SC COLLABORATOR: A SERVICE ORIENTED FRAMEWORK FOR CONSTRUCTION SUPPLY CHAIN COLLABORATION AND MONITORING

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I certify that I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

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Abstract

Importance of supply chain integration has been shown in many industry sectors. The construction industry is one of the least integrated among all major industries. One of the major reasons is that construction supply chains are unstable and often consist of numerous distributed members, most of which are small and medium construction companies. With the proliferation of the Internet and the current maturity of web services standards, service oriented architecture (SOA) with open source technologies is a desirable computing model to support construction supply chain integration and collaboration due to its flexibility and low cost. This thesis investigates and demonstrates the potential of the current web services technologies and SOA for construction supply chain collaboration and management, through a prototype service oriented system framework, namely SC Collaborator (Supply Chain Collaborator).

SC Collaborator is designed and implemented according to the system requirements for construction supply chain integration. The framework leverages web services and portal technologies, open standards, and open source packages. Although some web services systems allow user connection and integration through web services protocol, their system functions and operations are fixed and not adaptive to changes. The SC Collaborator framework enables flexible reconfiguration of internal service invocation, integration, and system layout without recompilation of the system. The framework can serve as a separate collaborative system, or integrate with other systems such as inventory management systems.

To align a collaborative system with the supply chains it integrates, this thesis proposes and demonstrates the incorporation of supply chain models in a service oriented system framework. Specifically, the Supply Chain Operations Reference (SCOR) framework, a widely used model developed by the Supply Chain Council, is employed to model construction supply chains. The SCOR modeling framework provides a generic and hierarchically structured means to specify supply chain networks and processes. The SCOR process elements and operations are wrapped as individual web service units, which are integrated and orchestrated in the service oriented SC Collaborator framework. A case example on a student center construction project is used to illustrate the SCOR modeling framework for performance monitoring.

The SC Collaborator framework is also extended to support collaboration among distributed service oriented collaborative systems. Due to the temporary project-based relationship among participants in construction projects, project participants that do not have direct business partnership may hesitate to expose and share sensitive and proprietary information with each other. The distributed SC Collaborator framework allows users to specify shared information and data. This thesis discusses how information consistency is ensured among distributed SC Collaborator systems. The distributed network of SC Collaborator systems is tested with a case scenario of a completed expansion project of a three-storey residential building.

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Chapter 1

Introduction

1.1 Problem Statement

A supply chain consists of a network of key business processes and facilities, involving end users and suppliers that provide products, services, and information [53]. Traditionally, marketing, distribution, planning, manufacturing, and purchasing units and organizations along a supply chain often operate independently. The value of integrating members along supply chains has been studied and identified in many industries [68, 87]. Supply chain integration helps reduce cost, improve responsiveness to changes, increase service level, and facilitate decision making. In an integrated supply chain, information is shared and becomes available among the members. This enhances supply chain visibility and avoids information delays and distortions. Insufficient supply chain visibility makes members vulnerable to quality and service level problems from business partners and therefore subject to risks [23, 67]. Information delays and distortions lead to an increase in demand signal variation along the supply chain upstream, a phenomenon called the bullwhip effect [57]. Therefore, information sharing is one of the keys to effective supply chain management.

Construction is one of the largest industries in any country of the world [41]. In the United States, the value of construction put in place was $1,072 billion in 2008 [97], or 7.5% of the U.S. gross domestic product (GDP) that year [18]. There are many companies and many trades involved in a construction project and development. Unfortunately, the construction industry is arguably the least integrated among all the major industrial sectors [34]. New [71] and Cox [26] have also suggested that supply chain research in construction should focus on the development of interactive, inter-organizational relationships, which requires integration.

Briscoe and Dainty [17] have summarized eight key attributes to successful construction supply chain integration: (1) managing communication, (2) managing information flow, (3) alignment of supply chain systems, (4) mechanisms for problem resolution, (5) engineering additional value in projects, (6) ensuring high quality standards, (7) securing commitment to the client and the project objectives, and (8) establishing long-term supply chain relations. Therefore, system frameworks that can easily align with other supply chain systems and facilitate communication and information flows are critical to integration of construction supply chains. O'Brien [75] also emphasizes the importance of good communication and information sharing between different parties to construction contracts. In addition, London et al. [61] indicate that strategic management combined with assured flows of information is critical to the creation of value across supply chains.

However, the high fragmentation and project-based nature of the industry pose a significant challenge to cross-enterprise integration of information and applications in construction supply chains. The characteristics of construction supply chains lead to various requirements for information and collaborative systems such as low cost and system adaptability. With the proliferation of the Internet and the current maturity of web services standards, this thesis aims to propose and demonstrate that integration and collaboration of construction supply chains can be improved by adopting web services and portal technologies, open standards, open source packages, and the concept of service oriented architecture (SOA). This thesis presents a prototype service system framework

that is designed for managing and integrating construction supply chains. This framework supports flexible system reconfiguration and integration of scattered information and application operations, alignment of supply chain configuration, and communication of distributed systems.

1.2 System Requirements for Construction Supply Chain Integration

Construction supply chains are characterized by the involvement of many companies from a wide variety of trades [74]. A construction project involves a diverse group of participants including contractors, architects, engineers, laborers, and developers [43]. A project of medium to large scale typically involve hundreds of different companies supplying materials, components, and a wide range of construction services [27]. The multi-participant and multi-domain characteristic is partly caused by the high fragmentation of the industry. According to a study on the construction industry in the United States [64], the top eight architectural, engineering and construction (AEC) companies control less than twenty percent of the market share while by contrast the top companies in the aerospace industry control over seventy-five percent of all trades within the industry. This is probably due to the fact that the construction industry is comprised of countless companies from many different trades, most of which are small to medium in size. Furthermore, AEC companies tend to use a wide range of hardware platforms and software applications for their own operations, posing many technical challenges in integrating the construction supply chains.

The temporary project-based nature of construction projects also hinders integration of construction supply chains. Even though the processes can be similar for construction projects of a specific kind, most construction projects create new products or prototypes and consist of temporary supply chains that organizations need to be reconfigured for

each project [99]. Sharing of information and integration of systems require trust and coordination. Since construction supply chains are highly dynamic and the organizational structure and the project team change frequently, it is, therefore, unlikely for project participants to work together long enough on a project to build enough trust and to share information willingly. A secure and customizable support system may help establish trust and encourage integration during short-term partnerships. A flexible system may facilitate adapting to new configurations and changes in supply chains. Based on the characteristics of construction supply chains, literature review, and feedbacks from practitioners in the industry, the following sections summarize the desirable requirements of a collaborative platform to enhance communication among members and integration of services in a construction supply chain.

1.2.1 Ease of Installation and Configuration

As discussed in [95], an information infrastructure to interface the members of a supply chain should simultaneously satisfy three requirements: (1) accommodating members with varying degrees of IT sophistication, (2) offering a wide range of functionalities, and (3) allowing constantly changing pool of suppliers and customers. The third requirement is particularly important for construction supply chains because additions, removals, and changes of project participants such as the second tier suppliers are common in construction projects. Furthermore, construction companies often need to extensively customize each individual business application before usage, because every construction project is characterized by a unique set of site conditions, project team, and relationships between project stakeholders [24]. As a result, information systems for construction supply chain integration should be flexible to allow quick installation and configuration at the beginning of a project, and to enable easy re-configuration and adaption for changes throughout the project.

1.2.2 Low Cost

Small and medium enterprises (SMEs) play a critical role as subcontractors and suppliers in construction supply chains. According to a study in the United Kingdom, about 83 percent of the contracting companies in the private sector employ three or less workers [27]. Almost 98 percent of all the companies employ 24 or less workers, which are generally defined as small companies. Medium-sized companies that employ between 25 and 114 workers account for a further 2 percent. These SMEs are usually reluctant to invest much time, money, and effort in information systems and technologies. To create a network to support data exchange and communication among information sources and software applications can be expensive. Large corporations routinely spend up to 50 percent of their information technology budgets on application integration [14]. Most of the SMEs in the construction industry are not able and/or willing to make such a huge investment. Solutions that are economical are needed.

1.2.3 Ease to be Connected and Integrated

As noted earlier, ability to accommodate users with varying degrees of IT sophistication is one of the three requirements for supply chain information infrastructure [95]. The requirement especially applies to the construction industry because participants on a construction project are from a wide variety of domains and possess different levels of experience and educational backgrounds. In addition, according to the technology acceptance model (TAM) [30], the perceived ease of use of a system affects the early willingness to try and use the system and the subsequent adoption of the system. Therefore, systems for managing construction supply chains should provide user-friendly and easily accessible communication interface. It is also important that the communication interface allows disparate systems to be connected through machine understandable protocols. In this way, information and applications residing inside a

system can be integrated with other applications and systems in the IT infrastructure of an organization or company.

