexity	Value focused approach	Implemented decision-support system provides capabilities for answering different supply chain configuration related questions.
Vila et al. (2006)	Limited and regulated availability of raw materials	Divergent supply chain structure	Facility layout transformation and reassigning of activities. 15.4 percent expected increase of after tax profits.

12.3 Review of Other Applied Studies

A number of papers describe small-scale case studies and examples of application of developed models. Thomas and Griffin (1996) survey several early applied studies on strategic supply chain planning, which include some aspects related to the supply chain configuration problem.

Dogan and Goetschalckx (1999) develop a multi-period supply chain configuration model and a model-solving algorithm. The model is tested by applying it to reconfiguration of a supply chain for a company that supplies packaging to breweries and soft drink manufacturers. Optimization of inefficient transportation patterns is the main objective of the study. Demand seasonality substantially influences product allocation and inventory build-up decisions. Numerical studies conducted indicate that the proposed model-solving approach is suitable for dealing with real-life problems. Experimentation with the model shows that inventory build-up enables saving 2 percent of total costs. Therefore, integrating tactical factors in the configuration model can result in substantially improved decisions.

Arntzen et al. (1998) describe a redesign of 3M supply chains. Supply chain operations are executed in multiple countries across the world. Prior to detailed discussion of the case study, country-by-country variations of factors relevant to global supply chains are analyzed. Fixed costs are identified as relatively insensitive while other costs, especially labor, vary substantially. Complex patterns of international transportation rates are illustrated. Variations in duties, duty drawbacks, local trade, and taxation are also discussed. Out of the multiple 3M supply chains, the paper focuses on the consumer products and electrical products supply chains. The consumer products supply chain is reconfigured because of a shift in demand from developed countries to developing countries. The modeling process starts with data gathering and preliminary data analysis, which shows that the imbalance between production capacity and demands is expected to occur. The model used for supply chain configuration is adopted from the study by Arntzen et al. (1995). The initial modeling run, using the fixed supply chain network indicates expected growth of logistics costs. Supply chain redesign leads to cost reduction by 17 percent, which does not meet the reduction target of 21 percent. The reduction is achieved by closing several plants. Further reduction is possible by improving the manufacturing process. The model is also used to elaborate investment plans in existing manufacturing facilities. Excess capacity and insufficient competitiveness are also reasons for restructuring the electrical products supply chain. The model is used to create a time-cost trade-off curve to balance cost and responsiveness objectives. Multiple scenarios are evaluated using the model. The scenario-based analysis is aimed at understanding factors influencing supply chain performance (for example, what is the impact of taxes). The model indicates opportunities for reducing costs by 10 percent and improving business cycle-time by 28 percent. A new manufacturing strategy is established on the basis of modeling results. This clearly indicates relationships between supply chain configuration and other managerial problems.

Tsiakis et al. (2001) develop a comprehensive supply chain configuration with particular emphasis on scenario-based representation of demand uncertainty. The supply chain produces 14 types of products, operates three manufacturing plants, and sells products in 18 customer zones across Europe. The supply chain configuration problem is ascertaining the location of distribution centers and warehouses given a set of candidate locations. A similar model, which also accounts for taxes and intellectual property, is developed by Papageorgiou et al. (2001). The application of this model is demonstrated by an example, which is derived from a real life supply chain configuration situation in the pharmaceutical industry.

Jayaraman and Ross (2003) develop a simulated annealing-based methodology for solving large-scale supply chain design problems. Applicability of the methodology is analyzed by testing the computational efficiency in the case of realistic input data from the retail industry.

An illustrative plant and distribution center location problem in the presence of governmental subsidies is described by Kouvelis et al. (2004). The supply chain investigated sells a single product in 40 countries in different regions. The decision-modeling problem is location of plants and distribution centers. Additionally, results suggest a type of subsidies to be requested. Detailed demand and cost data are provided. The configuration problem is initially solved for a base scenario without governmental subsidies. The second scenario includes governmental subsidies covering fixed investment costs. The subsidies provided leads to the relocation of manufacturing plants. The plant relocation, in turn, alters the structure of the distribution network. Subsidies and relocation have enabled an increase in expected profit by about 7 percent for the given network. Another scenario investigates tax incentives. It is shown that the larger the difference between rates of low-tax and high-tax countries, the more centralized the network structure becomes. Configuration decisions are also affected by governmental trade agreements and local content requirements.

Ingalls and Kasales (1999) develop a supply chain simulation tool for Compaq, a major computer manufacturer now merged with HP. This tool is designed for dealing with strategic decision-making problems with regard to supply chain dynamics. Evolving demand forecasts are identified as the most important dynamic factor. Simulation models are designed using eight standard structures — customer, company, inventory, manufacturing, geo (a sales location), product divisions, products, capital, and countries. The authors emphasize that the simulation model provides results on such important performance measures as service level and inventory obsolescence. The results obtained show that there is a trade-off between these performance measures and profitability.

Abrahamsson and Brege (1997) conduct qualitative analysis at five medium-size manufacturing companies, which have implemented structural changes in their supply chains, such as the reduction in number of production units, suppliers, and distribution facilities; centralization of administration, and decentralization of sales organization. Consolidation of distribution facilities is identified as the most often considered structural change. Information technology has been identified as a major enabler of these changes. Introduction of structural changes have resulted in 30-50 percent distribution cost reduction and improved customer service.

The problem initialization step of the supply chain configuration process is explored by Harland (1996) in investigating the supply chain of UK National Health Service. This supply chain accounts for about $8 billion in annual spending and includes about 25,000 suppliers and 450 customers (e.g., hospitals). The strategic analysis is applied to identify the supply chain structure for different groups of products, and to determine key elements of supply chain strategy. Such an analysis is needed because of extreme complexity and the size of supply chain.

A similar complexity is also encountered in automotive supply chains. Therefore, Choi and Hong (2002) perform mapping of real-life automotive supply chain networks to understand their structure and characteristics. Networks are characterized by formalization, centralization, and complexity. Particular supply networks are center console supply chains for Honda Accord, Acura CL/TL, and DaimlerCrysler Grand Cherokee vehicles. Information about the supply networks is gathered through interviews with representatives from automotive Original Equipment Manufacturers (OEM) and their suppliers, document and data analysis, and observation data. The formalization is characterized by a level of documentation of supply chain management procedures. The centralization is described by a level of collaboration between OEMs and their suppliers, as well as OEMs' impact on upstream supply chain management decisions. Different centralization patterns are encountered. In the centralized case, there is high reliance on a few core suppliers. In the less centralized case, OEMs do not influence configuration decisions made by their suppliers. The complexity is characterized by such measures as total number of entities (varies from 41 to 76) and distance between network nodes. From the reconfigurability perspective, suppliers switching cost is an important parameter. Values of this parameter vary substantially from case to case. Relationships between OEMs and their suppliers concerning profit sharing are also analyzed. Propositions about relationships among the analyzed network characteristics are made.

Senter and Flynn (1999) discuss structural changes leading to consolidation in the general structure of automotive supply chains, while Potter et al. (2004) investigates the evolution of the steel supply chain towards more integrated structures.

Gupta et al. (2002) report implementation of a distribution network design decision support system at Pfizer, manufacturer and distributor of pharmaceutical products. The decision support system is needed to support continuous updating of supply chain information and to enable rapid decision making. A comprehensive database is a core part of this system. The distribution network optimization model is one of several modules. The decision support system supports both optimization and simulation-based approaches to network evaluation. Commercially available simulation and optimization tools are used in implementation.

Graves and Willems (2005) develop a dynamic programming model for choosing supply chain partners at each stage of product manufacturing. The model is applied in diagnostic studies at a major computer manufacturing company. The supply chain configuration process is driven by a predefined target manufacturing cost. Alternatives are described by lead time, direct cost added, and several intangible factors. Initially, alternatives are narrowed by selecting those satisfying the intangible factors that are often expressed qualitatively. Further selection is based on minimizing the total supply chain cost, which is also influenced by lead time as a determinant of safety stock requirements. A presented sample case considers supply chain design for a notebook computer.

Eskigun et al. (2005) investigate computational aspects of a large distribution network configuration for an automotive company. Decision-making objectives are location of distribution centers, selection of transportation modes, and selection between direct shipments and shipments through distribution centers. These decisions are made to minimize total distribution costs, as well as delivery lead time. Incorporation of delivery time leads to nonlinearity, which is averted by linearization using additional binary variables. Therefore, the developed mathematical programming model includes several millions of binary variables. A Lagrangian relaxation model-solving procedure is developed and extensively tested. The average computational time over scenarios analyzed is 10.1 hours. The sensitivity analysis illustrates the trade-off between costs and delivery lead time and its impact on supply chain configuration (for instance, if the lead time dollar value is high, direct shipments are used more often and fewer distribution centers are open).

A simultaneous product and supply chain design is investigated by Lamothe et al. (2006). The proposed approach is applied for product and supply chain design in the automotive industry. Initially, a generic product bill-of-materials is created. A supply chain configuration mathematical programming model incorporating this generic bill-of-materials is elaborated. The model contains facility opening and resource build-up decision variables. In the case presented, a wiring harness supplier chooses a product design out of 48 alternatives to minimize the total supply chain costs. The main point of interest is location of labor intensive subassembly processes in low-cost countries. In the three-tier supply chain, three to four alternatives exist for each manufacturing tier. The modeling results confirm the usefulness of locating the subassembly processes in low-cost countries.

Ding et al. (2006) use a simulation-based optimization approach to optimize supply chain configuration with respect to both profitability and delivery responsiveness. The model is applied to study supply chain configuration problems in the automotive and textile industries. The automotive case study considers multiple modifications of a single product produced at three plants and distributed through five distribution centers. Decisions concerning the closing of manufacturing facilities and distribution centers are made along with decisions on inventory policies to be used and determination of inventory management parameters. The results obtained indicate that the configuration depends upon a significance level attached to the optimization criteria (i.e., more plants are used to achieve higher responsiveness while fewer plants are used to boost profitability).

12.4 Summary

The surveyed case studies have a large diversity of business drivers and objectives. Also a large variety of features are considered in supply chain configuration models. None of the case studies has reported performance decline after implementing supply chain configuration decisions.

In a majority of the cases, supply chains are reconfigured rather then established from scratch. However, decision makers at least initially follow the clean-page approach to avoid getting stuck on inefficient solutions. Reconfiguration generally has led to reduction in number of supply chain units, especially in distribution tiers. Improved information exchange capabilities are a major enabler of this change (Geoffrion and Powers 1995).

The trade-off between manufacturing costs and transportation costs is one of the key drivers behind many case studies. Three important structural changes currently influence this trade-off: 1) rising fuel costs; 2) emergence of new consumption centers; and 3) the eventual increase of labor costs in developing countries. There was a tendency to relocate manufacturing to countries where labor and transportation costs were comparatively lower. Increasing fuel costs might affect this balance. However, reopening of plants to bring manufacturing closer to points of consumption in many cases can be an expensive option. In the long-term perspective, similar problems might arise due to rising manufacturing costs in developing countries. This can be offset to some extent by serving newly emerging points of consumption, as well as by another wave of relocation. The importance of the most upstream or raw materials supply tier is likely to increase as prices for commodities steadily rise.

The reported case studies often tend to avoid building large-scale optimization models because of time restrictions and data availability. The former restriction should be addressed by the scientific community to provide more general solution procedures for supply chain configuration models. The latter restriction can be addressed by achieving better integration between decision modeling and other data processing processes throughout an enterprise and a supply chain.

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13. Applications in Automotive Industry

13.1 Introduction

The automotive industry is one of the most economically important and technologically complex industries. The importance of supply chain configuration is high in the automotive industry. Supplier consolidation, manufacturing flexibility, and modular assembly are major factors influencing configuration decisions. This chapter discusses the impact of these factors on the configuration decision-making process. Specific cases on information modeling and the configuration of flexible supply chains under demand uncertainty are analyzed.

Section 13.2 discusses the general characteristics of the automotive supply chain and reviews related research on automotive supply chain management and configuration. The information modeling case study is presented in Section 13.3. The flexible supply chain configuration case is described in Section 13.4, and Section 13.5 provides a short summary.

13.2 Review of Problem Area

The main characteristics of automotive supply chains and literature on automotive supply chain configuration are analyzed before exploring the particular case studies.

13.2.1 Automotive Supply Chain: Trends, Issues and Opportunities

The automotive industry is characterized by a high degree of technological sophistication. Therefore, companies in this industry have focused on their core competencies to preserve high efficiency. Over the decades, complex supply chain structures have evolved. Technology-related aspects also determine that long-term partnerships are important in automotive supply chains, making them a typical case for supply chain configuration studies.

Automotive supply chains evolve around Original Equipment Manufacturers (OEM) (Fig. 13.1). Competitive pressures and mergers have reduced the global number of automotive OEMs to fewer than 20 companies. OEMs assemble vehicles and deliver them to dealers. The assembly is performed in a complex network of manufacturing plants. These plants do not merely put together vehicles but form a multi-tier manufacturing system including the manufacturing of such parts as exterior sheets and engines. The majority of product development work is done by OEMs.

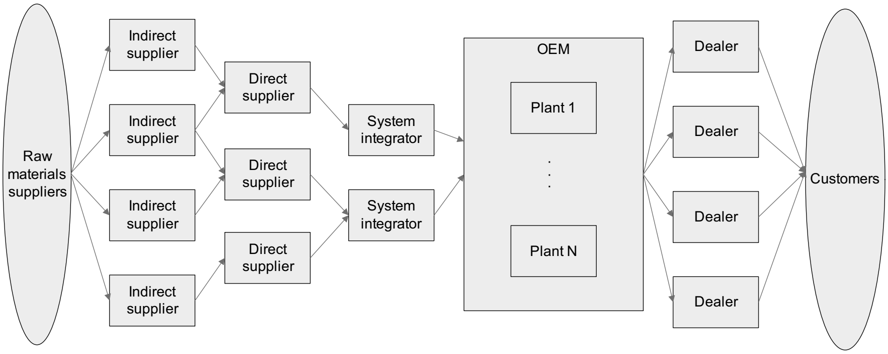

Fig. 13.1 A general automotive supply chain.

Consolidation has also affected the supplier tier, which includes the following groups of suppliers (Senter and Flynn 1999):

- indirect or lower-tier suppliers — manufacture parts sold to upper-tier suppliers (e.g., steel)
- direct-suppliers — manufacture parts sold directly to OEMs (e.g., tire manufacturers)
- system integrators — provide complex and often self-engineered modules directly to OEMs (e.g., dashboard manufacturers)

This grouping does not include suppliers of raw materials, which usually are also tightly integrated into supply chains by long-term contracts. However, they differ from other suppliers because they are less involved in product-engineering activities and many of the materials can also be purchased in the spot market.

Each company can belong to different groups of suppliers depending on the product. The system integrator tier has undergone a major change in its role in the automotive supply chain. A few decades ago, OEMs performed many functions of current system integrators. After OEMs outsourced the manufacturing of many parts, system integrators initially maintained strong relationships with their parent company. Currently, despite numerous obstacles, system integrators supply to multiple OEMs.

Many non-automotive suppliers (for which the automotive industry is not the primary market) have entered automotive supply chains as the variety of options offered to customers increases. That is especially apparent with electronics suppliers.