1.2.4 Ability to Integrate External Systems and Information

Supply chains involve many participating companies that are geographically distributed in locations. They may use different systems and keep their information separately. Not only is it desirable to expose internal applications and system operations securely to external systems, but it is also beneficial to allow connection and integration with external systems and information on a collaborative project. Some companies may be using ERP or database systems to support various business operations. A supply chain integration system should be able to access and combine these distributed information sources and systems.

Functionalities of a system become extensible if it can integrate external systems and information. Ability to extend the functionalities beyond an individual software system can facilitate usage. For example, functionality of ERP systems usually is limited and fixed. Therefore, functionality is an important factor for the selection and successful implementation of an ERP system [49, 50, 70]. An ERP system successfully implemented on one project may not be applicable to another project. Different projects may need different system functionalities depending on factors like the construction processes, project organizations, scopes of planning and management, hardware and software that the stakeholders use, and the materials and components involved in the project. It is difficult and costly to customize functionalities of a pre-packaged commercial ERP system typically for business applications for construction projects [105]. Many software packages such as CAD programs allow extension of functionality via application programming interface (API). Likewise, if collaborative systems for

enterprise-wide integration can conveniently extend their functionality, the usability of the systems will be greatly enhanced.

1.2.5 Customizable Access to Information and Applications

Security is an issue that many companies concern for collaborative systems. Some project participants may be reluctant to share information with other participants who do not have a direct business relationship. For example, although a subcontractor may be willing to share information with direct trading partners and suppliers, the subcontractor may not be willing to share information with the suppliers of other subcontractors even though they are involved in the same project. Moreover, many participants in construction projects work together on a project-based relationship. It is often difficult for all the project participants to build enough trust and share information with others. A system that enables users to control and customize the accessibility of information and applications can promote information sharing.

1.3 Current Practices for Supply Chain Integration

There are many attempts to develop methodologies, technologies, and tools to integrate various applications for communication and collaboration among supply chain members. For example, standards for Electronic Data Interchange (EDI) are developed to facilitate electronic exchange of business information over networks. Enterprise resource planning (ERP) systems are adopted for inter- and intra-organizational communication. The Internet has also been leveraged for communication, collaboration, and project management. The following sections discuss EDI standards, ERP systems, and the current web-based communication technologies in the construction industry.

1.3.1 Electronic Data Interchange (EDI) Standards

Good communications and information sharing among various parties in construction projects are critical and can be achieved through information technology integration [17, 27]. The issue of Electronic Data Interchange (EDI) for inter-organizational interactions has been discussed for over twenty years in both academia and industry [33, 40, 45]. National Institute of Standards and Technology (NIST) defined in 1996 that EDI was the computer-to-computer interchange of strictly formatted messages that represent documents other than monetary instruments [47]. The formatted data representing the documents may be transmitted via telecommunications or physically transported on electronic storage media.

Some companies in the manufacturing industry establish communication networks using EDI standards such as ANSI ASC X12 standards [5], RosettaNet standards [84], and ebXML [94] to connect and exchange data with partners. ANSI ASC X12 is the official designation of the U.S. national standards body founded in 1979 for the development and maintenance of EDI standards. RosettaNet is a non-profit consortium aimed at establishing standard processes for the sharing of business information. ebXML is a XML-based standard sponsored by Organization for the Advancement of Structured Information Standards (OASIS) and United Nations Centre for Trade Facilitation and Electronic Business (UN/CEFACT) for the exchange of electronic business information. These standards and infrastructures provide a stable means for electronic business communication. However, the implementation of such communication infrastructures usually requires high cost and long configuration time, partly due to the lack of information standardization among trading partners.

1.3.2 Enterprise Resource Planning (ERP) Systems

Recently, major construction companies have adopted enterprise resource planning (ERP) systems to integrate loosely distributed information and applications within and across

companies [24]. An ERP system is typically employed to seamlessly integrate all the information flowing through the company such as finances, accounting, human resources, supply chain, and customer information [29]. ERP systems can potentially enhance transparency across the supply chain by eliminating information distortions and increase information velocity by reducing information delays [3]. Many corporations have implemented ERP systems to facilitate their front-end customer relationship and to support their back-end operations.

ERP systems were not designed and are often not suitable for the construction industry [105]. There are many research studies and efforts on selection and implementation of 'generic' ERP systems in the construction industry [2, 24, 25, 86, 105]. Companies that use a generic ERP system often need to configure and customize it to support their own business needs. This configuration and customization process usually takes significant time, effort, and investment. In addition, most ERP systems on the market are mainly targeted to large companies with a stable supply chain, while construction supply chains are unstable project-based in nature. Furthermore, adoption of ERP systems does not often result in significant improvement in project performance as expected. One study estimated that 96.4% of ERP implementations failed [82] whereas another study reported that 70% of ERP implementations did not achieve their estimated benefits [4].

ERP systems have many technical limitations such as implementation complexity, integration problems, and customization problems [93]. Akkermans et al. [3] conducted an exploratory study on commercial implementation of ERP systems and concluded four major limitations of ERP systems that often led to unexpected underperformance of these tools: (1) inability to share internal data efficiently with supply chain partners across organizational boundaries, (2) inflexibility to accommodate changes of supply chain structures, (3) lack of functionality beyond managing transactions, and (4) lack of modular and open system architecture.

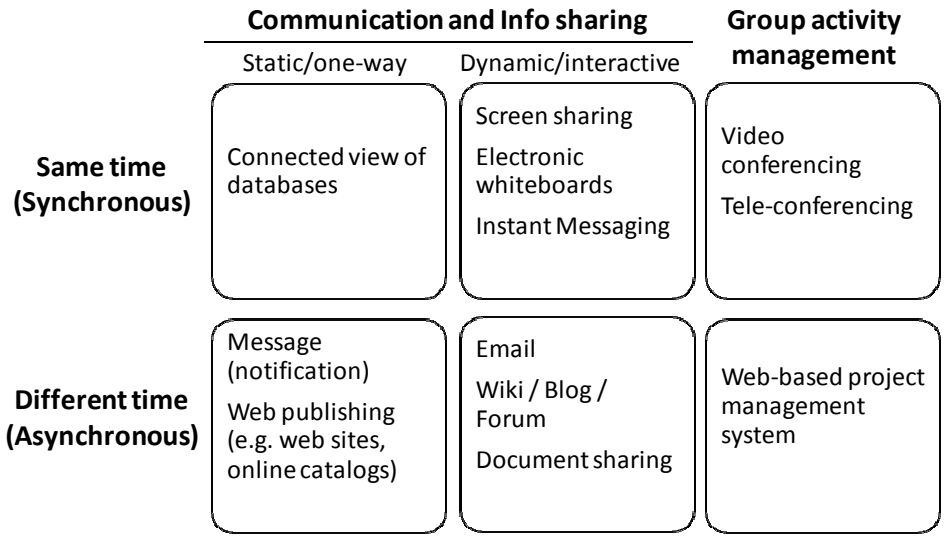


Figure 1.1: Commonly used web-based collaborative tools

1.3.3 Web-Based Collaboration and Project Management Systems in Construction

With rapid development of communication technology, the Internet has become ubiquitously and instantaneously accessible. The proliferation of the Internet makes it the most cost effective means of driving supply chain integration and information sharing [58]. Companies increasingly take advantage of the Internet to create a virtual value chain where individuals and business partners can communicate and collaborate with each other.

Nowadays in the construction industry, information technology and the Internet have been leveraged to support multi-organizational collaborations. Examples include web-based collaborations for design and learning [20, 73, 88], for document and knowledge management [62, 107], and for project monitoring and management [19, 22, 72]. Figure 1.1 categorizes various means that are currently used for web-based communication and

collaboration in the construction industry. In particular, web-based project management systems (WPMS) and construction project extranets (CPE) have been increasingly used to support communication in construction projects [11, 72]. CPE is a private network that is designed for the use of construction projects and hosted by Application Service Providers (ASP). Project participants can access a CPE through web browsers. System functionalities of CPEs, usually project specific, can include team communication, process and project management, organization directory, and document management. However, the use of these tools is slow in the construction industry because of barriers such as security issues, a lack of management commitment, high cost, and deployment inflexibility [63]. In addition, these tools are mostly standalone, specific applications that cannot be integrated nor extended easily.

1.4 Service Oriented Architecture and Web Services

An Internet-enabled system based on the service oriented architecture (SOA) can address many of the limitations of ERP systems and CPEs for supply chain integration. SOA is a model in which information sources and software functionalities are delivered as individual distinct service units, which are distributed over a network and combined to create business applications to solve complex problems. SOA enables the dynamic reconfiguration of supply chains, making them readily adaptable to changing business models, growing globalization and increasing coordination. Using the SOA approach, information sources and systems are converted into modular service components that can be discovered, located and invoked by other applications through a standard protocol. The service components can be reused by multiple applications or other services residing on a network. This “plug-and-play” capability allows agile development and quick reconfiguration of the system, which are essential for building a flexible system for fast changing supply chains.