Although automotive supply chains are established around a single OEM, pressure to reduce costs prompts several major companies to form long-term or temporary alliances, such as an alliance between General Motors Corporation and FIAT. These alliances have relatively minor impact on supply chain configuration at the assembly tier although they affect suppliers upstream a supply chain.

Although the automotive industry traditionally has had a strong focus on engineering and manufacturing, the customer tier has been gaining an ever increasing role. Many automotive companies have found themselves in difficulties because of the inability to respond to customer preferences. Achieving flexibility without compromising efficiency is among top priorities. Lean manufacturing coupled with automated manufacturing systems are among the main approaches in following this priority (Adler et al. 1999).

A shift of focus towards the customer tier is also influenced by the mass customization phenomena, which implies pairing of mass production efficiency with customer demand for customized products. Option-based customization dominates in the automotive industry (MacDuffie et al. 1996), implying that customers can configure vehicles by selecting from a range of available standardized options.

The distribution tier of the automotive supply chain remains comprised of dealerships associated with major automotive manufacturers. OEMs have largely abandoned direct sales plans, although they continue expanding the use of the Internet as a means to better connect with their customers by providing online vehicle configuration capabilities. The European Commission's competition rules have made it possible for dealers to sell products manufactured by multiple companies, although that is yet to have a significant impact on vehicle distribution. Sales to repair shops and other aftermarket consumers also playing an important role and can occur at any supply chain tier.

The leadtime of establishing an operational vehicle assembly plant is 5-10 years, and the expected operations time is at least 20 years to recover the initial investment. More importantly, closing existing facilities is complicated by political matters. Therefore, reconfiguration of automotive supply chains has a relatively small number of degrees of freedom. However, automotive manufacturers still attempt to bring their manufacturing facilities closer to their primary markets, which have a tendency to expand geographically. The opening of new facilities is mainly addressed on a case-by-case basis, and is governed by a large number of nonengineering factors such as incentives offered by local governments. The main configuration decision variables at the assembly tier represent product-to-plant allocation decisions and limited capacity expansion/subtraction decisions, rather than location or relocation of plants. Reconfigurability opportunities mainly arise at the indirect and direct suppliers tiers.

13.2.2 Literature Review

The OEM-dominated power structure of automotive supply chains influences the focus of research studies usually considering such aspects as production planning in multi-tiered manufacturing networks, supplier selection and evaluation, and providing product variety to customers. The high maturity of the automotive industry implies that configuration efforts are mainly concerned with modification of existing supply chains rather than establishing new structures. Two recent aspects of the configuration problem are: 1) the drive for system-wide flexibility, and 2) expansion in emerging markets.

Production planning in multi-tiered automotive manufacturing systems at the final assembly level has been investigated. Inman and Gonsalvez (2001) develop a decision support system for the tactical-level product to manufacturing line assignments. The system combines formal mathematical decision making with inputs made by a human decision maker. A similar system is developed by Alden at el. (2002). Its primary objective is allocating a new product to a specific plant by matching product characteristics and the capabilities of each manufacturing facility. Gnoni et al. (2003) combine optimization and simulation for monthly scheduling of production at interrelated manufacturing plants of a system integrator. The model developed accounts for demand uncertainty. Lower tiers of the manufacturing system, within the boundaries of OEMs, are analyzed by Bhaskaran (1998). A simulation model for investigation of efficiency of supply chain scheduling is developed. It focuses on the manufacturing of exterior sheets from raw materials. The overall account of problems in general manufacturing networks is given by Shi and Gregory (1998). The main problems identified include dealing with different stochastic factors, accounting for resource constraints, and achieving flexibility and agility. Mathematical programming and simulation are main techniques used for decision making. These studies relate to the supply chain configuration problem by considering the product-to-plant allocation problem. Hahn et al. (2000) focus on synchronization of production schedules at the operational level at Hyundai Motor Company. They also reveal the complexity of automotive supply chain. There are close to 3,000 first and second-tier suppliers, and nearly 1,000 end-customer serving locations in Korea alone. The distribution network is structured to help meet high delivery promptness and low end-product inventory targets.

As indicated above, a majority of automotive supply chain reconfiguration activities occurs at the supply tiers and is concerned with supplier selection and evaluation. Ittner et al. (1999) empirically analyze interactions between manufacturers and suppliers. The findings indicate that engaging in strategic partnerships is governed by a number of nonprice factors, such as certification and collaborative work. Sanchez and Perez (2005) survey a sample of automotive suppliers to identify the impact of flexibility on performance. The automotive industry is the largest provider of customized products directly to customers, even though the degree of customization varies greatly. Alford et al. (2000) argue that optional customization is the most appropriate type of customization for the automotive industry. Relationships with suppliers, characterized by emergence of system suppliers, are put forward as an important aspect for enhancing customization capabilities. The authors indicate that many suppliers tend to work in close proximity to OEMs and just-in-time deliveries are frequently used. MacDuffie et al. (1996) describe the automotive assembly process, including installation of custom options. Improved manufacturing technology that allows for shorter set up times and manufacturing flexibility are mentioned as the main operational enablers of customization. Just-in-time deliveries are argued as, not only reducing inventory, but also speeding up the assembly process by delivering components in the right assembly order.

Given that the basis of configuration decision making in automotive supply chains is relatively rigid, significant attention is devoted to improving supply chain characteristics within the existing framework. Strategic flexibility is one of the configuration-related solutions for improving supply chain performance. Koste and Malhorta (1999) identify several strategic manufacturing flexibility dimensions, including product-mix flexibility, volume flexibility, expansion flexibility, and new-product flexibility. Product-mix flexibility allows for relatively inexpensive shifts from the production of one product to another in response to changing customer preferences. Flexible product-to-plant allocation is one of the main enablers of product mix flexibility. Volume flexibility allows for changing production volumes. Strategic-level enablers of volume flexibility include maintaining slack capacity and resource sharing (Jack and Raturi 2002). In the supply chain context, it is important to ensure that flexibility requirements are met across the supply chain. Graves and Tomlin (2003) analyze the product-to-plant allocation problem in the automotive supply chain.

Products are allocated to plants in a manner that ensures product-mix flexibility at the final assembly tier as well as at supply tiers.

13.3 Information Modeling Case

13.3.1 Case Description

This case study considers the application of information modeling driven development of manufacturing supply chain simulation models. As indicated in the previous section, automotive supply chains are characterized by a high degree of complexity. These supply chains have developed over a long time period and include many horizontal and vertical layers. It is difficult to gain an overall understanding of all supply chain operations, and many different decision-making problems that arise in the supply chain are often addressed on a case-by-case basis. In this situation, it is difficult to obtain the data necessary for decision making, ensure consistency of models, and avoid extra model development efforts. The information modeling discussed throughout the book is well-suited for dealing with such problems. This study focuses on one separate part of the enormous automotive supply chain, namely the manufacturing of exterior sheets. While information modeling is the focus in this section, original business drivers for the study are the reduction of purchasing costs of raw materials (i.e., steel), identification of steel processing bottlenecks in the multi-tiered system, and reduction of outbound logistics costs. Use of information modeling within this problem framework is advocated because of expected usage of multiple decision-making models, including mathematical programming, simulation, and economical modeling methods.

The model development process follows the integrated simulation model building schema described in Chapter 9, where a supply chain simulation model is automatically generated on the basis of supply chain information models. The initial information is given as a database of products, manufacturing units, and resources used, while demand information is provided in spreadsheets. Additional information is obtained in interviews with domain experts. As a result, the object model of the manufacturing supply chain is developed. This model is used as the basis for automated generation of the supply chain simulation model and specification of modeling technique-specific data model.

The investigated steel processing manufacturing supply chain involves external suppliers, manufacturing plants, and both internal and external customers. The system is expected to meet strict delivery time requirements, which often force the plant to use a premium-cost transportation mode. Each plant processes up to a thousand products and their components using more than a hundred work stations. The stamping plant consists of blanking, pressing, and assembly departments. The blanking department cuts the raw steel into rectangular pieces. Work centers at this department are relatively flexible to process different products, and set up times are insignificant. The pressing department stamps the blanks into parts. Work centers at the pressing department are partially specialized. There are substantial set up times. Welding and other operations are performed on stamped parts at the metal assembly department. Work centers at the assembly department are specialized, where set up times are smaller than at the pressing department. Raw materials are supplied according to long-term contracts. However, to accommodate demand spikes, some raw materials and components are also sourced in the spot market.

Production is initiated according to a production schedule, elaborated according to customer demand. It specifies the quantity of products to be produced and resources (i.e., work centers) to be used in the production of these products. The production schedule is implemented in the rolling horizon environment. The resource assignments can be dynamically changed to adjust for the actual state of the system. The majority of costs in the system are fixed. Variable costs are the inventory holding cost and the transportation cost. The transportation cost consists of the cost for a standard mode of transportation and the cost for a premium mode of transportation. The standard mode of transportation is used for on-time deliveries. The premium mode of transportation is used if deliveries of ordered products are delayed. The stochastic factors in the system are set up times, processing times, and resource failures. Additionally, external demand used to elaborate the production schedule is stochastic. However, the demand for the current production period is fairly stable.

13.3.2 Data Models

Both general and modeling technique-specific data models are constructed. The general data model is developed using information available in relational databases characterizing the structure of the manufacturing supply chain (models of systems storing these data are not available), demand information provided in spreadsheets, and expert interviews. The modeling technique-specific models are developed to enable efficient data exchange between data sources and the modeling package used. In this case, ARENA is used for simulation modeling purposes.

General Model

The steel processing supply chain involves five subjects defined in the generic data model, namely *Customer*, *Product*, *Supplier*, *Plant* and *Resource*. The steel processing supply chain data model inherits these subjects and some adjustments are made. Resources are associated with particular manufacturing facilities represented by the *Plant* class. They possess limited flexibility (i.e., a resource can be used for processing more than one product, but not all products). This property could be represented by using either product-specific capacity or an indicator parameter. The latter alternative is used to improve readability of the model. There is also a most preferable work center for each product in the system. An additional parameter is introduced to represent this feature.

Fig. 13.2 shows the class diagram of the steel processing supply chain. The object model of the steel processing supply chain is developed on the basis of the class diagram. It provides a complete representation of the supply chain structure.

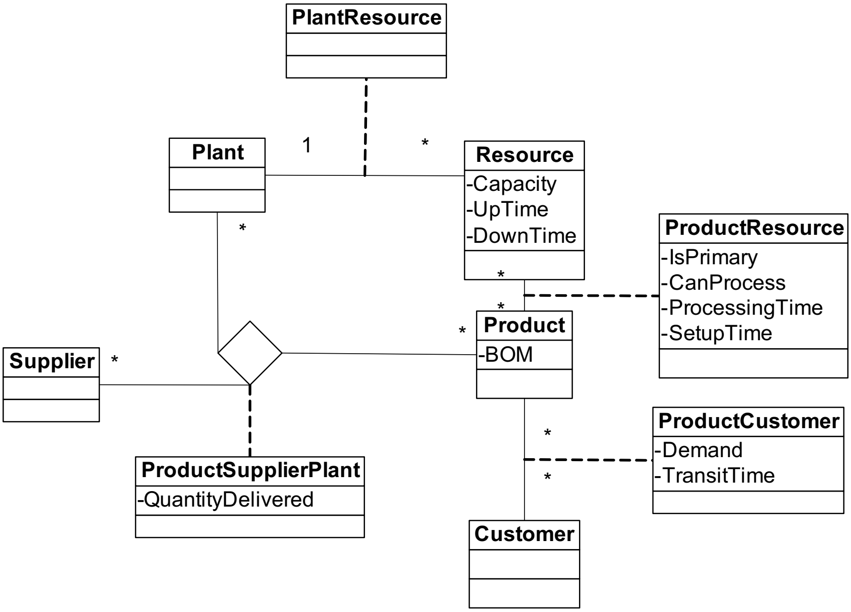

Fig. 13.2 The class diagram of the steel-processing supply chain.

Modeling Technique-Specific Data Model

The modeling technique-specific data model organizes data describing the system in a manner suitable for the simulation model building and execution of the simulation model. These data describe the structure of the system, the properties of production units and products produced, and the relationships of the system with its external environment, including customers. For purposes of execution of the simulation model, structuring of the data should ensure quick access of necessary data items.

The modeling technique-specific data model consists of multiple tables containing information about the structure and operational characteristics of the system. The structure of the system is described by bill-of-materials, product to plant and resource to plant assignments and other structural parameters. The structural information is also represented using several specialized tables that are designed to facilitate data retrieval by the simulation model. The operational characteristics describe processing time, set up time, and transportation time. The data model is implemented as a Microsoft Excel workbook. Table 13.1 lists tables included in the data model. The concept of a product and manufacturing facility pair is introduced to distinguish between the same products processed at different manufacturing facilities. In the class diagram developed in the previous subsection, pairs can be identified following associations between manufacturing facilities, products, and resources. Time parameters are specified using a string describing a probability distribution.

The elaborated data model representation allows describing a wide range of manufacturing networks. The main characteristics of these networks are as follows. A product can be produced in several units and it can be a component of several products produced in different units. A resource belongs to one particular unit (as specified in Table *ResourcePlant*). It has a finite capacity. Several products may share the same resource, and a product can be produced by using alternative resources as, specified in Table *PairResource*.

Data conversion from data sources to the modeling technique-specific model is also performed. The data conversion process is illustrated by an example. The raw data source contains data fields characterizing throughput for each resource in items per hour and a corresponding efficiency measurement in percent. The converter uses these data fields to determine processing time for each resource in hours per item (this value is used by the simulation model) and places the derived data item in the appropriate position of the data model.

Table 13.1 Tables of the Data Model

Table	Type	Description
Definitions	S	Dimensional data (e.g., number of products) and modeling control data (e.g., number of replications)
Demand	O	Customer demand per week
ProductsPlant	S	Shows products produced at each manufacturing facility
Pairs	S	Defines pairs
PairDestinations	S	Defines possible destinations for a product from the pair
ResourcePlant	S	Shows resources at each manufacturing facility
PairResource	S	Shows which resources can be used to process a product from the pair
BOM 1	S	Bill-of-materials, indicates components of each product by component number
BOM 2	S	Bill-of-materials, indicates items of each component needed
SetupTime	O	Set up time for products according to resource used
ProcessingTime	O	Assembly time for products according to resource used
TransTime	O	Transportation time for products according to destination
ResourceFailure 1	O	Time between two consecutive resource failures
ResourceFailure 2	O	Resource downtime duration

NOTE: Type S Refers to Structural Data and Type O Refers to Operational Data

13.3.3 Generated Simulation Model

The object model and the modeling technique-specific models are used to develop a simulation model. The simulation is automatically generated on the basis of a predefined template by a model generation module, as described in Chapter 9. The model generation module is modified to introduce some features specific to the steel-processing supply chain. Particularly, modifications for representing machine breakdowns are introduced. Details of the model generation are described in Chandra and Grabis (2003).

The generated model is the conventional ARENA model. A user can edit the model, use the standard output reporting features and perform other manipulations. At the beginning of the simulation, modeling data from the modeling technique-specific data model are loaded in the simulation model. Before loading, the intermediate data have been created by converting the data model tables from the Excel format into a text format, because ARENA reads text files much faster than Microsoft Excel files. Some of the data tables are loaded into ARENA arrays for access by

ARENA objects, while others are loaded in Visual Basic arrays for access by control functions.