The shortcomings of traditional ERP systems that were stated by Akkermans et al. [3] can be partially resolved using the SOA. First, SOA allows partners to share their internal data by deploying the data into individual service units that are made available over the network. Second, the "plug-and-play" ability of SOA allows easy and flexible reconfiguration to accommodate changes of supply chain structures. Third, service oriented systems not only allow information transfer across organizational boundaries, but also enable invocation of various applications via the service components. System functionalities therefore are not bounded and can be extended to operations such as analysis and evaluation of alternatives. Fourth, service oriented systems can be divided into modules for control, management and development, providing both modularity and scalability. As a result, systems using SOA can provide many of the functionalities by ERP systems while eliminating many shortcomings of ERP systems. Service oriented systems can potentially provide higher benefits and cost effectiveness to users than ERP systems.

Web services are the building blocks of SOA. Utilizing the Internet as the communication network, the web services technology has emerged as a promising tool to integrate distributed information sources and software functionalities in a flexible, scalable, and reusable manner. A "web service" can be described as a specific function that is distributed on the Internet to provide information or services to users through standardized application-to-application interactions. Leveraging well established Internet protocols and commonly used machine readable representations, web services can be located, invoked, combined, and reused. Web services can create dynamic responses and are different from conventional websites, which deliver only static information. Web services are self-contained in that the application using the web services does not need to depend on anything other than the services themselves. They are also self-describing in that all the information on how to use the services can be obtained from the services themselves. Web services are encapsulated, meaning that integrated web services can be updated or replaced without affecting the functionality or integrity of other independent services. Interoperability is also achieved by web services as applications written in

different languages and operating on different operating systems can be integrated via standardized web services protocol.

1.5 Research Objectives

Cross-enterprise integration of information and applications in construction supply chains is hindered by the high fragmentation and project-based nature of the industry. The current information and collaborative systems cannot fully fulfill the requirements of supply chain integration and management in the construction industry. The objective of this thesis is thus to investigate and to demonstrate the potential of the concept of service oriented architecture (SOA) and the current web services and open source technologies for construction supply chain collaboration and management. Using a service oriented approach, a collaborative system can be developed based on supply chain models to reflect the structure of a supply chain. Leveraging web services technology, a distributed network of collaborative systems can be supported to promote sharing of private information and operations. This thesis presents a prototype service oriented collaborative system framework namely SC Collaborator (Supply Chain Collaborator). SC Collaborator is designed according to the system requirements for managing and integrating construction supply chains, which are (1) ease of installation and configuration, (2) low cost, (3) ease to be connected and integrated, (4) ability to integrate external systems and information, and (5) customizable access to information and applications. This thesis also illustrates the modeling of construction supply chains, which results in supply chain models that can be incorporated in the developed prototype framework.

The prototype SC Collaborator framework presented in this thesis is designed to manage the procurement, production, and delivery processes among general contractors, subcontractors, and suppliers. The framework supports flexible system reconfiguration

and service composition, alignment of supply chain configuration, and communication among peer systems. The framework implements service oriented architecture leveraging web services and portal technologies, open standards, and open source packages. Unlike the current web services systems, SC Collaborator allows easy and flexible reconfiguration of system functions and operations, because internal information, applications and operations in SC Collaborator are delivered as individual web service units that can be integrated and reused.

1.6 Thesis Outline

This thesis presents the developed prototype system SC Collaborator framework designed for managing construction supply chains. Its system extensions to incorporate supply chain models and to support distributed network architecture are then discussed. This thesis is organized into the following four chapters.

- Chapter 2 presents the service oriented portal-based SC Collaborator system framework. Open source technologies are leveraged to support the system communication, the portal-based user interface, the business applications, and the data management and storage. Open standards for web services are used to implement SOA in SC Collaborator. This chapter also justifies the suitability of SC Collaborator for supply chain integration and collaboration in the construction industry. A procurement scenario and a project rescheduling scenario are included to demonstrate the potential of SC Collaborator.

- Chapter 3 demonstrates the modeling of construction supply chains and the leverage of supply chain models for system implementation using a service oriented approach. The Supply Chain Operations Reference (SCOR) framework is utilized for supply chain modeling. This chapter describes the SCOR framework and its uses to model mechanical, electrical and plumbing (MEP)

supply chains, with reference to a study of the MEP process of a student center construction project. The developed SCOR models are then integrated in SC Collaborator to build a service oriented model-based platform that monitors supply chain performance.

- Chapter 4 introduces a distributed SC Collaborator network architecture for promoting information sharing among organizations in a collaborative environment that each organization owns and fully controls the information it shares. This chapter discusses the communication between distributed SC Collaborator systems and addresses the information consistency issue potentially hindering a distributed network of systems. This chapter illustrates the approach of logging and fault handling in SC Collaborator for tackling the consistency issue. The proposed distributed SC Collaborator network is demonstrated and tested in this chapter using a case scenario based on a completed residential building expansion project.

- Chapter 5 summaries the development of the SC Collaborator system framework for facilitating integration of information and operations among supply chain members in construction projects. Research contributions and suggestions of potential future research directions are also provided.

Chapter 2

Service Oriented Portal-Based Framework – SC Collaborator

2.1 Introduction

A supply chain is a network of organizations that procure raw materials, transform them into intermediate goods and then final products, and deliver the products to customers through a distribution system [56]. These organizations often operate separately, leading to myopic operations with reduced efficiency and performance. Cross-firm coordination of processes is often needed among supply chain members to avoid conflicts, since these members may have different objectives and constraints. Therefore, business-to-business integration and collaboration are needed to achieve streamlined material, information, and financial flows across supply chains [81].

The essence of cross-firm supply chain collaboration is to share information, to jointly develop strategic plans, and to synchronize operations [16]. Collaborative systems exist to facilitate communication, information sharing, and alignment of supply chain operations. Some of them enable users to access, retrieve, and modify information

residing in those systems through standardized web services protocol. A few of them also allow invocation of web services to exchange data between external systems and to combine internal system operations with the functionality provided by external web services. However, current collaborative systems tend not to be easily reconfigured and extended. For example, service invocation specifications are often embedded in the source codes which cannot be easily modified. In addition, built-in system operations and information schema are fixed and are difficult to modify for changing needs.

SC Collaborator (Supply Chain Collaborator) is a prototype system framework developed for supporting information sharing and system integration along construction supply chains. In SC Collaborator, invocation and aggregation of web services can be performed and modified easily without the need to recompile the system. Internal information, applications, and system operations are wrapped and deployed as separate web service units for invocation and integration. Therefore, system functionality and operations can be reconfigured and extended flexibly. The system framework leverages web portal technology to provide a customizable user interface, and utilizes open source technologies to minimize implementation costs which hinder the system usability in construction companies that are SMEs.

A supply chain is a network of business entities collectively responsible for procurement, manufacturing, and distribution activities associated with one or more families of products [44]. The SC Collaborator system thus focuses on the buyer-supplier interactions among suppliers, subcontractors, and general contractors in the processes of procurement, manufacturing, and delivery. The framework addresses the five system requirements for construction supply chain management, which are (1) ease of installation and configuration, (2) low cost, (3) ease to be connected and integrated, (4) ability to integrate external systems and information, and (5) customizable access to information and applications.

This chapter is organized as follows. Section 2.2 discusses the service oriented portal-based framework that the development of SC Collaborator is based on. Section 2.3

presents the system architecture and components of the SC Collaborator system framework. Section 2.4 describes the implementation of SOA in SC Collaborator. Section 2.5 discusses how the SC Collaborator system addresses the system requirements for construction supply chain integration. Section 2.6 illustrates the flexibility and extensibility of SC Collaborator through two example scenarios. The first scenario is an electronic procurement example while the second one is a rescheduling example based on data collected from a completed construction project of a supermarket in Sweden. This chapter is concluded with a summary in Section 2.7.

2.2 Service Oriented Portal-based Framework

A web portal is a web-based system that acts as a gateway to a larger system or a network of web applications. It is a useful tool to aggregate scattered, distributed information and services into a single point of access regardless of their location or storage mechanism. The basic operational units of a portal system are web portlets, which are sub-programs that encapsulate a single or a number of web applications. Portlets generate only a fragment of a complete HTML code, and therefore need to be contained in a portal system in order to become visible and accessible. Through the portal system, multiple information sources and applications can be accessed, retrieved, and integrated into a workflow or a supply chain.

Web portals are commonly used to build an intranet for content and document management within organizations [66]. They serve as a repository of information and documents for data storage, publication, and retrieval. Due to their security and customizability, web portals allow users to securely access sensitive personal information, and enable system administrators to manage a huge amount of information in a centralized manner. There is also a trend to build portal systems for cross-organizational collaboration. However, there is little, if any, rigorous research on portal

design, development, maintenance, and updating for facilitating supply chain management decisions [98].