The generated simulation model represents the structure of the manufacturing supply chain. Afterwards, it is used to identify bottlenecks in the system and for pilot testing of manufacturing scheduling algorithms (Chandra and Grabis 2003). Using the common information basis for the model development enables further development of different variations of optimization models.

13.4 Stochastic Optimization Case

The presented case study represents the supply chain configuration problem encountered by the Ford Motor Company. This configuration problem is driven by the company's strategic objective of becoming more responsive to customer demands. Strategic-level manufacturing flexibility is set as one of the founding pieces of this strategy. The presentation is based on studies also reported in Chandra et al. (2005) and Chandra and Grabis (2005).

13.4.1 Business Objectives

The goal of the supply chain configuration effort is to improve customer service and the company's profitability. The specific business objectives of the study are:

- To determine the most appropriate strategy for achieving manufacturing flexibility
- To test alternative product-to-plant allocation schemas
- To determine capacity requirements both at the assembly and supply tiers
- To evaluate the robustness of proposed supply chain configurations with regard to market conditions and regulatory requirements

13.4.2 System

The system consists of multiple assembly plants and parts manufacturers (Fig. 13.3). The parts manufacturers are represented by parts supply capacity. The planning problem is to determine both assembly and supply capacity requirements to maximize profit. The planning horizon is five years. Product-mix flexibility is achieved by having some plants capable of producing several products (but not all plants can produce all products). Out of the volume flexibility enablers discussed, overtime, slack capacity, and flexible product-to-plant assignments are relevant to this problem. The slack capacity is used both at the assembly and supply stages. Volume flexibility is affected by two problem-specific factors; namely, marketing cost and industry-wide regulatory requirements.

The developed extension is aimed to reveal an impact of product variety on the value of flexibility. It explicitly distinguishes different configurations of products, and customer demand is given for a specific configuration. Products and their configurations differ from one another by their profitability and contribution to regulatory constraints. To keep the optimization model manageable, only one part (which is of most interest and referred here as an A part) is treated separately. This part has multiple models. A customer demands a product configuration with a specified model of the A part installed. However, the customer choice is limited because not all models of the part are available for all products. Requirements for other parts are represented using a set of common parts and a set of unique parts needed to assemble a product.

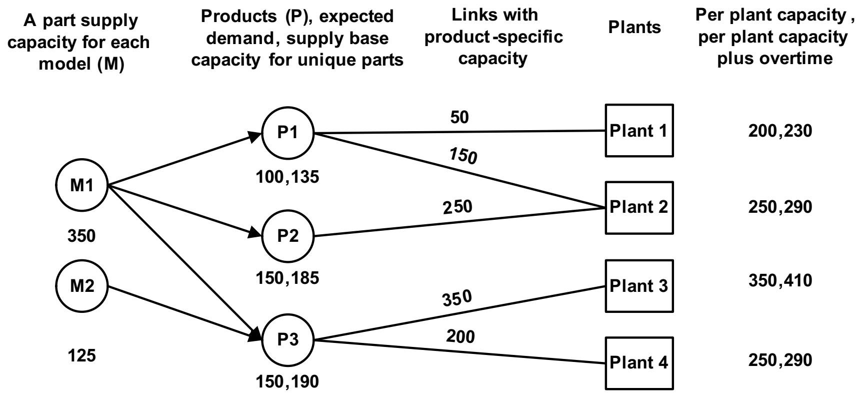

Fig. 13.3 A fragment of the manufacturing supply chain.

13.4.3 Model

The mathematical formulation of the decision-modeling problem is given in the following subsection. A specialized genetic algorithm-based model-solving approach is also proposed to address computational complexity of the developed mathematical model.

Model Formulation

Mathematically, profit is calculated as a function of income from product sales and expenses due to assembly plant capacity investments and maintenance, parts supply capacity investments (split among investments in common parts capacity, unique parts capacity, and capacity for the A part), and marketing. The optimization problem is solved subject to demand satisfaction, assembly capacity restrictions, supply capacity restrictions and legislative constraints.

The mathematical expression for maximization of expected profit is given in Eq. (10.1) in Chapter 10 (a detailed description of the objective function and constraints is given in the Appendix of this chapter).

Optimization of the capacity adjustment coefficients is performed without knowing the future demand in a deterministic sense, but rather by obtaining the best average result over an ensemble of demand scenarios. For each demand scenario, another optimization step is performed to allocate existing capacity so as to produce an optimal sales decision variable $\mathbf{Q}$. Stochastic demand for each product at the given time period is expressed using Eq. (10.2).

Model Solving

The complexity of the optimization problem (Eq. 10.1) prevents its analytical evaluation. Therefore, a simulation-based optimization approach is employed. For purposes of simulation-based optimization, the expected profit is expressed as

$$E\left[P\right] = R^{-1}\sum\nolimits_{r=1}^{R} P(r) \tag{13.1}$$

where $P(r)$ is profit at the rth replication and R is the number of replications. The optimization steps below are shown in Fig. 13.4:

1. The optimization procedure takes fixed product-to-plant assignments and the level of part commonality as inputs.
2. An optimization algorithm generates values of $\boldsymbol{\delta}$, λ, and ν that specify the production system capacities for the coming evaluation. The simulation is initialized using a current capacity profile defined by the capacity adjustment coefficients.
3. The external demand for vehicles is generated by sampling from the demand distributions defined by expression (Eq. 10.2).
4. The optimization problem (Eq. 10.1) is solved using the generated demand and capacity adjustment coefficients from Step 2. $\mathbf{Q}$ contains the only decision variables. Under these circumstances, the optimization problem reduces to a simple linear programming problem. The

optimization result is the allocation of existing production capacity to manufacturing vehicles demanded by consumers.
5. The profit under the current demand realization is calculated. If the simulation is not completed, the algorithm returns to Step 3.
6. The expected profit for the given capacity profile is calculated. If the optimization is not completed, return to Step 2.
7. The model selects the maximum expected profit and the capacity profile yielding this value.

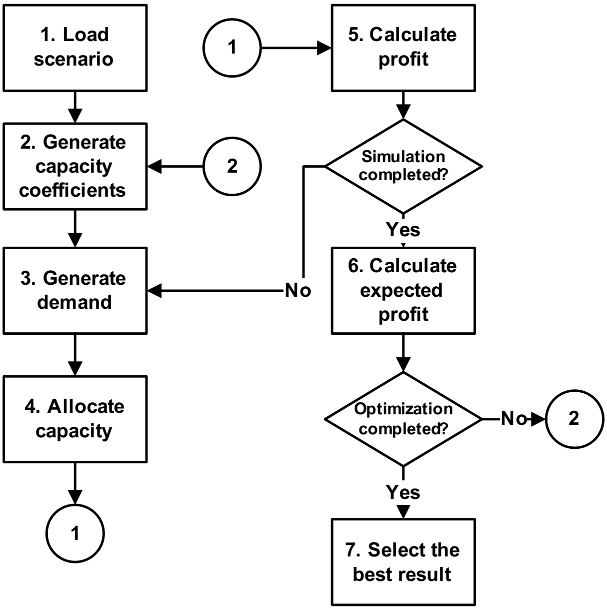

Fig. 13.4 The model-solving procedure.

The linear-programming model used at Step 4 can be modified to include additional constraints. This should be done with care in order not to increase computational time substantially.

Optimization is performed using the commercially available RISKOptimizer 1.0, which uses a genetic algorithm to select new values of decision variables (Step 2). Random variables (in this case, external demand) are generated using Latin-Hypercube sampling. Generation of correlated samples is supported, and used to ensure some autocorrelation in demand strength for a given vehicle, as well as autocorrelation of the industry-demand variable I_t. In Step 4, the linear programming optimization is performed using LINGO, which is integrated with the RISKOptimizer using a custom-built program.

The described model solving procedure also yields the profit distribution, which is valuable for quantification of decision-making risk.

13.4.4 Results

The model is used to analyze the performance of the flexible manufacturing chain under various scenarios. This section reports selected studies on the impact of product variety on the value of flexibility. If profitability of products remains constant (i.e., product variety only allows preserving the market position), product variety is expected to reduce the total profitability of the system because higher demand uncertainty requires an increase in slack capacity at the assembly level, and pooling of parts capacity is possible to a lesser degree. On the other hand, in the case of higher variety, the manufacturing system improves the ability to allocate overloaded resources to manufacturing of more profitable products and their configurations.

The experimental factors used are level of product variety and flexibility of product to assembly plant assignments. Two levels of product variety considered are:

1. All products are assembled using the same model of the A part — no configurations are offered (denoted as V1).
2. At least two models of the A part can be used to assemble each product — at least two configurations of each product are available (denoted as V2).

The two levels of flexibility in product-to-plant assignments are standard (S) and higher (H) levels. In the case of the standard level, slightly more than half of all vehicles can be produced at two plants. The higher level represents a flexibility level where every vehicle can be produced at more than one plant. The ratio of common parts 0.25, and the regulatory restrictions are imposed.

The value of flexibility is determined using the expected profitability of the optimized manufacturing system. Volume flexibility is described by a function relating the expected profitability to the total demand. Product-mix flexibility is described by a distribution of the sales-to-demand ratio (i.e., the ratio between units manufactured and units demanded by customers). If this distribution is uniform, then the manufacturing system is capable of producing all products at the similar rate. However, this distribution is also affected by other factors such as the availability of unique parts. The experimental procedure is organized similarly, as described in Chandra et al. (2005).

Table 13.2 reports the value of flexibility depending upon the level of product variety and the level of flexibility in product-to-plant assignments. The increased product variety results in significant loss of profitability because capacity slack needs to be maintained for each model of the A part (the model does not include an eventual cost penalty for offering low variety). There is some evidence that having more flexible product-to-plant assignments is more beneficial in the case of larger product variety. That is indicated by a slightly quicker relative increase of profitability when moving from the S flexibility level to the H profitability level in the case of V2.

Table 13.2 The Value of Flexibility According to Product Variety and the Level of Flexibility of Product to Assembly Plant Assignments

Level of Flexibility	Level of Product Variety	$E[P]$
S	V1	9564 (±125)
S	V2	8954 (±113)
H	V1	9922 (±118)
H	V2	9358 (±121)

Measurements of volume flexibility are shown in Fig. 13.5. The volume flexibility curve (it is obtained by polynomial smoothing of original data) shows that the system is expected to operate profitably for a majority of plausible demand scenarios. The profitability falls below zero if the total demand is lower than approximately 670,000 units. This margin is relatively stable for all experimental cases If the total demand is low profitability is higher in the V2 case, especially, if the standard product-mix flexibility level is considered. That can be explained by the impact of the supply capacity slack for unique parts (not shown) because it is higher for the V1 case and results in more substantial losses in the case of low total demand.

In the case of S and V1, the distribution of the sales-to-demand ratio has the average value equal to 0.9 and the standard deviation equal to 0.1. In the case of S and V2, the distribution of the sales-to-demand ratio has an average value equal to 0.88 and the standard deviation equal to 0.11. That indicates that the higher customer service can be achieved if less variety is offered (again, there is no penalty for not providing variety). The product-mix flexibility is also higher as indicated by the lower standard deviation of the distribution. The shortage of particular models of the A part demanded by customers causes this reduction of product-mix flexibility achieved in the case of V2. Therefore, volume flexibility represented mainly by supply slack capacity is also an important enabler of product-mix flexibility.

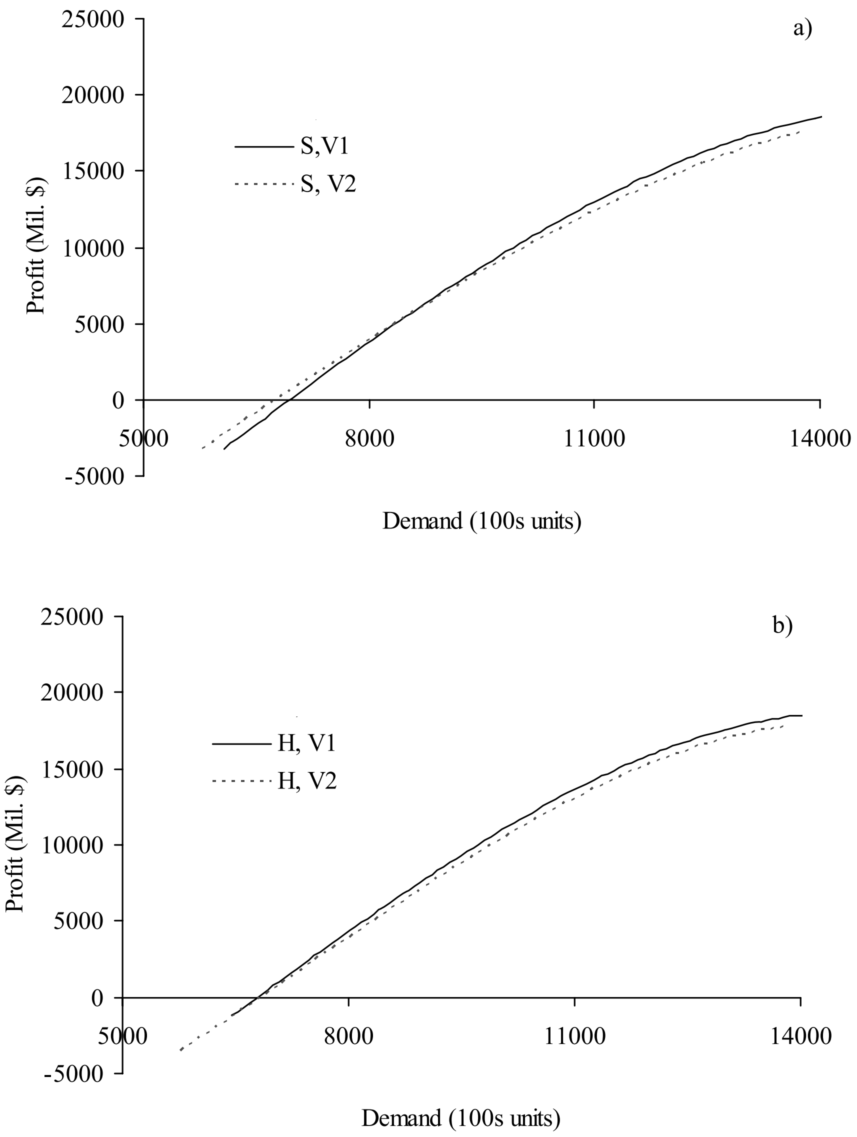

Fig. 13.5 Measurements of volume flexibility, (a) for S flexibility level, and (b) for H flexibility level.

Some of the main findings reported here, and in Chandra at el. (2005), indicate that the gain in profits going from the least flexible scenario to the most flexible is approximately $1.1B for the 8-plant, 14-vehicle system. These results are obtained by taking in account regulatory requirements on fuel efficiency, over five years of simulated production, and a 25 percent discount rate net present value. This level of profit increase is > $300M/year on average without discounting. The profit increases that can be achieved in other cases are still quite substantial, from a few to 17 percent, depending upon the specific scenario. However, as has been noted before, these increases must be modified to account for costs associated with, for example, implementing flexibility. The experimental results show that increasing levels of flexibility, as well as part commonality, yield improvements in production profitability. On average, gross vehicle sales are also improved with greater flexibility or commonality. The results provide no strong evidence for an interrelation of the impacts of flexibility and part commonality.

Increasing product-mix flexibility marginally affects the level of total demand at which production becomes profitable, under the specific scenarios considered. Meanwhile, increasing product-mix flexibility improves profitability given a constant total demand, most significantly if the total demand is larger than the system's capacity.

It has been shown that within the model, setting capacity at an optimal (appropriate) level leads to substantial improvements in the profitability of the flexible system compared to the case with levels of slack capacity currently used to accommodate hit products and years with very high industry sales. However, it must be noted that the model has a number of simplifications and modifications of the real-world planning problem to make it tractable. It is certainly expected to be the case that changes in the level of flexibility and/or commonality will likely require changes in old approaches to setting capacities. The model points out that with increases in mix flexibility and part commonality, capacity in the supply base for the remaining unique parts for high-profit vehicles should be increased.

13.5 Summary

The current state of the automotive supply chain can be characterized as a transition from strongly established legacy supply chains to more flexible reconfigurable supply chains. This transition period is relatively long, and to some extent it is difficult to define its border because of different impacts on each of the major companies. To reduce legacy costs, the North American companies faced by competition from overseas are undergoing general restructuring at the strategic management level. A successful completion of this process would allow for designing more dynamic supply chain structures. Japanese manufacturers have attempted to strengthen their local presence in the American and European markets. Major changes in designing and managing automotive supply chains could be brought by increasing demand and production in emerging markets. However, these developments are characterized by a high degree of uncertainty.

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Appendix

Notation

Indices *i*, *j*, *l,* and *t* refer to particular product, plant, model of the A part, and year, respectively. *M*, *N, L* and *T* denote the number of products, the number of plants, the number of models for the A part, and the planning horizon, respectively.

α_t - discount factor in year *t*

p_{il} - profit for product $\{i,l\}$ (i.e., product *i* with model of the A part *l*)

φ_{il} - contribution to regulatory constraints for product $\{i,l\}$

Q_{ilt} - quantity of the product $\{i,l\}$ produced and sold in year *t*

Q'_{ijlt} - quantity of the product $\{i,l\}$ produced at the plant *j* in year *t*

D_{ilt} - demand per product *i* in year *t*

$\bar{D}_{ilt}$ - yearly average demand per product *i* in year *t*

γ_1 - unique parts supply capacity build-up cost per capacity unit $\gamma_1 < \gamma_2$

γ_2 - plant capacity build-up cost per capacity unit

γ_3 - yearly capacity maintenance cost per capacity unit $\gamma_3 < \gamma_1$

γ_4 - overtime cost per capacity unit used $\gamma_4 < \gamma_3$

γ_5 - savings for avoiding capacity build-up per capacity unit $\gamma_5 < \gamma_2$

C_i^1 - supply capacity of unique parts per product *i*

C_j^2 - capacity per plant *j*

C_j^4 - overtime capacity per plant *j*

C_{ij}^5 - product-specific plant capacity for the product *i* at the plant *j* (shows how many capacity units at this plant are available for this product regardless of model of the A part used), $<= C_j^2$

C_l^6 - the A part supply capacity per model l

U_{jt} - units produced in overtime per plant j in year t

F_1 - a function describing marketing costs per unit, function of actual demand/forecast demand

C^* - initial capacity

β - proportion of common parts

κ_1 - common parts supply capacity build-up cost per capacity unit, $\kappa_1 < \gamma_2$

κ_2 - the A part supply capacity build-up cost per capacity unit $\kappa_1 < \gamma_2$

Optimization Model

$$Z = \max_{\boldsymbol{\delta}\in\boldsymbol{\Lambda},\lambda\in\boldsymbol{\Lambda},\nu\in\boldsymbol{\Omega},\varphi\in\boldsymbol{\Phi},\mathbf{Q}} E\left[P\right]$$

$$P = \sum_{i=1}^{M}\sum_{l=1}^{L}\sum_{t=1}^{T}\alpha_t p_{il} Q_{ilt} - \sum_{i=1}^{M}\sum_{l=1}^{L}\sum_{t=1}^{T}\alpha_t F_1\left(Q_{ilt}/D_{ilt}\right)Q_{ilt}$$
$$-\left(1-\beta\right)\gamma_1\sum_{i=1}^{M}\delta_i\bar{D}_i - \gamma_2\left(C^* + C^{3-}\right) - \gamma_3\lambda\sum_{j=1}^{N}\sum_{t=1}^{T}\alpha_t C_j^2 - \gamma_4\sum_{j=1}^{N}\sum_{t=1}^{T}\alpha_t U_{jt}$$
$$+\gamma_5 C^{3+} - \beta\kappa_1\nu CPC - \kappa_2\sum_{l=1}^{L}\phi_l\bar{D}_i$$

$Q_{ilt} \le D_{ilt}, i = 1,...,M, l = 1,...,L, t = 1,...,T$ — production-demand balance

$\sum_{l=1}^{L} Q_{ilt} \le C_i^1, i = 1,...M$ — unique parts supply capacity requirements per product

$Q_{ilt} = \sum_{j=1}^{N} Q'_{ijlt}, i = 1,..., M, l = 1,...L, t = 1,...,T$

$C_i^1 = \sum_{l=1}^{L}\bar{D}_{ilt} + \delta_i\sum_{l=1}^{L}\bar{D}_{ilt}$ — adjusted unique parts supply capacity

$\sum_{i=1}^{M}\sum_{l=1}^{L} Q'_{ijlt} \le \lambda C_j^2 + U_{jt}$ — production-capacity balance

$U_{jt} \le \lambda C_j^4$ — overtime limit

$\sum_{l=1}^{L} Q'_{ijlt} \le \lambda C_{ij}^5$ — plant capacity requirements per product

$C^* = \sum_{j=1}^{N} C_j^2$ — initial system's capacity

$C^{3+} = \max\left(C^* - \lambda\sum_{j=1}^{N} C_j^2, 0\right)$ — positive difference between initial and adjusted capacities

$C^{3-} = \max\left(\lambda\sum_{j=1}^{N} C_j^2 - C^*, 0\right)$	negative difference between initial and adjusted capacities
$CPC = C^* + \nu C^*$	adjusted common parts supply capacity
$\sum_{i=1}^{M}\sum_{l=1}^{L} Q_{ilt} \le CPC, t = 1,...,T$	availability of common parts
$\sum_{i=1}^{M} Q_{ilt} \le \phi_l C_l^6, l = 1,...,L, t = 1,...,L$	availability of the A part supply capacity
$FE \le \sum_{i=1}^{M}\sum_{l=1}^{L} \varphi_{il} Q_{ilt},\ t = 1,...,T$	regulatory requirements, where FE is a threshold required

14. Application in Retail: Locating a Distribution Center

Oksana Soshko, Yuri Merkuryev, and Martins Chakste

14.1 Introduction

Retailers are dominant players in many supply chains today. To stay competitive, their supply chains must meet high customer service requirements as well as achieve significant cost efficiency. The retailer faces the challenge of managing the distribution of hundreds of thousands of stock-keeping units (SKU) from many manufacturers and distributors (for example, a medium-size fashion store handles about 4,000 SKUs). At the same time, retailers face pressure from competitive forces, industry consolidation and increasingly fastidious consumers. Other problems are interpreting large data, reducing lead-times, forecasting, eliciting the best efforts from employees, etc.

Effective retail supply chain management revolves around balancing the three key dimensions of inventory, cost, and service. Managing these trade-offs efficiently can result in supply chains that improve business performance and drive competitive advantage.

This chapter describes an applied retailing supply chain reconfiguration study in the Baltic region of the European Union (EU). It highlights important aspects faced by companies redesigning their supply chains in response to changing operational environments and issues relevant to direct sales of high-end consumer products. The main general problems of supply chain configuration illustrated by this case study are internationalization, with an emphasis on the impact of removing trade barriers and consolidation of supply chain operations.

A continuous facility-location approach is used to make configuration decisions. Simulation is used as the main modeling tool. It provides managers with an experimental platform that allows them to make management decisions and to experience their results in a way that is close to a real world situation. The simulation-based analysis conducted addresses supply chain management concerns, both at strategic and tactical levels. The special purpose supply chain simulation tool LORD is used in this case study.

The following section discusses the general aspects of the supply chain configuration problem in the retail industry. To introduce methods and tools used in the applied study, Sections 14.3 and `4. 4 discuss the facility location problem and special purpose simulation modeling tools, respectively. The applied study is presented in Section 14.5. Summary of the case study and obtained results is provided in Section 14.6.

14.2 Retail Supply Chain

A retail tier links customers and vendors in many supply chains. The retail supply chain is a supply chain where the retail tier assumes the focal position. It receives individual orders from customers (Fig. 14.1). These orders are satisfied either from the inventory held at retailing locations or by direct shipments from manufacturing or wholesale tiers. In the latter case, the retailer avoids holding inventory (Netessine and Rudi 2006). This structure is mainly used by Internet-based and catalog retailers (Maltz et al. 2004). The retail tier and the wholesale tier can be at least partially controlled by a retailing company, while direct shipments are handled by third party logistics providers. Retail companies also often establish tight relationships with manufacturers by ordering products carrying the retailer's brand names. Major retailers often supplement traditional retailing with the use of Internet and catalogs as alternative distribution channels. However, traditional retailing still dominates these alternative distribution channels (Grau 2006). The manufacturing and wholesale tiers are composed of a large number and variety of facilities. Persistence of relationships between supply chain partners vary between long-term partnerships to loose associations. For instance, Amazon.com uses leased distribution centers that are located with regard to customer concentration zones and tax rates, and are opportunistic in exploring options for relocation and expansion. Christopher et al. (2004) describe apparel retailers Zara and Benetton, which achieve a high degree of agility by contracting with a large number of small manufacturers capable of adjusting quickly to changing customer demand. The retailing tier is not uniform. Different types of retailing establishments include department stores, discount stores, and specialty stores. Management of retail supply chains involves dealing with such problems as demand planning, product pricing, facility management, inventory management, transportation, and handling of returns (Hugos and Thomas 2005). Supply chain configuration is also one of the key issues to be addressed.

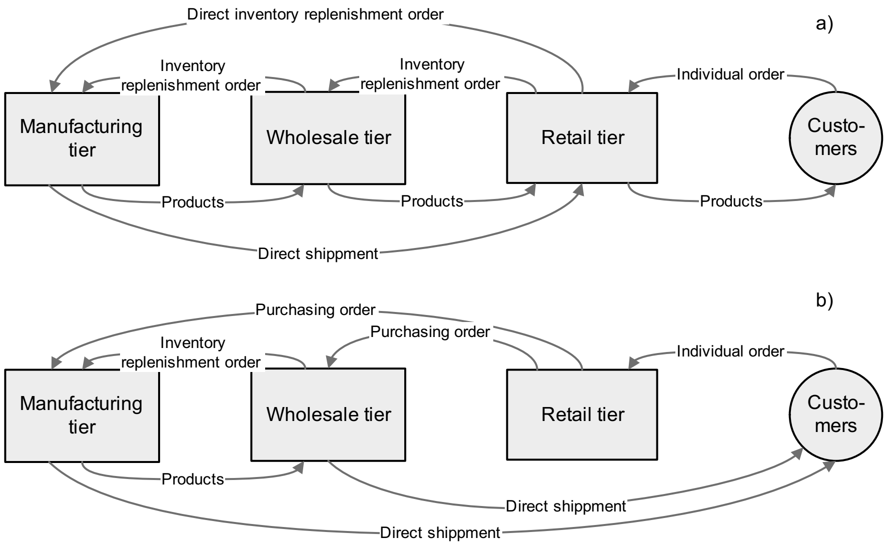


Fig. 14.1. The retail supply chain with (a) inventory held at the retail tier and (b) direct shipments from the upstream tiers to customers.

Major retailers such as Wal-Mart and Home Depot have experienced massive growth in the last two decades. These retailers determine developments and trends in retail supply chain management. Their supply chains are characterized by a large number of customers, a wide supply base, large product variety, use of multiple distribution channels, employment of modern information technology solutions, and internationalization. Wal-Mart serves 176 millions customers weekly and operates more than 2500 retail units in more than 15 countries. Product variety can exceed 100,000 (and even larger variety is offered through the Internet) and the number of suppliers are several 10,000s (data according to *www.walmartfacts.com*). Although Wal-Mart is the biggest retailing company, there are many other retailing companies operating on a comparable scale (Chain Store Age, 2006). Additionally, retail supply chains operate in a highly competitive environment and face elevated customer expectations concerning price, delivery responsiveness, and other service characteristics. That contributes to the resulting complexity of retail supply chains.

To handle the complexity, the structure of retail supply chains assumes a variety of forms and undergoes continuous evolution. Supply chain configuration techniques and policies include strategic partnerships, use of third-party logistics services, advanced inventory management strategies, supply chain consolidation, and integration.

Third-party logistics providers in retail supply chains perform all or part of inventory management and product delivery functions. Bolumole (2001) identifies the following drivers behind choosing third-party logistics services: 1) complex supply chain due to fragmented supply basis, 2) increasing volume of product returns, 3) need to improve service, 4) cost benefit through larger volumes, 5) access to existing infrastructure, 6) simplification of supply chain processes, 7) consistent delivery times, accuracy, and efficiency, and 8) reduced overheads. Complexity reduction, service improvement, cost benefits, and delivery consistencies are especially important in the retail industry. Additionally, third-party logistics allows exploiting new distribution channels and expanding geographical reach.

Advanced inventory management strategies, such as vendor managed inventory and quick response (Simchi-Levi et al. 2003), determine the nature of relationships between suppliers and retailers. The shift of power from suppliers to retailers has led to difficulties in balancing the interests of all supply chain members (Blatherwick 1998). For instance, the survey conducted by Birtwistle et al. (2006) indicates that suppliers perceive the quick response strategy more as a strategy for retailers rather than for the whole supply chain. Retailers can put pressure on suppliers because of their large share in suppliers' total sales. For instance, Mattel Corporation’s sales to Wal-Mart exceed 20 percent of their sales total (Ramaswamy 2004).

Supply chain consolidation occurs at several dimensions. Retailers attempt to control product variety by brand consolidation and alternative distribution channels for slow moving products. Although consumers demand variety, companies have recently adopted a more critical view on achieving an appropriate level of variety, and some consolidation of product lines have taken place (Thonemann and Brandley 2002). Takeovers and mergers at both retail and supply tiers is another consolidation dimension. This phenomenon has been particularly well-observed in food retailing (Wrigley 2001). Analysis of consolidation in the UK food retail sector by Hollingsworth (2004) suggests that expected future consolidation might lead to adverse competitive consequences.

Advanced information technologies are a major enabler of supply chain integration. High information availability allows dealing with the retail supply chain complexity and dynamic supply chain reconfiguration (Kent and Mentzer 2003; Witte et al. 2003; Samli et al. 2005). Adoption of information technology solutions is often driven by big retailing companies (Kinsella 2003). Radio-frequency identification (RFID) is one of the latest developments aimed at improving data processing and reducing costs

(Vijayaraman and Osyk 2006). However, its wide-spread adoption and positive returns on investment are yet to be achieved.