SC Collaborator is designed and implemented following a service oriented approach as a portal-based system. A service oriented portal-based framework is a system development framework that leverages web portal technology to provide a secure and customizable user interface and implements SOA to integrate information, applications and services in a flexible and reusable manner. As illustrated in Figure 2.1, conceptually, there are three functional components in a service oriented portal-based framework.

- The service deployment component allows information sources, application functionalities and system operations to be wrapped and deployed into individual web service units, which can be located and invoked by application portlet units via standardized protocol.

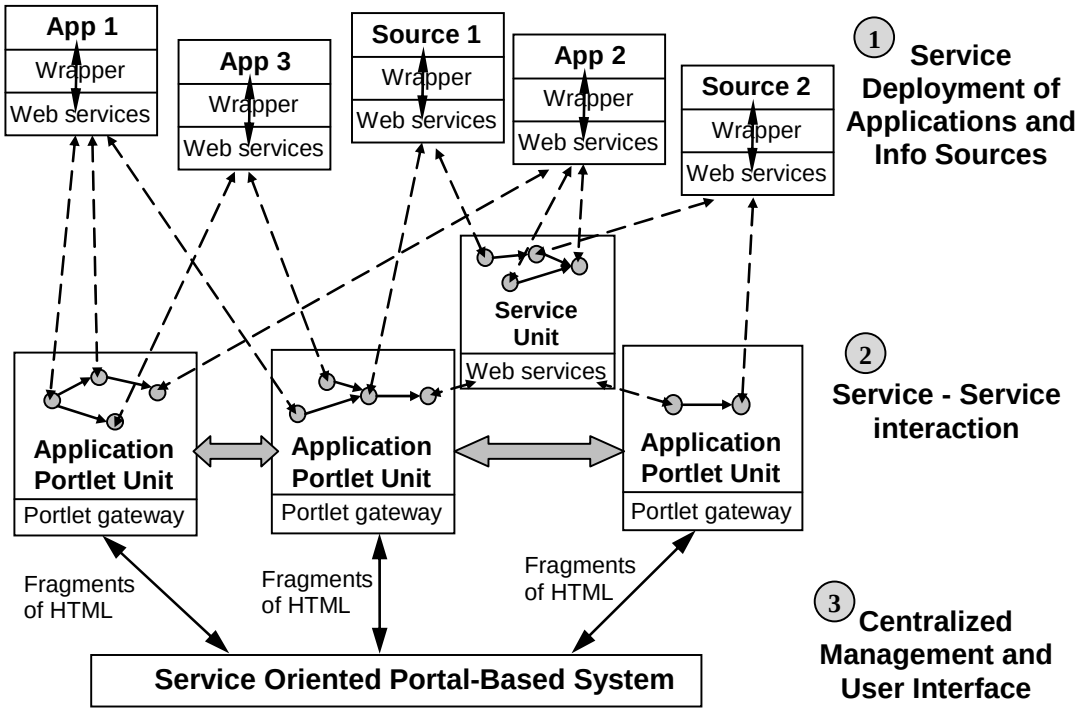


Figure 2.1: Conceptual framework of service oriented portal-based framework

- In the service-service interaction component, web service units are connected, integrated and orchestrated into various workflows to perform different business tasks. The service invocation and composition can be performed by application portlet units and by web service units. Web service units can be reused in different workflows or reused multiple times in the same workflow. As a result, development of repeated system operations is avoided, and applications and information sources can be used concurrently. In addition, modification of system functionalities becomes easy and quick as every business process is divided into separate atomic reusable web service components.

- The centralized user interface component is provided by a web portal system. The layouts specified in the application portlet units are combined and displayed through the portal-based interface. As the system layout is independent of the service implementation, changes in the location or implementation of a web service unit do not affect the system interface from a user's perspective. System reconfiguration is therefore facilitated.

The system architecture which is designed to support these three system functions is described in the following section in detail.

2.3 System Architecture

Figure 2.2 shows the system architecture of the SC Collaborator framework. The framework consists of a database support and four layers of integrated functionalities – a communication layer, a portal interface layer, a business applications layer, and an extensible computing layer. The communication layer provides a communication channel for users to access the system. The portal interface layer serves as a unified and customizable platform to support interactions between users and the system. The business applications layer provides an environment that connects to internal and external

web service units for executing various business processes such as order management and material delivery monitoring. The extensible computing layer may include databases, software applications, and web services that the business applications layer can integrate to support high-level or computationally intensive business functions.

As highlighted in Figure 2.2, SC Collaborator implements the service oriented portal-based framework shown in Figure 2.1. The service deployment component is represented by the extensible computing layer and the services repository component on the business applications layer of SC Collaborator. The service-service interaction component is implemented by both the service units and the application portlet units residing on the business applications layer of SC Collaborator. The centralized user interface component is supported by the communication layer and the portal interface layer of SC Collaborator.

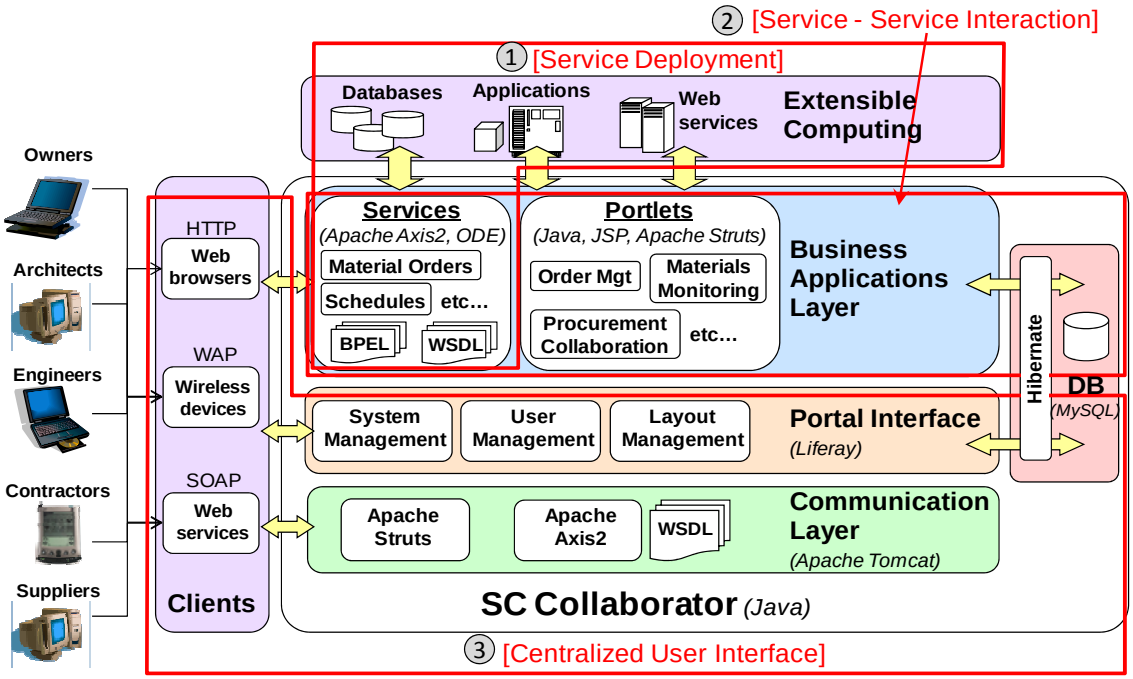


Figure 2.2: System architecture of the SC Collaborator system

This multi-layer, modular architecture permits flexible system installation and maintenance because each layer can be modified or altered easily and independently. For example, suppose a user has already installed another communication application server in the company server. To install SC Collaborator on the same server, the user does not need to install the bundled communication layer and run both communication servers simultaneously in the same machine, which may affect the performance of both servers. The user can extract other components from the SC Collaborator, bundle and install them with the existing application server in the server machine. This flexibility makes system maintenance easier.

Open standards and open source technologies are utilized in the system design and implementation of SC Collaborator. Open standards are standard specifications that are available to the general public and developed through the collaboration of multiple organizations. Open source software is computer software that is technology-neutral, that does not place restriction on other software, that distributes the source codes freely, and that allows users to modify, integrate, and redistribute the software [79]. The open standards used in SC Collaborator are:

- *Simple Object Access Protocol (SOAP)* [102], an XML-based protocol and encoding format specification released by World Wide Web Consortium (W3C) for data exchange between web services,

- *Web Service Description Language (WSDL)* [104], an XML-based specification released by W3C for describing web services, and

- *Business Process Execution Language (BPEL)* [80], an XML-based specification released by Organization for the Advancement of Structured Information Standards (OASIS) for composition and orchestration of web services.

These open standards support the implementation of service oriented architecture in SC Collaborator. The details of the structure of these web services standards and their

relationships will be discussed in Section 2.4. The open source tools leveraged in SC Collaborator are:

- *Apache Axis2* [7], a framework developed by the Apache Software Foundation that supports deployment of web service units and provides system accessibility using standardized SOAP and WSDL technologies,

- *Apache Orchestration Director Engine (ODE)* [9], an execution engine developed by the Apache Software Foundation that deploys and implements BPEL processes,

- *Apache Struts* [8], a framework developed by the Apache Software Foundation that offers system accessibility using web browsers or wireless devices and enables control of page flows and management of consistent layouts,

- *Apache Tomcat* [6], a servlet container developed by the Apache Software Foundation that executes web applications which are programmed and packaged using the Java Servlet technologies,

- *Hibernate* [83], a framework developed by JBoss, Inc. (now part of Red Hat) that provides flexibility to use different relational databases by mapping object-oriented Java classes to data in traditional relational databases,

- *Liferay Portal* [60], a web portal system developed by Liferay, Inc. that offers a web-based user interface with functionalities such as login authentication, content management, and blogging, and

- *MySQL* [90], a relational database management system developed and owned by MySQL AB (a subsidiary of Sun Microsystems) that provides data storage, retrieval, and management.

The following sections discuss the leverage of the open standards and open source tools in the main components of the SC Collaborator framework in detail.

2.3.1 Communication Layer

A user-friendly and readily accessible communication channel is essential to the usability of a system. The SC Collaborator system uses open source packages – Apache Tomcat [6], Apache Struts [8], and Apache Axis2 [7] – to enable the connectivity and access to the system. Apache Tomcat serves as a container for the communication frameworks, Apache Struts and Apache Axis2. While some information systems require the client-side to install particular communication software in order to be connected, the Struts framework that resides in SC Collaborator allows users to access the system using web browsers, which are commonly available on every computer. Basic security control of user login with password is provided by the portal interface layer. Figure 2.3 shows the guest homepage that allows users to log into the system through web browsers. The Struts framework also enables remote users to access the system using wireless devices such as personal digital assistants (PDA) via the Wireless Application Protocol (WAP).

Figure 2.3: Homepage of the SC Collaborator system

The Axis2 framework residing on the communication layer enables system operations of the SC Collaborator system to be exposed as standard web services. WSDL documents are used to describe the deployed web service units for service discovery, description, and invocation. Users can request information from the system and execute internal operations by invoking the service units via the standardized web services protocol SOAP.

2.3.2 Portal Interface Layer

2.3.2.1 System Management

An open source web portal system – Liferay Portal [60] – is leveraged to provide a flexible and customizable user interface in the system. The portal user interface of the SC Collaborator system is managed in separate modules. Every module represents a project, an organization, or a group of similar business functionalities. For example, Figure 2.4 shows the layout of a system administrative user with accessibility permissions to seven modules designated for a single project namely "SHS Project." The My Community module is unique for users to host personal application portlets. The company module (shown as "GenCon" in Figure 2.4) is available for all the users registered with the company. The Guest module does not require authentication and is intended to display project information to the public, if any. The General Contractor, Subcontractor, and Supplier modules are accessible to the designated users performing the role of general contractor, subcontractor, or supplier in the SHS Project. The System Config module contains applications for managing and configuring the system and is available to users with system administrator role only.

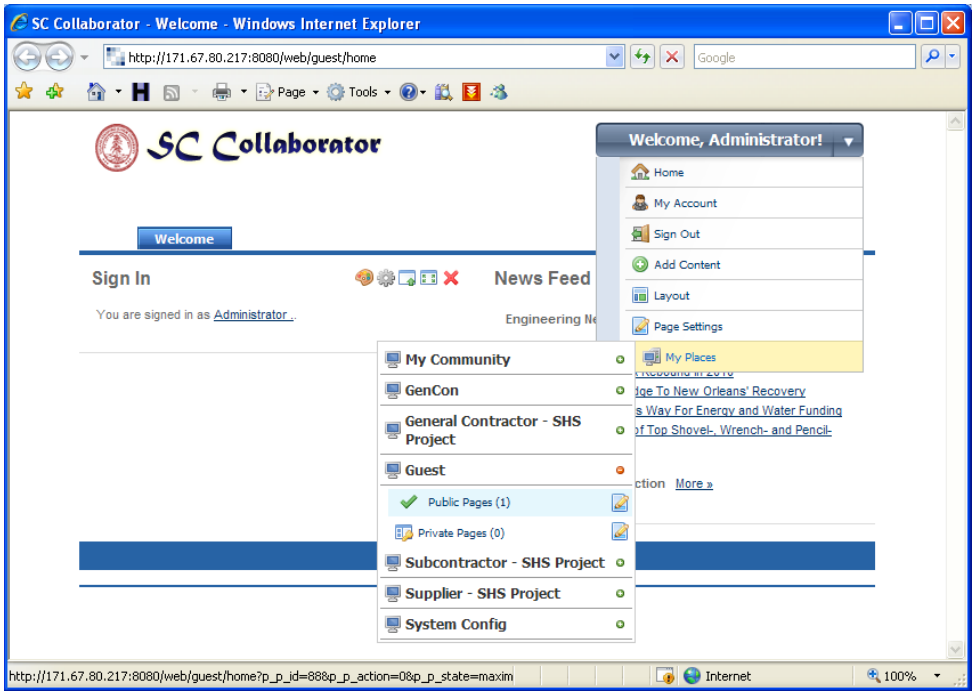


Figure 2.4: System administrator selecting different modules in SC Collaborator

A single module contains a number of sub-module pages, each of which can contain multiple application portlet units. Configuration, permissions, and layout can be configured for each module, sub-module page, and portlet. Figure 2.5 shows the application portlet unit accessible in the System Config module for system administrators to change the display settings of the six sub-module pages in the Subcontractor module. System management also includes activity logging, user tracking, and computer resources utilization configuration. It helps the system administrators evaluate the system and configure it to suit different needs.

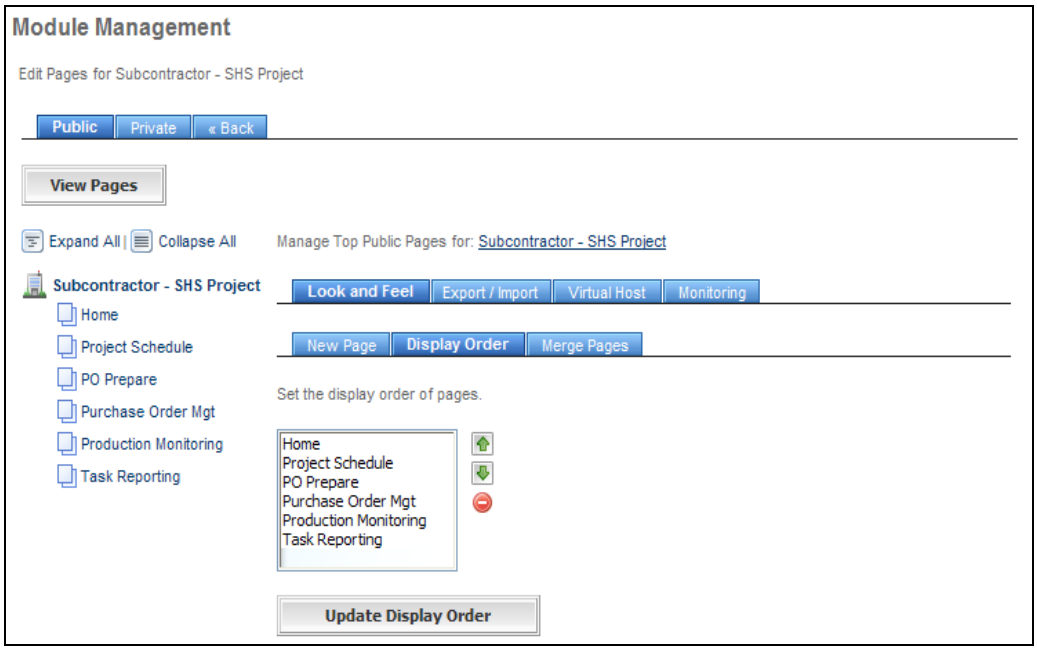


Figure 2.5: System administrator managing the sub-module pages

2.3.2.2 User Management

Accessibility of the system functionalities and the internal information and operations can be assigned to a user at the levels of roles, organizations, user groups, and individual users. Every user inherits the permissions that are assigned to the role, organization or user group that the user belongs to. The types of roles in the SC Collaborator system are system administrator, module administrator, module member, normal user, and guest. Each role has its predefined set of permissions to the system, layout, modules, sub-module pages, and portlets. For example, users with system administrative role can view, configure, and assign permissions of every module, sub-module page, and application portlet unit. An organization is the company that a user belongs to. A user can be associated with multiple roles, but only one organization.