Evaluation of supply chain configuration decisions is made subject to the main performance criteria used in the retail industry: 1) price, 2) delivery responsiveness, and 3) quality. Configuration decisions are also tightly interrelated with inventory management and transportation. Chopra (2003) states customer service criteria influenced by the structure of the distribution network are response time, product variety, product availability, customer experience, order visibility, and returnability. Network designs such as manufacturer storage with direct shipping, distributor storage with package carrier delivery, manufacturer/distributor storage with costumer pickup, and retail storage with customer pickup are analyzed with regard to these criteria depending upon product characteristics (e.g., low/high demand, variety, value, supply basis). This way retail storage is preferable for high-demand products while direct shipments from either manufacturers or distribution facilities are preferable over low demand and large variety products.

Additionally, configuration decisions are also made with regard to continuous expansion of the retail industry. The expansion manifests as opening of new facilities, where facility location plays an important role, and internationalization of retailing supply chains. Coe and Hess (2005) analyze international expansion of large retailing companies. The Swedish company IKEA stands out among others with operations in 43 countries and its share of international sales reaching 92 percent of the total. The authors also indicate that recent expansion is directed to emerging markets in Eastern Europe and East Asia. The expansion also has profound impact on supply chain configuration. Supply chain reconfiguration activities due to the international expansion identified by Coe and Hess (2005) are centralization of procurement, logistical upgrading, supply network shortening and new intermediaries, imposition of quasi-formal contracts, and development of private standards. Arrival of global retailers influences local suppliers by providing them growth opportunities, or on the contrary, exposing them to increased foreign competition. Procurement is centralized by replacing per-store procurement systems with the distribution center model used in established markets. Direct relationships are established with large suppliers while specialized wholesalers are used for specific products. The consolidation of procurement is usually accompanied by the adoption of advanced logistical technologies.

The applied study presented in this chapter investigates internationalization and consolidation aspects of retail supply chain configuration.

14.3 Supply Chain Reconfiguration and Facility Location

In this chapter, we study a supply chain reconfiguration case at the Zepter's Baltic subsidiaries. The company is interested in conducting a network analysis and looking for an ideal location for its distribution center in the Baltic.

The redesign of existing logistics networks and supply chains notably became a topical problem in the Baltic region with the removal of trade barriers after joining the European Union. In this aspect, facility relocation is a strategic planning problem of vital concern for companies whose supply chains are placed in the Baltics, which is a small but quickly growing and strategically well-positioned region in the European Union. It has a developed transport infrastructure with two European corridors (Tallinn-Riga-Kaunas-Warsaw in the Northern-Southern direction, and Kiev-Minsk-Vilnius-Klaipëda in the Eastern-Western direction), international airports, ice-free ports, and developed railway and road networks. These features will undoubtedly facilitate increasing transit flows in the future, as well as provide the impetus for developing industrial facilities in the Baltic region. Logistics facilities for production and warehousing are concentrated in industrial territories of the largest cities in the Baltic region – Vilnius, Kaunas, Klaipëda, Riga, Tallinn, Pärnu, and Tartu. Riga has the most favorable geographical location and biggest industrial concentration in Latvia, and is becoming a logistic center of the Baltic region. Companies are eager to explore new business optimization opportunities and have multiple choices for locating their facilities.

Facility-location is a strategic problem that affects many tactical decisions, such as inventory policy and transportation. In a large retail chain, the location of the distribution centers and retail outlets influences the effectiveness of the overall operation. Illustratively, adding additional warehouses will affect transportation costs by reducing transportation links and total transportation distance. For example, the average distance from warehouses to consumers in the United States can be reduced two-fold by increasing the number of warehouses from one to two (Van Landeghem 2006). Centralized distribution systems can decrease safety stock, increase the service level, and decrease overhead costs. These savings must be balanced with a potential increase in customer leadtime and transportation costs. Thus, optimizing the location of facilities can significantly reduce product cost and hence increase its competitiveness.

A range of facility-location methods at company's disposal is discussed before presenting the case study.

14.3.1 Facility Location Techniques

The facility-location problem generally is formulated using given sets of demand points and locations where facilities may be opened. The goal is to find locations to open facilities and assign demand points to facilities such that the total cost of opening facilities and of connecting demand points to facilities is minimized.

A number of location methods have been developed to support analysts in decision-making about facility location. Exact methods (both mathematical programming, and heuristics) and simulation are usually mentioned as basic techniques for the facility-location problem (Simchi-Levi et al. 2003).

Exact Methods

Examples of exact methods are linear programming, mixed-integer linear programming, and dynamic programming, which remain the dominant methods for solving the location problem. An advantage of exact methods is the fact that they guarantee the optimal solution from a mathematical point of view. The main disadvantage of this is that all inputs (such as demands, distances, and transportation times) are taken as known quantities, and outputs are specified as one-time decision values. While such problems can provide planners with insight about general location selection, they are not able to adequately model the uncertainties inherent in making real-world strategic decisions. But, in real life, costs, demands, transportation times and other inputs to classical facility location models may be highly uncertain. Therefore, models for facility location under uncertainty are developed. Among different optimization techniques, stochastic programming is the main approach to optimization under uncertainty. It is a fast developing area of optimization and mathematical programming. Heuristic methods are also related to exact methods because mathematical programming usually is a part of the solution procedure for real-world facility location problems. Generally, there are many principles or concepts that contribute to reducing the average time needed to search for a solution. When applied to location problems, good solutions are quickly obtained from numerous alternatives. Although the heuristic methods do not guarantee that an optimum solution has been found, there are several reasons why these are used for facility-location, such as benefits of reasonable computer running time and memory requirements, good representations of reality, and a satisfactory solution quality.

Different models are used depending upon the characteristics of the facility-location problem. Ballou (1999) identifies the following characteristics:

- Driving force makes analysts determine one or more factors that are more critical than others. For example, for retail service location, revenue generated by a location is often the determining factor. Accessibility to the site is the primary location factor for service operations, such as hospitals and banks. Another important way to measure the effectiveness of a facility location is by determining the average distance traveled. Developing optimization models for solving location problems, those factors are usually input into objective functions
- The number of facilities divides a problem of location into two groups: single-facility location and multi-facility location. Locating one facility is a considerably different and simpler problem than locating many facilities at one time
- Discreteness of the choices allows dividing facility-location problems into continuous location and discrete location. The first one means that every possible location along a space continuum could be selected as a solution to the location problem. Discrete location allows the decision maker to select a location from a list of possible choices that have been preselected for their reasonableness
- In the context of time horizon, location methods can be static or dynamic. Static methods find locations based on the data for a single time period, such as one year. However, locations planning may cover many years at once, especially if facilities represent a fixed investment and the costs of moving from one location to another are high. Dynamic methods are methods that handle multi-period location planning

Owen and Daskin (1998) review location problems as a critical element of strategic planning and classify location models according to static, dynamic, and stochastic nature of the time component.

- Static models take constant, known quantities, such as inputs and derive a single solution to be implemented at one point in time. The solution will be chosen according to one of many possible criteria, as selected by the decision maker. Most of the static models are expressed mathematically, and could be solved using a mixed-integer linear programming technique. Following are several examples:
  - Median and P-median problems are aimed at minimizing the total weighted travel distance (distance between demand nodes and facilities with the associated demand quantity) between demands and facilities
  - Covering problems are focused on minimizing the cost of facility location such that a specified level of coverage is obtained. The set covering problem allows examining how many facilities are needed to guarantee a certain level of coverage to all customers. These models

are known as location set covering problems. The maximal covering problem seeks to maximize the amount of demand covered by locating a fixed number of facilities
  - In P-center problems, locating a given number of facilities in such a way that minimizes coverage distance requires coverage of all demands. These problems are also known as a minimax problem, because the objective is to minimize the maximum distance between any demand and its nearest facility
- Dynamic location problems deal with the uncertainties inherent in facility location related to planning for future conditions. This model is much more complicated because decision makers must not only select robust locations which will effectively serve changing demands over time, but they must also consider the timing of facility expansions and relocations over the long term.
- Stochastic location problems deal with uncertainty due to the limited knowledge of model input parameters. This class of the location models can be divided into two basic approaches:
  - Probabilistic approach considers the probability distributions of the modeled random variables
  - Scenario planning approach considers a generated set of possible future variable values

Snyder (2006) has studied stochastic and robust facility-location models. The area of real-world applications, presented in the paper, include allocation of a consumer electronics company, an ambulance center, fire station location, hazardous waste treatment facilities, and different logistic supply chain facilities. The conclusion is that the available stochastic optimization technology has become extremely powerful, but it has only begun to be used in models for facility location. There is great potential for solving complex, realistic problems by leveraging the available and emerging stochastic programming technology.

Although systems of facilities usually exist as hierarchical systems, location problems have been mostly studied for single-level systems. Only several papers recognize a hierarchy in the facility-location context, but they do not consider hierarchical features explicitly. Sahin and Sural (2005) present an illustration of real-world hierarchical systems that have been considered in the location analysis, and then provide a formulation of well-known location methods in the context of hierarchy. Production-distribution systems are usually considered a multi-level system. It should be noted that hierarchical design is critical for production-distribution systems (also for retailer) because most of the distribution networks could be considered as multi-echelon systems. The authors mark out two basic distinct mixed-integer programming models in the hierarchical facility location literature: flow-based and assignment-based formulations. In flow-based formulations, demand flows from facilities at one level to the next level of the hierarchy. The latter formulation allocates demand to facilities at each hierarchical level, as might be the case in assignment problems. Both formulations are commonly employed for p-median location problems, and covering problems as well.

Besides well-known location models based on mathematical programming, specialized procedures like conventional heuristic methods are also developed for hierarchical location problems. For example, Sun (2005) presents a tabu search heuristic procedure to solve the uncapacitated facility location problem. Gill and Bector (2005) formulate a problem of warehouse location and retailer allocation in supply as a 0-1 integer programming model and present a heuristic algorithm for solving a large scale problem consisting of two steps. First, the warehouse locations are chosen from the available set of candidate warehouse locations, which can cover the retail locations based on a per-assigned maximum threshold distance. Then the retailers are allocated to these chosen locations in a manner that the distance of a retailer to its assigned warehouse is minimal.

The case study described in this chapter deals with the single facility location problem. An exact center-of-gravity method is used to find a placement for Zepter's distribution center for one of the location scenarios. It is the simplest way to find a solution for the single-facility location problem, when it is necessary to find a location for a single plant, terminal, warehouse, or retail/service point (Ballou 1999). The main idea of the method can be formulated as follows: given a set of points that represent source points and demand points along with their volumes that are to be moved to/from a facility of unknown location and their associated freight rates, calculate a point where the facility should be located by minimizing the total transportation costs. It should be mentioned that many location models are based on the implementation of this Newton's law of gravitation. For example, in Bruno and Improta (2006), this principle is used for evaluating a location for a new university site. Drezner and Drezner (2006) use this principle within a classic p-median problem. The authors propose that the gravity p-median problem differs from the classical problem implementation due to the assumption that users divide their patronage among all facilities according to the gravity rule (in classic models there is an assumption that each user is serviced by the closest facility).

After finding the best location for facilities, the expedient step is to evaluate a supply chain operation with a new solution. For this purpose, a simulation could be used very successfully. It can also be applied in cases where finding a new location by using mathematical methods is a complicated task due to various reasons. For the case study mentioned, simulation is used for evaluating the performance of alternative supply chain configurations.

Simulation

Due to many and influential sources of uncertainties and stochastic variations within supply chains, simulation became a highly effective tool to support engineers and managers in decision making. Many companies are currently using simulation for supply chains very successfully (for example, Flextronics, which owns the simulation tool SimFlex, has successfully used and validated it in over 150 projects during the last 3 years).

Matwijec and Buxton (1999) call simulation the *friend of change* because it recognizes uncertainty and makes allowance for it. The simulation is defined as a process of creating a computer model of a real or proposed system and conducting experiments of the model to describe observed behavior and predict future behavior before investing any time or money. Four main simulation activities are defined in (Groumpos and Merkuryev 2000):

- Specifying operation algorithms (i.e., how the modeled system operates)
- Developing a computer program that realizes this algorithm (i.e., simulation model)
- Experimenting with the developed simulation model
- Analyzing and interpreting the results of simulation experiments

Simulations have been used to deal with just about every planning problem in supply chain management. In 1960, Shycon used simulation to aid locating warehouses. Flextronics use its own tool, SimFlex, to deal with strategic planning problems on many fronts, including transportation, procurement, and distribution. Terzi and Cavalieri (2003) present a survey on application of simulation in supply chains. The paper provides a comprehensive review of more than 80 articles, with the main purpose of ascertaining which general objectives simulation is generally called to solve, which paradigms and simulation tools are more suitable, and deriving useful prescriptions both for practitioners and researchers on its applicability in decision-making processes within the supply chain context. The authors underline two macro objectives of simulation studies: network supply chain design and supply chain strategic decision support. The facility-location problem, called *node localization* within the survey, belongs to the first macro objective. The authors recognize only few simulation models and tools, among those reviewed that deal with the problem of geographic disposition of industrial nodes. As an example, they mention the paper of Belhau et al. (1999), which describes the application of simulation for location distribution centers using the simulation tool Create!. It should be noted that more simulation studies are addressed to strategic supply chain network planning and design. For instance, Persson and Olhager (2002) present a supply chain simulation study for a real case concerned with the manufacturing of mobile communication systems. The objective is to evaluate alternative supply chain designs with respect to quality, lead times, and costs as the key performance parameters. A discrete event simulation software, Taylor II, is used to support this study. Van der Vorst et al. (2000) develop methods for modeling the dynamic behavior of food supply chains and evaluating alternative designs of the supply chain by applying discrete event simulation. The Simulation model used within a study is based on Petri-nets to support decision making when redesigning a supply chain. Several scenarios are developed for evaluating the potential benefits of alternative designs for this supply chain in terms of logistical performance.

A number of simulation languages and packages have been developed to assist engineers and managers in constructing models of their systems. Although general purpose languages are still widely used, numerous software vendors have endeavored to develop software packages specifically adapted to the modeling and analysis of supply chains. For the list of discrete event simulation software, Swain (2003) offers an excellent survey of simulation software. In the context of facility location, there are supply chain simulation software and simulators developed more directly to be facility locators. Some examples of supply chain simulators will be presented in Section 14.4, but for the list of location simulators see Ballou and Masters (1999).

14.4 Supply Chain Simulators

The analysis of supply chain design is a complex task. Now simulation tools are developed to facilitate the analysis of supply chains by using supply chain models. Such models are usually developed by means of modeling software specifically oriented toward special logistics processes at strategic, tactical and operational planning levels. These systems are designed to model a specific class of systems that usually have a map-based interface and are supported by ready-made blocks (or templates) for representing the main elements of a system, such as plant, warehouse, harbor, terminal and others.

The following subsections provide an overview of selected supply chain simulation tools and describe the simulation tool LORD (Remix Ltd., 1999) in more detail.