Users can be grouped and assigned with a user group name. For instance, SC Collaborator has three user groups with names “supplier”, “subcontractor” and “general

contractor." Suppliers can manage and respond received purchase orders, and share production and delivery information with customers. Subcontractors and general contractors can submit and manage purchase orders, monitor product production and delivery information, and update the information of project tasks. General contractors can also edit the overall project schedule. Users of different roles, organizations, and/or user groups can collaborate using the SC Collaborator system.

2.3.2.3 Layout Management

The user interface for web browsers and wireless devices can be configured through the layout management portlet unit. The portlet unit allows users with either a system administrator role or a module administrator role to add and delete sub-module pages, to set up the permissions of sub-module pages, and to configure the sub-module page style. On each sub-module page, the administrative users can add, delete, and allocate application portlet units. The administrative users can also grant individual users the permissions to view and configure a specific module, sub-module page, and portlet. Therefore, the system layout can be highly customizable so that some modules or portlet units are available only to the designated users, organizations, or user groups. This ensures that the right information is delivered to the right person at the right time. Figure 2.6 shows that the system administrator is adding a "view" permission of the "Directory" portlet unit displayed in the Subcontractor module to the user "Peter Kane."

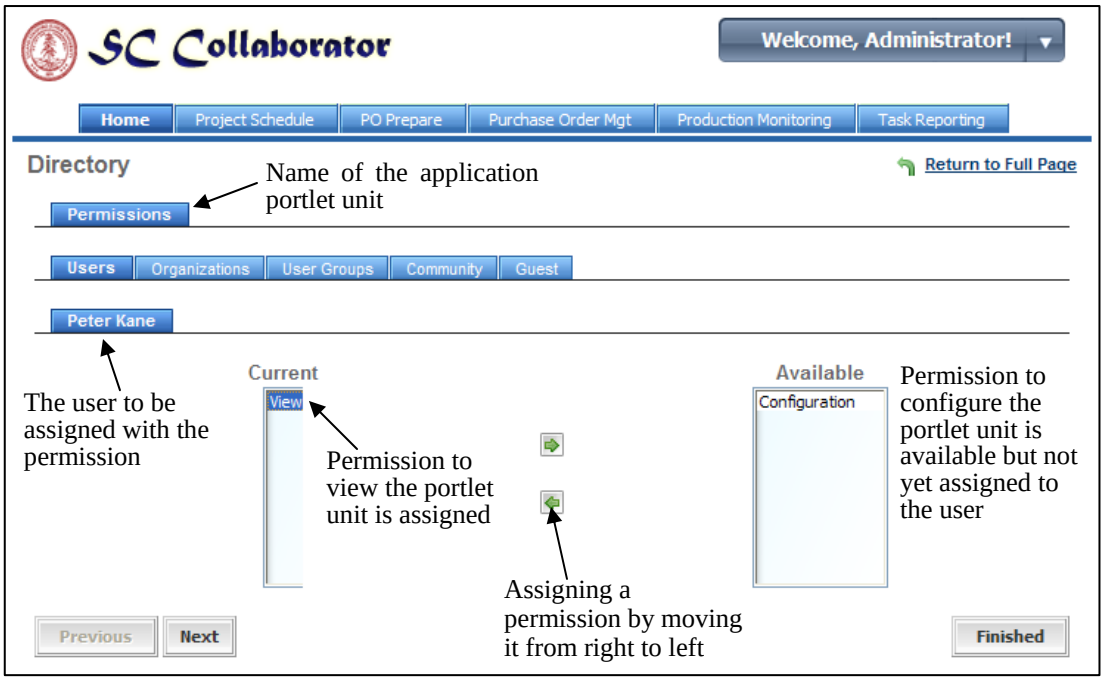


Figure 2.6: The application portlet unit for configuring the user permissions of the "Directory" portlet unit

2.3.3 Business Applications Layer

The business applications layer implements the service oriented architecture (SOA) in SC Collaborator. As shown in Figure 2.2, the business applications layer consists of two components – a repository of web service units and a collection of application portlet units. The web service units can be simple services performing basic information and application operations, or composite services supporting complex business processes. The application portlet units specify the layout of the user interface and invoke both internal and external web service units.

There are three distinct functional roles of a component in a service oriented computing model – service providers, service consumers, and service aggregators [13]. Service providers offer the service implementation, deploy the services, and supply their service descriptions. Service consumers are the end-users which invoke, locate, and execute the

services. Service aggregators consolidate multiple services into a new, single orchestrated service offering which is commonly known as a business process. A service aggregator can be considered as a consumer of multiple services and a provider of the final composite service. The details of service deployment, invocation, and aggregation on the business applications layer will be presented Section 2.4.

2.3.4 Database Support

In the database tier, an open source relational database – MySQL [90] – is used to store the application data as well as the system information including user information, layout configurations, and system settings. The dependencies of the major information managed in the database are depicted in Figure 2.7. For example, configuration of system layout and authentication of web service units are dependent on the access rights information, which is user-specific and organization-specific. Each product item is associated with information about its buyer and supplier, its purchase order, if any, its product specification, and the project task that the item is needed. A timestamp is also generated for all the products at every change in item status (item proposed, purchase order submitted, purchase order confirmed, item delivered, estimated item arrival, and actual item arrival). This information is stored in the system to aid evaluate the performance of business partners and plan the life cycle of each material product. Bottlenecks of the construction supply chain may also be noticed at an early stage of the project.

The SC Collaborator system is not bounded to a particular database system. The system can be installed with any Java Database Connectivity (JDBC) [89] compliant database without any complicated configuration and modification of codes due to the use of the Hibernate framework. The Hibernate framework maps the objects in a relational database into object-oriented Java classes. If a user has already installed other databases such as PostgreSQL and Oracle database, SC Collaborator can integrate with the existing database with little effort. The user does not need to install and execute MySQL in order for SC Collaborator to run.

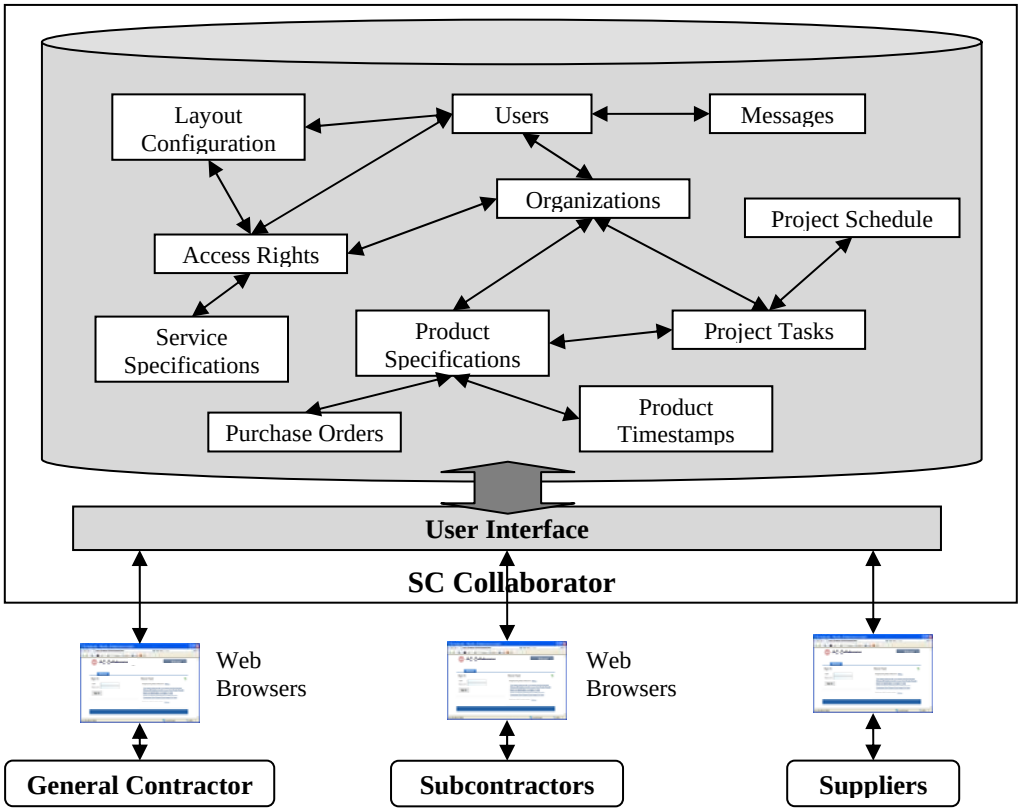


Figure 2.7: Schematic representation of the major information managed in SC Collaborator

2.4 Service Oriented Architecture in SC Collaborator

Service oriented architecture (SOA) in SC Collaborator is implemented on the business applications layer. The layer is comprised of two components – (1) the services component that takes the roles of service provider and service aggregator, and (2) the portlets component that takes the role of service consumer. As illustrated in Figure 2.8, there are three main parts on the business applications layer:

- Basic web service units, residing on the Apache Axis2 framework, which perform basic operations such as providing information, running an application, or manipulating data,

- Application portlet units, residing on the Apache Struts framework, which provide system layout and allow invocation of web service units, and

- BPEL process service units, residing on the Apache ODE engine, which combine and orchestrates web service units, which can be basic web service units or BPEL process service units.