14.4.1 Overview

The following special purpose simulation software can be used to facilitate the development and analysis of any supply chain:

- Simflex, owned by Flextronics (*www.flextronics.com*), enables companies to simulate supply chain dynamics, and thereby evaluate multiple planning criteria and real-world variations. The accuracy of the results generated by SimFlex enables companies to make strategic and cost-conscious decisions concerning complex supply chain issues. An overview and brief tutorial of SimFlex is presented in Williams and Gunal (2003)
- IBM Supply Chain Analyzer, the IBM product, provides modeling functions for seven different supply chain processes: customers, manufacturing, distribution, transportation, inventory planning, forecasting, and supply planning. In addition to its use to model IBM's own supply chain, the software has been extensively applied to help IBM clients improve their supply chains (*www.ibm.com*)
- Supply Chain Builder from Simulation Dynamics, Inc. provides a simulator for supply chains that helps to understand and predict supply chain performance under alternative strategies. Supply Chain Builder enables one to model the entire network, including the policies of every facility in the network, and to model demand patterns, ordering policies, forecasts, and physical routing policy (*http://www.simulationdynamics.com*)
- Caps Logistics Toolkit is a comprehensive decision-support software package developed for logistics. The toolkit consists of several packages for transportation management, warehousing management, supply chain analysis, and shipment planning (*http://www.caps.com*)
- Logistics ReDesign is a software that is used to transform supply chains to meet the latest market requirements. The planning objectives include not only costs, but also delivery performance and inventory reduction. This system can be used for simulation of logistics networks, defining improved policies in current network, testing new supply chain initiatives, sensitivity analysis, and maintaining supply chain partnerships. This software will be described below.

14.4.2 Modeling Process

Regardless of the modeling tool used, a simulation modeling process includes five major modeling steps.

1. *Problem and model definition.* The objective of this stage is to define the problem area. The outcomes of this are the problem definition, objectives, critical dimensions, model boundaries, and validation criteria. The problem definition is the process of finding actual issues to be solved. Objectives are the scope of goals to be achieved. Critical dimensions are deduced from objectives and are used to evaluate alternative strategies. Model boundaries are defined from the problem definition, objectives, and critical dimensions. Model boundaries detail elements that are included in the model. A simulation time for the model has to be discussed in this stage. An optimal time dimension for LORD models is from 6 months to 3 years, which is a time horizon for both tactical and strategic decisions.
2. *Modeling current state.* The current state of the problem area has to be modeled first. Experience has proven that usually the current state has to be modeled in two phases: rough and detailed. The objective of the rough model is to quickly make a structure that describes the main features of the model boundary. This framework is used as the basis for the detailed model. A typical rough model includes only facilities of the model, a few products, a few customers, and rough estimations for control rules, cost structures and time delays. Usually, the data accuracy is at quite an aggregate level for rough models.
3. *Modeling alternative strategies.* Possible changes in the initial strategy are considered. They have to be evaluated to achieve the goal and solve the problem. Usually, one alternative strategy is a set of small modifications and changes in the supply chain structure. The generation of alternative strategies does not start after the current-state modeling. The collection of the idea generation, modeling features, and data has already started, at the beginning of the project. The objective of this phase is to collect these ideas and, with the help of the built model, generate new ideas and improve old ones. This phase is iterative.
4. *Analysis of strategies.* Analysis is mainly done for the critical dimension defined in the beginning. But some dimensions and measures can be updated during the modeling process. Alternatives should always be analyzed according to several dimensions like: profit, customer service parameters, and efficiency. As it is hard to validate alternative strategies, sensitivity analysis should always be included.
5. *Decision:* Models do not make decisions but only support the making of decisions. The best models can provide some support and insight to the problem area, but decisions should not rely only on the model's results.

The benefit of the model is not only the result itself. With the help of the modeling project, the problem itself and alternative strategies are better understood.

14.4.3 Supply Chain Simulation Tool LORD

The supply chain simulation tool known as LORD (from Logistics ReDesign) was developed through an European Union research project and commercialized by Remix of Finland (a more advanced version of LORD, SimFlex – a supply chain simulation software, now owned by Flextronics). LORD is used in transforming supply chains to meet the latest market requirements. The planning objectives include costs, delivery performance and inventory reduction. This system can be used for simulation of logistics networks, defining improved policies in current network, testing new supply chain initiatives, sensitivity analysis, and maintaining supply chain partnerships. The tool is designed for:

- Industrial companies and distributors: analysis of alternative logistics strategies or supply chain development directions
- Logistics service providers: new business development, demonstrating competitiveness of service offering for customers, including planning as a part of the service package
- Consulting companies: using the tool to provide a consulting service, supporting marketing activities, exploring new innovations and demonstrating benefits to clients
- Other users include public administration, training, and research

The following are the main key features of LORD:

- Business focus on logistics planning: cost, time, delivery performance, and inventories included in the analysis
- Possibility of multi-company planning scope
- In addition to logistics operations, production and value-added operations are included
- Real-world behavior included like fluctuating volumes, trends, and variations.
- Map-based interface used in placing facilities, terminals, customers, and other logistics model components to the right locations (see Fig. 14.2).

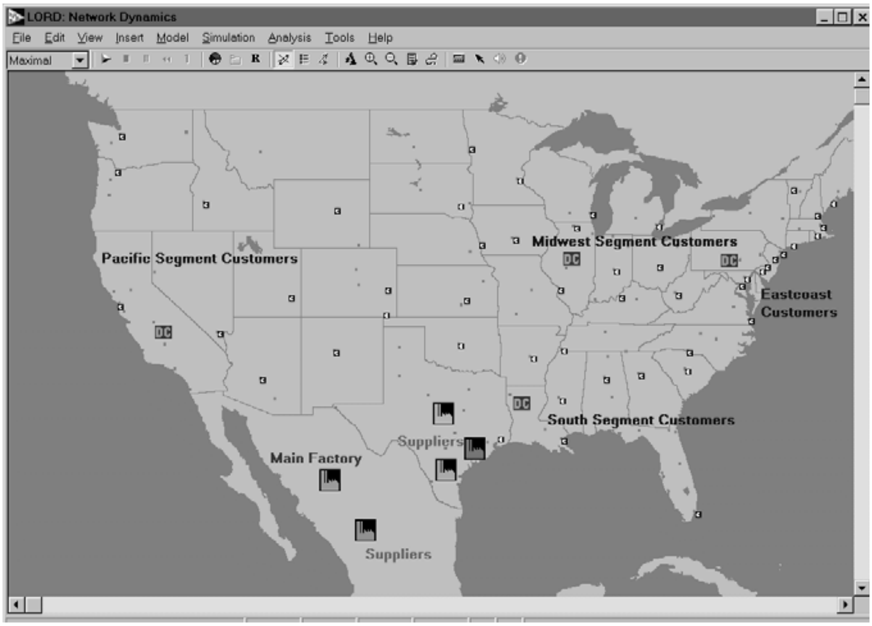


Fig. 14.2 Map-based interface.

- Best analysis environment
- Top-down planning approach for quick first results: model building starts from making a very rough but relevant model and then continues by adding modeling details in the most important areas. In many cases, it is not necessary to make very detailed models, as it takes time and doesn't always lead to better results
- Global features: currency rates, multiple measurement systems, international transport networks

Analysis Manager is one of the most advanced features of the system, allowing users to freely tailor graphical analysis views for tailored company purposes. A special technology exists for free selection of analysis dimensions (e.g., total costs, time, service, assets, and volumes) and the analysis perspective (e.g., total supply chain, company, facility, and segment). The analysis views can be used before, during, and after simulation. Analyses results windows viewed during the simulation are updated continuously. LORD includes numerous ready-made analysis views that can also be used as a starting point for new analysis.

All graphical and numeric views can be printed, and the data can be exported to text processors or spreadsheet programs for later reporting. All analyses can be linked by hyperlinks to each other. This helps make live presentation with the actual model. In the same way, Microsoft PowerPoint presentation slides can be opened from hyperlinks.

A typical supply chain model creation process by LORD includes the following steps:

1. Creating a new model
2. Creating companies
3. Creating products and components
4. Adding facilities (plants, sales offices, and terminals) to companies
5. Creating customers and demand
6. Defining supply and delivery links
7. Defining transport services, transport links, production and inventory control, and other structures, if necessary.

14.5 Case Study: Locating a Distribution Center

The presentation of the case study starts with the description of Zepter International and its operations in the Baltic region. The following subsection describes drivers behind the reconfiguration initiative. Optimization of inventory management is one of the main drivers. It can be achieved by consolidation of distribution operations. The consolidation opportunities have arisen due to removal of trade barriers as the result of accession of the Baltic countries to the EU. The problem definition is followed by description and evaluation of alternative supply chain configurations.

14.5.1 Current Supply Chain

Zepter International produces, sells and distributes exclusive high-quality consumer goods around the world. As a direct sales company, Zepter does not have stores but offers products through catalogues and samples through sales representatives, as well as samples in the regional customer service centers. Zepter's products are manufactured in seven factories in Germany, Italy, and Switzerland. Although the company has concentrated on demonstrating its products on a personal level by way of direct sales, Zepter also has many presentation pavilions located in major cities in the sales network that covers European countries, as well as the United States, Israel, New Zealand, and Australia. Over the past few decades, Zepter has become a global enterprise with sales in over 40 countries on five continents across the world.

Currently, the company has independent subsidiaries in each Baltic country. Each country has its own warehouse, administration, and separate supply chain. In big cities such as Riga and Vilnius, goods are delivered door-to-door to their customers every day, goods are delivered but to regional offices on a weekly basis according to their actual demand. Zepter Baltic's simplified supply chain is illustrated in Fig. 14.3.

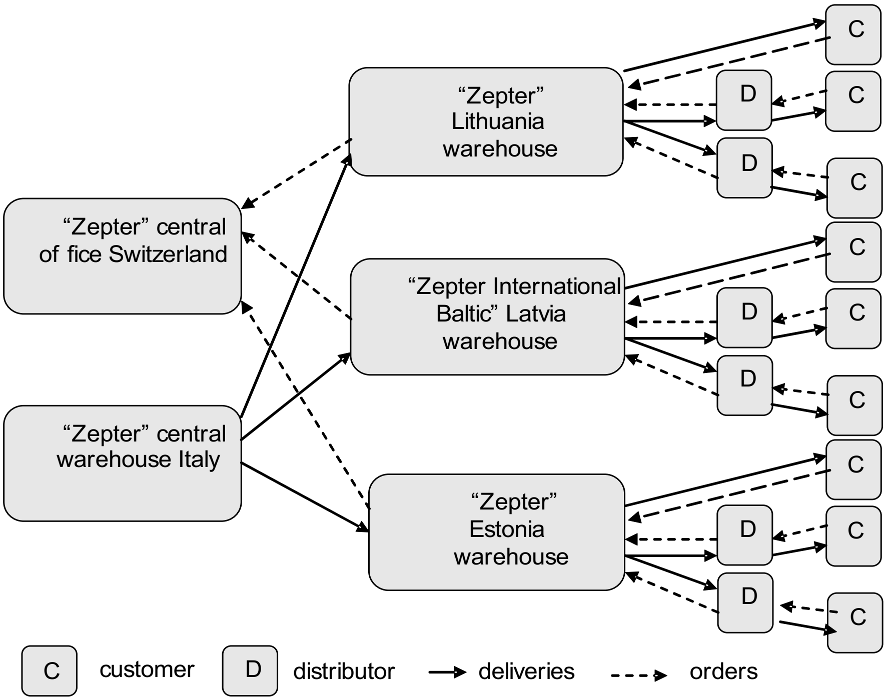


Fig. 14.3 Zepter Baltic's supply chain.

14.5.2 Problem Definition

Zepter International has noticed that customer-service levels can be maintained with less stock and administrative costs because of free goods movement in the European Union. Taking advantage of this opportunity, the company is interested in conducting a network analysis and looking for an ideal placement of its distribution centre as well.

To see optimization potential, a first analysis was made to see the stock turn-around times per year. It could be seen that the smallest country (Estonia) had the lowest turnaround rate, and Lithuania, which is the biggest country had the best turnaround rate. However, even Lithuania's result was not satisfactory, compared to figures of similar companies in the retail business.

On the basis of a deeper analysis, it was found that *A* group items have good turnaround figures, even lower than average in the market, but a large quantity of stock has arisen from spare parts and slow-moving goods. The cause of this situation is separate safety stocks in each of the countries, as well as the size of the demand in each country in comparison with minimum order quantities from the supplier.

A matter that makes supply chain more complex is the fact that Zepter International owns many production plants. Order lead time for most products is more than two months. From logistics theory, it is known that due to the long lead time, safety stock will increase because of the demand fluctuations, as well as possible transportation or production delays.

Another factor, that influences stock is minimum order quantities. If minimum order quantities are significantly higher than monthly local market demand, then it directly increases company's stock. It is a problem for many retail companies in small markets because that does not allow them to work directly with producers, as they usually request minimum order quantities which for the small market can be more than yearly demand — meaning frozen money in stock.

The impact of all the above-mentioned factors on the stock level can be reduced by increasing demand supplied from one warehouse. As mentioned previously, the worst stock turnaround rate was in the smallest market Estonia. To reduce stock level in Baltic supply chain, it was decided to look for one central warehouse that could service all Baltic countries. It would reduce the stock of slow moving products and spare parts significantly. Another benefit would be reduced warehouse maintenance and stock-holding costs.

After finding the optimal location of a distribution center, the company has to match savings from reduced holding costs with additional expenses. If savings are bigger, the project has to be implemented. Besides obvious savings, reduced stock and holding costs have also other benefits, such as substitution of fixed costs with variable costs, which makes business more elastic and responsive to market changes. The reduced stock also allows faster phase-out of old products, leaving space for new product launches.

14.5.3 Evaluation of Alternatives

Zepter is interested in conducting a network analysis as well as looking for a cost effective location for its distribution center. Three scenarios defining alternative supply chain configurations are evaluated:

- Scenario 1 simulates the current supply chain

- Scenario 2 simulates the supply chain with one distribution centre in Riga
- Scenario 3 simulates the supply chain with the distribution center located in a point calculated according to the center of gravity method, which is an exact technique applied to solving the facility-location problem

In the search for an ideal location for the distribution center, Zepter believes that transportation costs are the major factor influencing supply chain efficiency, and reduction of fixed costs is approximately the same for all alternative designs — which include just one warehouse. Therefore, a single performance measure (i.e., transportation costs will be used for analysis). At the same time, 100 percent service level is required. The first scenario is used to benchmark performance of proposed alternative supply chain configurations.

During the analysis, two types of decisions have to be made. The first decision regarding distribution center location has to be made initially as a strategic decision that sets conditions for supply chain performance during the next three to five years. In Scenario 2, the location of the distribution center is determined by Zepter managers. In Scenario 3, an exact mathematical method, known as the centre of gravity method is applied. Because optimization does not allow evaluating the performance of the modeled system through time, a simulation model is used. Therefore, the center of gravity is found and the result is provided as an input to the simulation mode. After a strategic decision is made, tactical decisions about inventory policies and delivery service should be made. In this case, tactical decisions concern inventory management at the distribution center.

Scenario 1

The first scenario of a distribution network simulated in LORD is Zepter's current distribution network (see Fig. 14.4). The distribution scheme is the following: 1) goods are delivered monthly from Milan, and 2) goods are delivered to regional centers every week. The simulation is conducted based on information about sales amounts in Latvia, Lithuania, and Estonia in 2003 and 2004. Annual sales for 2004 are shown in Table 14.3. Demand has a seasonal character (Fig. 14.5).