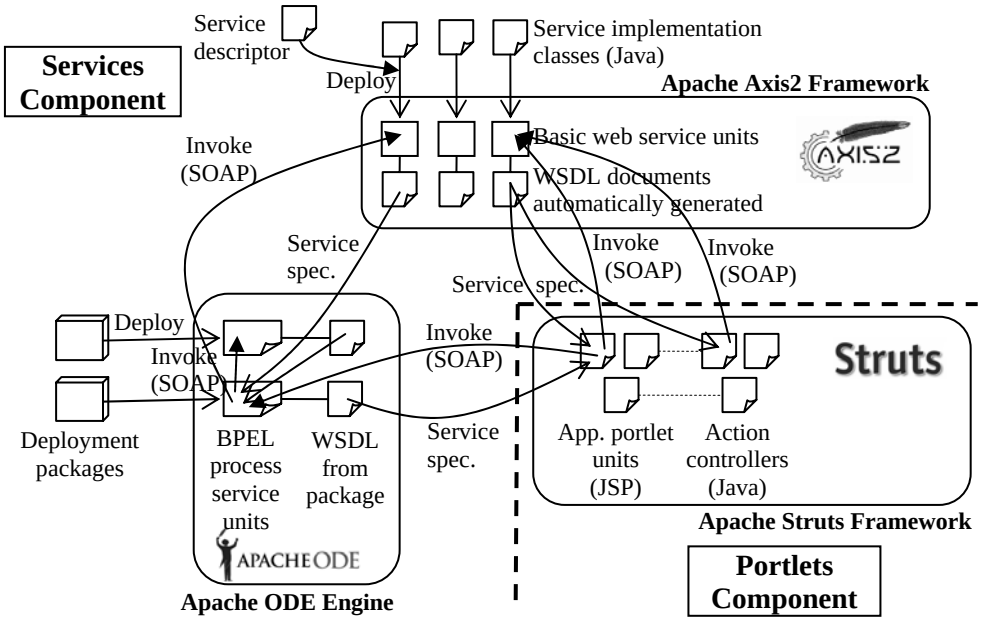


Figure 2.8: Interactions among different parts on the business applications layer in SC Collaborator

As illustrated in Figure 2.8, basic web service units are deployed from service implementation classes written in Java language. Each basic web service unit is associated with a WSDL document, which is exposed to provide the service consumers with the information on how to invoke the service unit. A BPEL process service unit is deployed using a deployment package. The package includes a BPEL process file that executes service orientation, and a WSDL file that provides service specification information of the BPEL process service unit. Application portlet units and the associated action controllers refer to the service specification provided by the WSDL documents and invoke the basic and BPEL service units via SOAP.

The following sections discusses (1) implementation and deployment of basic web service units, (2) system layout configuration and service invocation in application portlet units, and (3) orchestration, development, and deployment of BPEL process service units.

2.4.1 Deployment of Basic Web Service Units

Basic web service units provide fundamental functionalities to support complex operations. A web service unit can provide one or more operations. For example, the web service unit Material Order Service in SC Collaborator includes the operation “getItemDeliveryDetailsById” that obtains the delivery information of a particular product, the operation “getItemIdByOrder” that provides a list of product items in a specific purchase order, the operation “changeItemTargetDelivery” that changes the target delivery date of a product, and the operation “reportItemArrived” that reports the arrival of a product.

There are two types of web service operations – data service operation and transaction service operation. Table 2.1 shows some of the data service operations and transaction service operations of the web service unit Material Order Service as an example.

Table 2.1: Examples of the operations of the web service unit Material Order Service in SC Collaborator

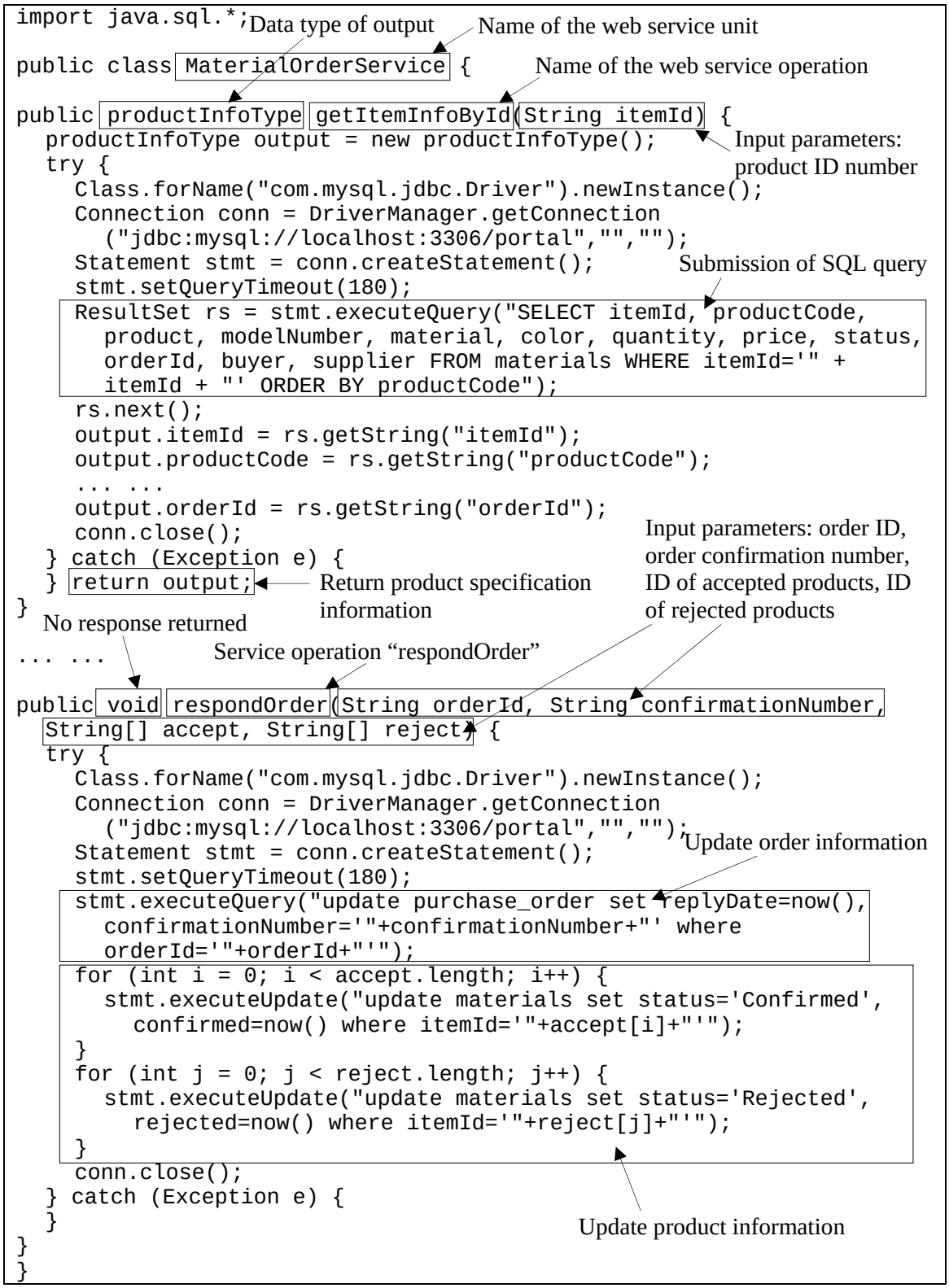
Data / Transaction	**Operation Name**	**Input Parameters**	**Output Parameters**
Data	getItemIdByOrder	orderId	itemId
	getItemIdByTask	taskId	itemId
	getItemInfoById	itemId	buyer, color, itemId, material, modelNumber, orderId, price, product, productCode, quantity, status, supplier
	getItemDelivery-DetailsById	itemId	arrival, buyer, deliveryEstimate, deliveryTarget, itemId, orderId, product, productCode, quantity, requested, shipped, supplier
Transaction	addItem	itemId, productCode, modelNumber, product, buyer, supplier, color, material, quantity, price	notification
	changeItem-TargetDelivery	itemId, deliveryTime	---
	reportItemArrived	itemId	---
	reportItemOrdered	itemId, orderId	---
	respondOrder	orderId, confirmationNumber, accept, reject	---

- Data service operations provide data to the consumers. This type of operations may connect to databases and submit queries, run a legacy software application and obtain the simulation outputs, locate a document and parse it for useful information, or simply manipulate the input values and offer the results. Data service operations are request-response in nature and contain both request inputs and response outputs. For instance, as illustrated in Table 2.1, the data service operation “getItemDeliveryDetailsById” that provides contractors with the

delivery details of a purchased product requires both request inputs and response outputs. For service operations that do not require an input parameter, an empty request message needs to be sent for service invocation.