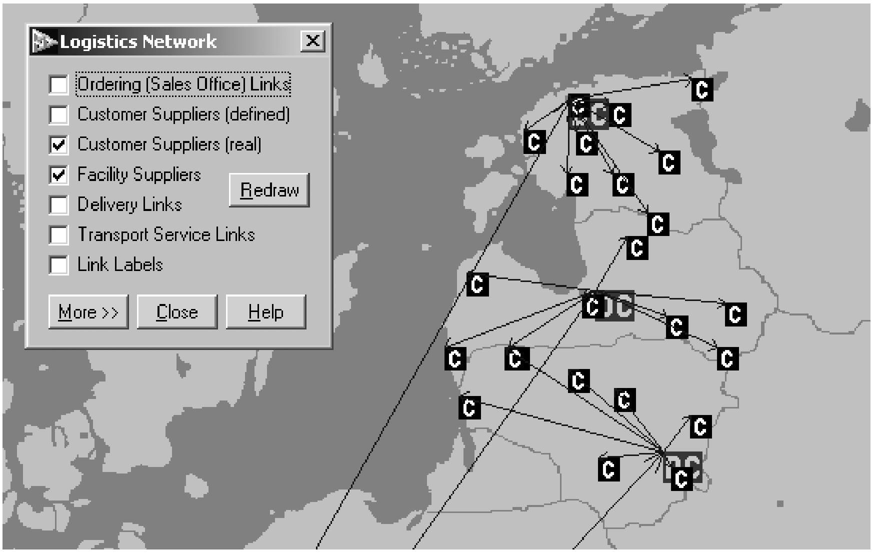


Fig. 14.4 A representative distribution network of Zepter in LORD .

A logistics services provider charges 4 EUR for door to door delivery in the city and 70 EUR for deliveries to regional centers within the country. For future analysis, it is admitted that transportation rates among countries is 140 EUR. The list of transportation routes and rates is shown in Fig. 14.6.

One of the LORD features is that it calculates distances between cities using its own database. It is only necessary to define its costs and, if required, the speed of delivery (the time of delivery is not taken into consideration in the examined model, therefore it is accepted that all routes speed is 60 km/h).

To determine a stock renewal policy for each distribution center, the necessity of extra stocks is taken into consideration, for the following purposes: safety stock, exclusive goods, and corporate gifts. After running the simulation several times it is ascertained that the optimal monthly order size is 1.6 multiplied by the average monthly demand. This quantity allows for providing sufficient extra stocks, but at the end of a year when demand usually exceeds the average quantity by about 50 percent, this is the minimal monthly order size, just to prevent stock out (see Table 14.4). Safety stock is the difference between the amount of renewal stocks and average monthly demand.

Table 14.3 Demand in the Baltic by City

Estonia	Demand (SKU)	Lithuania	Demand (SKU)	Latvia	Demand (SKU)
Harjumaa	161	Vilnius	7691	Riga	6424
including Tallinn	2122	Kaunas	3844	Liepaja	271
Ida-Virumaa	726	Klaipeda	3197	Ventspils	514
Jogevamaa	3	Panevezys	1237	Valmiera	297
Laane-Virumaa	30	Siauliai	1281	Rezekne	553
Raplamaa	5	Visaginas	1053	Jekabpils	73
Viljandimaa	65	Marijampole	1027	Daugavpils	743
Vorumaa	7	Utena	511	Total	8875
Parnumaa	131	Alytus	629		
Jarvamaa	19	Telsiai	151		
Tartumaa	232	Mazeikiai	179		
Valgamaa	29	Plunge	23		
Saaremaa	10	Silute	225		
Polvamaa	4	Total	21048		
Total	3544				

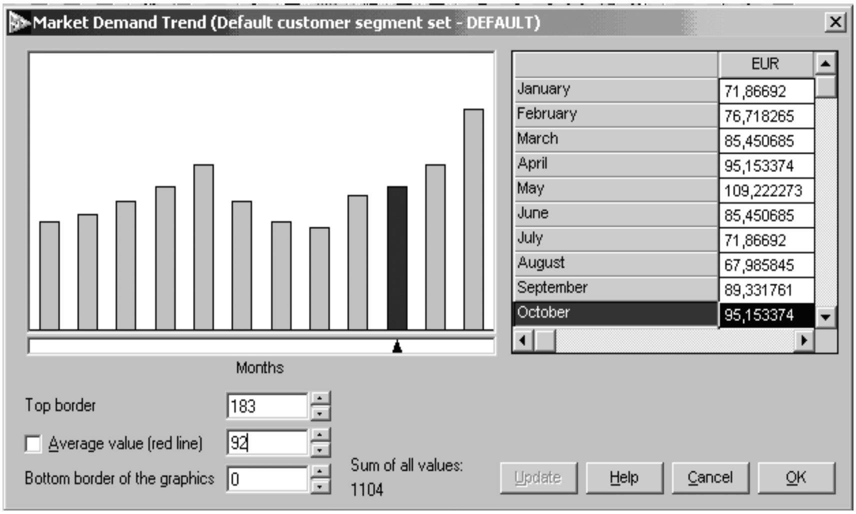


Fig. 14.5 Demand pattern input screen in LORD.

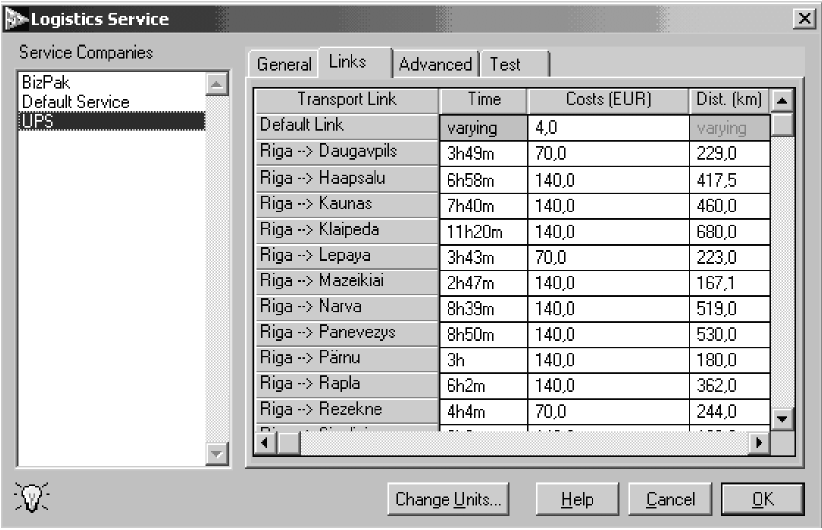


Fig. 14.6 Delivery service definition screen in LORD.

Table 14.4 Calculation of Stock Renewal Quantity for Distribution Centers

Country	Annual demand (SKU)	Monthly demand (SKU)	Coefficient	Amount of stocks renewal (SKU)
Latvia	8875	740	1,6	1184
Estonia	3544	295	1,6	472
Lithuania	21048	1754	1,6	2807

Using the advantages of the top-down approach, LORD allows the decision maker to simulate even when there is no access to all data about the system being modeled. Thus, after inputting the available data, it is possible to simulate the initial scenario. A simulation time is defined as one year. Some of the analysis windows are available during a simulation (see Fig. 14.7).

After simulation, the primary analysis of results is conducted. According to simulation results, transportation costs are 73,564 EUR. Dynamic inventories partially shown in Fig. 14.7 are compared with the behavior of the actual inventories to validate the results.

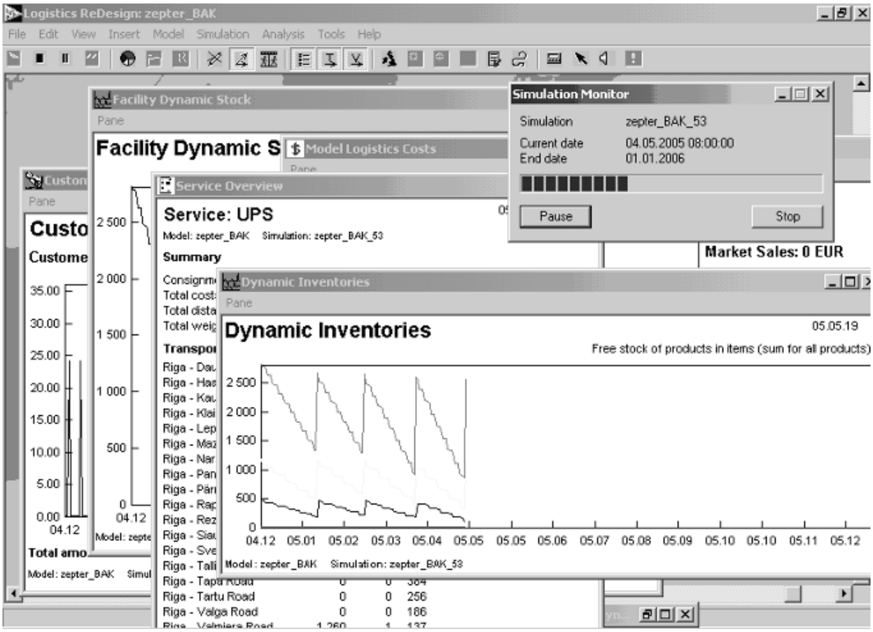


Fig. 14.7 Analysis windows during a simulation.

Continuing the experiments with the model, the next step is to simulate the performance of the supply chain with its own enterprise transport service. Up to now, Zepter does not have their own transportation system, so freight rates can be calculated using the United Parcels Service (UPS) prices. The transportation costs per kilometer are calculated as follows (the weight of packages has almost no influence on transportation costs): because the average transportation distance is about 200 km, freight rate can be calculated as 70 EUR/200km = 0.35 EUR/km. After inputting a new transportation service into the model, the transportation costs are 73,537 EUR. This is almost similar to UPS tariffs. Therefore, this type of transportation can also be used for the given supply chain configuration.

Scenario 2

By simplifying Zepter's distribution network, one of the most logical decisions is to leave a single distribution center in a geographical center (i.e., in Riga) to decrease administrative costs (see Fig. 14.8). One distribution center also helps to decrease stock amounts, which increases the effectiveness of an enterprise, but this aspect is only analyzed in the final stage to simplify the simulation process.

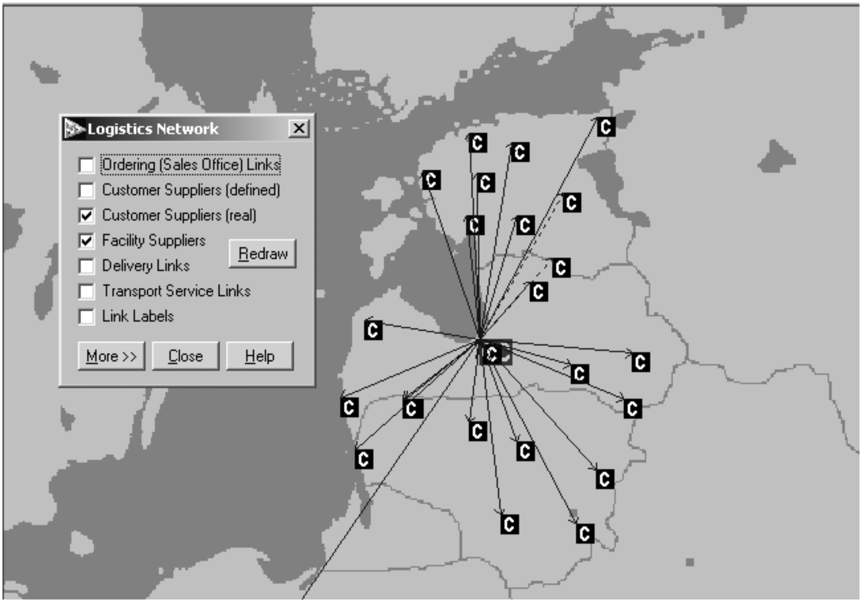


Fig 14.8 Scenario with the distribution center in Riga.

For creating the second strategy, LORD's features of scenario creation are used. This allows creating a new scenario based on the previous model by inputting only new parameters. By doing this, distribution centers in Estonia and Lithuania were removed and delivery links from the Riga distribution center to customers were created. An inventory policy of Riga distribution center now uses the sum of three distribution centers' stock policies. Transportation costs obtained from the simulation of the second scenario are 127,938 EUR. Fig. 14.9 shows that the stock policy corresponds to earlier introduced conditions.

Scenario 3

The last scenario to be evaluated consists of one distribution center located in a gravitation centre. Gravitation center coordinates are calculated with the Excel Visual Basic module. It is possible with Excel graphics to almost exactly determine linear coordinates for each city so that points on the graphic coincide with cities on the map (see Fig. 14.10). The iterations of the centre of gravity model are provided in Table 14.5. Gravitation center coordinates are X = 4.66 and Y = 2.26.

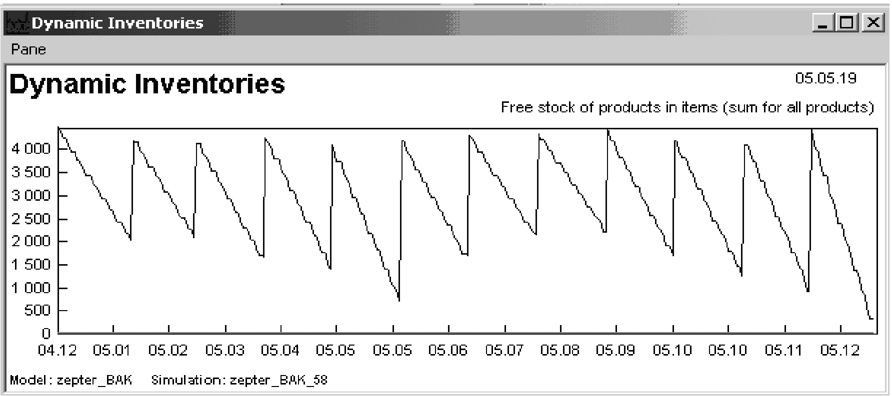
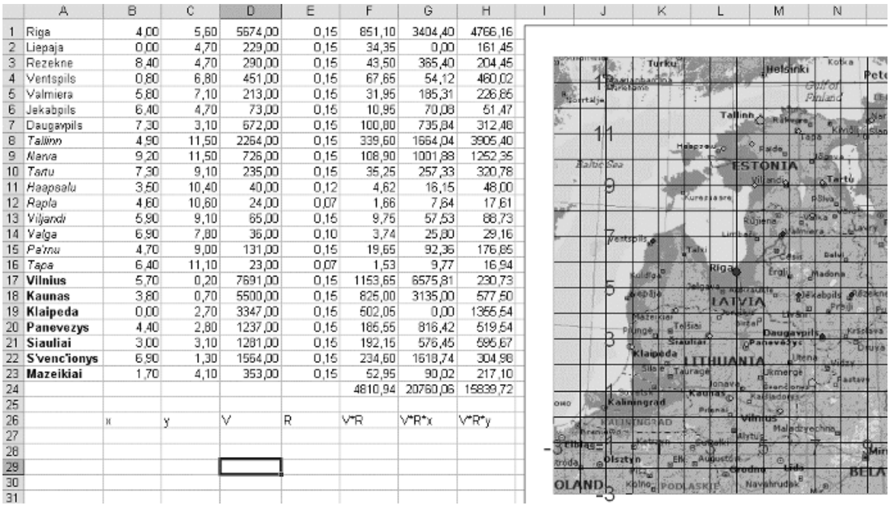


Fig. 14.9 Dynamics of stock ion Riga distribution center.



	A	B	C	D	E	F	G	H
1	Riga	4,00	5,60	5674,00	0,15	851,10	3404,40	4766,16
2	Liepaja	0,00	4,70	229,00	0,15	34,35	0,00	161,45
3	Rezekne	8,40	4,70	290,00	0,15	43,50	365,40	204,45
4	Ventspils	0,80	6,80	451,00	0,15	67,65	54,12	460,02
5	Valmiera	5,80	7,10	213,00	0,15	31,95	185,31	226,85
6	Jekabpils	6,40	4,70	73,00	0,15	10,95	70,08	51,47
7	Daugavpils	7,30	3,10	672,00	0,15	100,80	735,84	312,48
8	Tallinn	4,90	11,50	2264,00	0,15	339,60	1664,04	3905,40
9	Narva	9,20	11,50	726,00	0,15	108,90	1001,88	1252,35
10	Tartu	7,30	9,10	235,00	0,15	35,25	257,33	320,78
11	Haapsalu	3,50	10,40	40,00	0,12	4,62	16,15	48,00
12	Rapla	4,60	10,60	24,00	0,07	1,66	7,64	17,61
13	Viljandi	5,90	9,10	65,00	0,15	9,75	57,53	88,73
14	Valga	6,90	7,80	36,00	0,10	3,74	25,80	29,16
15	Pärnu	4,70	9,00	131,00	0,15	19,65	92,36	176,85
16	Tapa	6,40	11,10	23,00	0,07	1,53	9,77	16,94
17	Vilnius	5,70	0,20	7691,00	0,15	1153,65	6575,81	230,73
18	Kaunas	3,80	0,70	5500,00	0,15	825,00	3135,00	577,50
19	Klaipeda	0,00	2,70	3347,00	0,15	502,05	0,00	1355,54
20	Panevezys	4,40	2,80	1237,00	0,15	185,55	816,42	519,54
21	Siauliai	3,00	3,10	1281,00	0,15	192,15	576,45	595,67
22	S'venc'ionys	6,90	1,30	1564,00	0,15	234,60	1618,74	304,98
23	Mazeikiai	1,70	4,10	353,00	0,15	52,95	90,02	217,10
24						4810,94	20760,06	15839,72
25								
26		x	y	V	R	V*R	V*R*x	V*R*y
27								
28								
29								
30								
31								

Fig. 14.10 Gravitation center calculation using Microsoft Excel.

Table 14.5 Iterations of Gravitation Centre Calculation

X	Y	Total Cost (EUR)
3.865	2.475	30,6571.7
4.396	2.453	17,5597.1
4.579	2.399	17,2126.9
4.636	2.364	17,1653.7

4.653	2.338	17,1591.4
4.658	2.318	17,1576.3
4.66	2.304	17,1569.6
4.661	2.293	17,1566.2
4.662	2.285	17,1564.3

The nearest city to the calculated coordinates is Paneveza, thus it is possible to move a model distribution center to Paneveza. The amount of transportation costs as a result of simulation is 122,346 EUR.

Comparison of Scenarios

According to information from Zepter International, the costs of a single distribution center related to warehouse maintenance are reported in Table 14.6. The other administrative costs, which are concerned with order processing, are not included in this table, as if the network configuration would be chosen only with one distribution center and orders would be served in every country separately. The comparison of examined distribution center location choices is provided in Table 14.6.

The results in Table 14.7 show that Scenario 3 is most cost effective. Nevertheless, an additional analysis has to be conducted for making the final decision. The first step in conducting this is to perform several simulation runs in order to setup the best inventory policy of distribution center. Choosing the best placement of a distribution center, the costs of a new or leased structure against its necessary service levels, as well as several other factors have to be weighed.

Table 14.6. Warehouse maintenance costs

Type of costs	Costs, monthly [EUR]	Costs, annually [EUR]
Warehouse rent costs	1311	15,732
Telephone calls	317	3,802
Public facilities	450	5,392
Total		2,4926

Comparison of Scenario 1 and Scenario 3 shows that the savings from reducing the number of distribution centers is relatively small. The analysis accounts only for transportation and fixed distribution centers costs. However, there are several other factors influencing reconfiguration decisions. A considerable advantage of establishing a single distribution center would be market expansion and consolidation of unmarketable or slow-moving goods in one place, thereby considerably diminishing a useless stock of goods whose monthly demand up to now was much smaller than

Table 14.7. Comparison of distribution centre location choices

Scenarios	Transportation costs [EUR]	Warehouse rent costs [EUR]	Total Costs [EUR]
Three distribution centre (Scenario 1)	73,537	74,778	148,315
Distribution centre in Riga (Scenario 2)	127,938	24,926	152,864
Distribution centre at gravitation centre (Scenario 3)	122,346	24,926	147,272

the amount of the minimum package/purchase. Creation of a single distribution center in the Baltic region diminishes stock accumulation in the systems that are linked to the delivery of remote goods, long-term ordering processes that increase inventory management risks. Reduced safety stock also insures faster replacement of phase-out goods with new collections. Empirical analysis and comparison with inventory turnover rates in Poland indicate that savings from safety stock reduction could achieve EUR 68,000 at the 8 percent discount rate.

Another benefit that should be pointed out is that the fixed costs are replaced by variable costs by diminishing the number of the distribution centers. That makes business much more flexible against changes in demand. If business has seasonality, than variable costs can give great benefit to cash flow.

The decision between placing the distribution center in the gravity centre or in major cities closest to the gravity center, like Riga, Vilnius, or Kaunas, can be made by checking infrastructure possibilities, qualified workforce availability and so on. The optimal location according to the center of gravity method is the border of Latvia and Lithuania. However, an essential element for selection of the location is also the infrastructure. Because the city of Riga is situated closer to this theoretical, most advantageous distribution center than Vilnius or Kaunas, the optimum option would be establishment of the distribution center in Riga.

14.6. Summary

In this chapter, the applied problem of distribution center location for the international company has been investigated. The facility-location methods and simulation have been employed as analysis techniques. Simulation enables exploring of dynamic and stochastic aspects of supply chain behavior. Special purpose supply chain simulation software such as LORD facilitates development of supply chain simulation models and provides an intuitively appealing model execution environment. Facility-location techniques allow the identification of candidate locations for supply chain units.

The problem of redesigning supply chains in response to changing trade regulations is of high importance to many companies. Zepter International took this step in response to enlargement of the European Union. The chosen supply chain redesign strategy was consolidation of distribution facilities. The consolidation allowed

- Reducing fixed costs
- Reducing safety stock requirements.
- Improving management of slow-moving goods and avoiding products becoming obsolete

The quantitative results were subjected to additional managerial analysis. In this way Riga, the most centrally located of large cities, was chosen in preference to the location found using the center-of-gravity method. Availability of infrastructure was the primary reason behind this selection.

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15. Future Research Directions in Supply Chain Configuration Problem

15.1 Introduction

As in the case of any open and adaptive system, the structure of supply chain has evolved progressively over time from a sequential supply chain, to a global supply chain, a supply network, and alliance networks, respectively. This evolution has reflected the change in business environment from static to dynamic. In Chapters 1 and 2, we discussed such supply chain configuration phenomenon and shed light on its sources and causes. It was also observed that various components of supply chain have a significant impact on its structure. So what does the future hold for the supply chain configuration problem? To answer this question, we review the anatomy of a supply chain from the perspective of trends and opportunities and their impact on its structure. Then, we propose an agenda for future research in supply chain configuration, which takes into account the confluence of interdisciplinary research and the increasing use of emerging technologies.

15.2 Trends and Opportunities in Supply Chain Configuration

To prognosticate trends and opportunities in the area of supply chain configuration, one only has to review some of the vital issues driving the development of manufacturing in the twenty-first century (Cheshirehenbury 2006; Gregory 2000; NRC 1998):

- *Economic conditions,* such as homogenous markets, limited competition, balance of supply and demand, regulated markets, limited customer expectations, and commonality of life styles that favored mass production in the twentieth century have changed to favor customization in the twenty-first century (Agogino and Chidambaram 1997; Chandra and Grabis 2004; Ramani et al. 2004)

- *Changing perceptions* of products, including individual customization, shorter product life cycles, and re-configurable products to meet emerging needs
- *Emergence of global markets* and competition, forcing manufacturers to rapidly respond to changing market needs
- *Accelerating pace of technological advances* including the increasing importance of information technology, communication science, new manufacturing processes, and new materials are opening up a wide array of possibilities and operational methods
- *Impact of the Internet and advanced information technologies* is transforming design and manufacturing from a data-intensive activity to a knowledge-extensive process
- *Outsourcing* as a viable option for gaining competitive advantage is changing the way product design, manufacture, and after-sales service functions are being implemented
- Adoption of the *world-wide product team* concept is enabling implementation of distributed, as well as collaborative, design and manufacturing, resulting in products that appeal to a broader global consumer base and developed with reduced time-to-market
- Use of information technology that has permeated almost all aspects of product life cycles is providing innovative ways of exploiting different *time zones* across various global locations for design, manufacturing, and logistics activities in reducing product lead times and increasing overall enterprise productivity

As manufacturing organizations endeavor to deal with some or all of the issues outlined above, they may experience various forms of transformations. For instance, it may transform itself from a single node (one plant location) manufacturing unit to either multiple fixed nodes (multiple fixed locations) manufacturing networks, or multiple variable nodes (multiple configurable locations) manufacturing networks. Correspondingly, decision-making environments may be centralized, decentralized, or autonomous. Similarly, the problem-solving environment can be designed as deterministic or stochastic. As additional factors related to product design such as product structure, degree of customization, and order patterns are brought in the decision-making mix, the manufacturing enterprise takes on varying levels of complexity. To support the resultant decision-making process, information requirements become more rigorous.

Research on new methodologies is providing novel ways for companies to continue to streamline and shorten their design and manufacturing methodologies internally and then across suppliers, thereby reducing and/or eliminating inefficiencies. The Internet is playing an increasingly dominant role in enabling and evolving new technologies, often in unpredictable ways.

The prevalence of computer-aided-engineering tools has enabled more people to participate in the design process to create sophisticated products and manufacture them cost effectively. As a result of these tools becoming more widely available, product lifecycles have reduced and product innovation has continued to increase. The increase in complexity of products spawned another type of industry evolution, where companies started to separate out many functions that were not core to their operations (Prahlad and Hamel 2001) and resulted in an increase in tier 1 suppliers. With increased complexity of products, suppliers began looking into modular design methods and strategies on the one hand and outsourcing on the other.

The evolution and increasing adoption of Internet-aided design, manufacturing, and commerce by firms is changing the supply chain management landscape by placing importance on planning, coordination, and synchronization of its activities as never seen before.

With increasing specialization in the supply chain and the continual need to lower costs and increase quality per component, transaction costs and logistics costs are more important for firms to manage. Hence, large companies have started adopting the early and sophisticated collaboration and supply chain management tools needed to reduce supply chain management and interaction costs. Interoperability of computer-aided engineering systems has started taking on a more important role, with vendors following their own internal standards. The Internet is playing a bigger role in linking various entities in conducting the business of supply chains.

15.3 An Agenda for Future Research in Supply Chain Configuration

The increasing role of the Internet in supply chains has the potential of creating unique capabilities for improving supply chain management. Therefore, it is befitting to recognize that it will have a prominent role in defining the agenda for future research in supply chain configuration. As described in previous chapters, information sharing and information integration are two of the key problems in supply chain management. As the size of the supply chain network grows, there is an exponential increase in the amount of data — and therefore, information and eventually knowledge — that needs to be acquired, stored, managed, processed, and serviced for various decision-making needs while managing the supply chain. This problem needs efficient solution both from an operational perspective, (forecasting and inventory management) as well as development of efficient information processing methodologies and techniques. *Cyberinfrastructure* offers that venue for supply chain configuration research.

Some of the other key dimensions to be considered for future research in supply chain configuration area are as follows:

Design of Problems. As we have elaborated in previous chapters, supply chain configuration can have potentially a complex web of problems, which may have to be dealt at different decision-making levels. These problems need to be coordinated to design efficient problem-solving solutions. Therefore, the design of new supply chain solutions must account for appropriate relationships among these problems.

Design of Solutions. The development of solutions for modification to supply chain information systems, and the integration of advanced decision-making components by adopting modern software engineering techniques, offers opportunities for better supply chain management.

A System-of-Systems Approach. It is needed to design complex supply chain networks. This is especially true as supply chains assume global proportions, whereby the number of entities and their relationships multiply disproportionately. It also recognizes the concept-to-fruition notion of product and service delivery, which in the case of a supply chain may sometime span several heterogeneous and independent systems, and must be integrated together to be effective in delivering the product.

Private and Public Standards. Such standards are highly relevant and important for the design, modeling, and implementation of supply chain networks. Adopting standards facilitates meta-modeling of complex networks, thereby saving on design and modeling time for a system. The Supply Chain Operations Reference (SCOR) model is an example of successfully applying industry process standards to conceptual modeling of supply chain networks (Stewart 1997).

Interconnectedness. Designing and recognizing interconnectedness among supply chain components is one of the keys to achieving supply chain configuration. Connectivity can be achieved either logically or technologically. Logical connectivity is achieved through implementation of innovative and progressive strategies and policies to manage the supply chain. Technological connectivity is achieved through implementation of emerging technologies, such as radio frequency identification (RFID), sensors and so on.

Design-Time Reconfigurability of Supply Chain. The emerging trend towards product customization has implications throughout the product life cycle. A new or revised existing customer requirement for a product specification may spawn modifications and/or enhancements, with potential impact on the physical and logical systems enabling the realization of the product. The ramifications of such changes should be considered during the conceptualization phase in product design. Changes in product specification typically affect the essential ingredients for competitiveness — namely, minimal cost, lead time, and optimal product variety. The complexity of changes in such a system is magnified when the design, manufacture, and logistics of the product is accomplished in a distributed environment.

Postponement of Operations in Supply Chain Life Cycle. As the trend toward mass customization of products takes hold, it is essential that its impact be properly reflected in the design of supply chain solutions. The postponement strategy would require coordinating various strategies, policies, processes, and deployment of resources in a manner that postpones implementation of operations as far as can be delayed in the supply chain life cycle, without adversely impacting product lead time and cost.

The agenda for future research in supply chain configuration must recognize the urgent need for providing solutions that particularly satisfy public policy applications, a need of our times, in addition to traditional applications in a vast array of manufacturing and service industries. A generic example of this is the design of supply chain configuration for the *unknown*, which may be any of the following applications:

- Community issues affecting local (i.e., region, city), state, country, and global levels
- Mega-disasters, including man-made and natural disasters
- Disease prevention and control
- Management of environmental issues
- Public finance issues
- Energy consumption and preservation issues

These issues are tightly related with emerging focus on reverse logistics, green supply chains, long-term sustainability, and supply chain transparency. The recycling tier is likely to become an integral part of the majority of supply chain configuration models. Concerning sustainability, a major concern is balancing the typical two up to ten years planning horizon with environmental and social sustainability targets having substantially longer planning horizons. Supply chain configuration tools could be a decision-making tool not only for commercial enterprises, but for governmental institutions to investigate potential impact of particular regulatory requirements. Supply chain transparency (i.e., availability of information about supply chain structure and origins of products) is becoming more important. Companies like McDonalds and BodyShop use supply chain transparence as a marketing tool.

Other future areas of research are improving computational capabilities of supply chain configuration models and techniques. In this regard, an important area is elaboration of methods for integration of models in decision modeling, and models in information systems design, to offer integrative decision-modeling capabilities. These could certainly be tied to research in cyberinfrastructure. To recognize an inter-operable environment offered by the Internet.

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