- Transaction service operations create, modify, or remove data in an underlying system. This type of operations may change the data in databases, the values of a model in software applications, or the content of a document. Transaction service operations can be request-only or request-response in nature. For example, as illustrated in Table 2.1, the transaction service operation "reportItemArrived" that allows contractors to report arrival of product delivery returns no response message.

Web services can be implemented in programming languages such as Java and C# and be deployed in various ways using different engines. In SC Collaborator, web services are implemented in Java and deployed using the open source Apache Axis2 framework developed by the Apache Software Foundation. A Java service implementation class can contain multiple functions, each of which will be represented as an individual web service operation after deployment. As an example, Figure 2.9 shows the Java service implementation class for a data service operation "getItemInfoById" and a transaction service operation "respondOrder" of the service unit Material Order Service in SC Collaborator. As shown in Figure 2.9, the operation "getItemInfoById" receives a product identification number, submits SQL query to the back-end database, and returns product specification information in the format of *productInfoType*, which contains elements such as product code and status (refer to Figure 2.10). The operation "respondOrder" receives an order identification number, an order confirmation number, an array of identification numbers of the product items accepted by the supplier, and an array of identification numbers of the items rejected by the supplier. The operation then updates the product information and the purchase order information at the back-end database and returns nothing.




```
import java.sql.*;

public class MaterialOrderService {

public productInfoType getItemInfoById(String itemId) {
  productInfoType output = new productInfoType();
  try {
    Class.forName("com.mysql.jdbc.Driver").newInstance();
    Connection conn = DriverManager.getConnection
      ("jdbc:mysql://localhost:3306/portal","","");
    Statement stmt = conn.createStatement();
    stmt.setQueryTimeout(180);
    ResultSet rs = stmt.executeQuery("SELECT itemId, productCode,
      product, modelNumber, material, color, quantity, price, status,
      orderId, buyer, supplier FROM materials WHERE itemId='" +
      itemId + "' ORDER BY productCode");
    rs.next();
    output.itemId = rs.getString("itemId");
    output.productCode = rs.getString("productCode");
    ... ...
    output.orderId = rs.getString("orderId");
    conn.close();
  } catch (Exception e) {
  } return output;
}

... ...

public void respondOrder(String orderId, String confirmationNumber,
  String[] accept, String[] reject) {
  try {
    Class.forName("com.mysql.jdbc.Driver").newInstance();
    Connection conn = DriverManager.getConnection
      ("jdbc:mysql://localhost:3306/portal","","");
    Statement stmt = conn.createStatement();
    stmt.setQueryTimeout(180);
    stmt.executeQuery("update purchase_order set replyDate=now(),
      confirmationNumber='"+confirmationNumber+"' where
      orderId='"+orderId+"'");
    for (int i = 0; i < accept.length; i++) {
      stmt.executeUpdate("update materials set status='Confirmed',
        confirmed=now() where itemId='"+accept[i]+"'");
    }
    for (int j = 0; j < reject.length; j++) {
      stmt.executeUpdate("update materials set status='Rejected',
        rejected=now() where itemId='"+reject[j]+"'");
    }
    conn.close();
  } catch (Exception e) {
  }
}
}
```

Figure 2.9: Excerpt of the service implementation class for the Material Order Service

```
public class productInfoType {
   String itemId = "";
   String product = "";
   String productCode = "";
   String modelNumber = "";
   String material = "";
   String color = "";
   int quantity = 0;
   double price = 0;
   String buyer = "";
   String supplier = "";
   String orderId = "";
   String status = "";

   public String getItemId() {
      return itemId;
   }
   public void setItemId(String itemId) {
      this.itemId = itemId;
   }
   public String getProduct() {
      return product;
   }
   ... ...
}
```

Parameters of the output data type "productInfoType"

Figure 2.10: Java class for data type "productInfoType"

```
<service>
  <parameter name="ServiceClass" locked="false">
    MaterialOrderService
  </parameter>
  <messageReceivers>
    <messageReceiver mep="http://www.w3.org/2004/08/wsdl/in-only"
    class="org.apache.axis2.rpc.receivers.RPCInOnlyMessageReceiver"/>
    <messageReceiver mep="http://www.w3.org/2004/08/wsdl/in-out"
    class="org.apache.axis2.rpc.receivers.RPCMessageReceiver"/>
  </messageReceivers>
</service>
```

Name of the web service unit

Definition class of message receivers for request-only operations

Definition class of message receivers for request-response operations

Figure 2.11: Service descriptor file "services.xml"

The Java service implementation classes are deployed in order to be discovered, located, and invoked to. To deploy the web service unit Material Order Service using the Axis2 framework, for example, the Java service implementation class and the associated Java classes are compiled to a single folder. Next, the service descriptor named as "services.xml" is created to define the class to be used by the service and the appropriate message receivers, as illustrated in Figure 2.11. The service classes and the service

descriptor file are then combined and packaged into a file with an extension of "aar." Finally, the packaged file is deployed either by using the Axis2 web administration application or by copying it to the Axis2 services directory.

Once a web service is successfully deployed in the Axis2 framework, a Web Service Description Language (WSDL)[1] [104] file is automatically generated in the framework. WSDL is a W3C standard for describing web services. WSDL document specifies the location of a web service on the network, the specific operations available, and the request and response message formats of a web service. Service consumers can know how to use a web service by referring to its WSDL document. Figure 2.12 shows an excerpt of the WSDL of the service unit Material Order Service automatically generated when the service unit is deployed in the Axis2 framework. There are five major sections in a WSDL document.

- The Types section specifies the schema definitions of the data types used in the service.
- The Message section describes an abstract, typed definition of the request and response messages being exchanged.
- The PortType section provides an abstract set of operations, each of which is an abstract description of an action supported by the service.
- The Binding section specifies a concrete protocol and data format specification for a particular port type.
- The Service section is a collection of ports, each of which defines a connection endpoint as a combination of a binding and a network address.

[1] WSDL 1.0 was developed by IBM, Microsoft, and Ariba in 2000. The WSDL 1.1 standard was released in 2001 while the current version WSDL 2.0 was released in 2007.


```
<?xml version="1.0" encoding="UTF-8"?>
<wsdl:definitions xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/"
xmlns:soap12="http://schemas.xmlsoap.org/wsdl/soap12/"
xmlns:xs="http://www.w3.org/2001/XMLSchema"
targetNamespace="http://ws.apache.org/axis2">
<wsdl:types>
   <xs:schema xmlns:ns="http://ws.apache.org/axis2"
      targetNamespace="http://ws.apache.org/axis2">
      <xs:element name="getItemInfoById"><xs:complexType> <xs:sequence>
         <xs:element name="itemId" type="xs:string"/>
      </xs:sequence> </xs:complexType> </xs:element>
      <xs:element name="getItemInfoByIdResponse"> <xs:complexType> <xs:sequence>
         <xs:element name="return" type="ns1:productInfoType"/>
      </xs:sequence> </xs:complexType> </xs:element>
      <xs:element name="respondOrder"> <xs:complexType> <xs:sequence>
         <xs:element name="orderId" type="xs:string"/>
         <xs:element name="confirmationNumber" type="xs:string"/>
         <xs:element name="accept" maxOccurs="unbounded" type="xs:string"/>
         <xs:element name="reject" maxOccurs="unbounded" type="xs:string"/>
      </xs:sequence> </xs:complexType> </xs:element>
      ... ...
      <xs:complexType name="productInfoType"> <xs:sequence>
         <xs:element name="buyer" type="xs:string"/>
         ... ...
         <xs:element name="supplier" type="xs:string"/>
      </xs:sequence> </xs:complexType>
</xs:schema> </wsdl:types>
<wsdl:message name="respondOrderRequest">
   <wsdl:part name="parameters" element="ns0:respondOrder"/> </wsdl:message>
<wsdl:message name="getItemInfoByIdRequest">
   <wsdl:part name="parameters" element="ns0:getItemInfoById"/> </wsdl:message>
<wsdl:message name="getItemInfoByIdResponse">
   <wsdl:part name="parameters" element="ns0:getItemInfoByIdResponse"/> </wsdl:message>
... ...
<wsdl:portType name="MaterialOrderServicePortType">
   <wsdl:operation name="respondOrder">
      <wsdl:input message="ns0:respondOrderRequest" Action="urn:respondOrder"/>
   </wsdl:operation>
   <wsdl:operation name="getItemInfoById">
      <wsdl:input message="ns0:getItemInfoByIdRequest" Action="urn:getItemInfoById"/>
      <wsdl:output message="ns0:getItemInfoByIdResponse"
         Action="urn:getItemInfoByIdResponse"/> </wsdl:operation>
   ... ...
</wsdl:portType>
<wsdl:binding name="MaterialOrderServiceSOAP11Binding"
   type="ns0:MaterialOrderServicePortType">
   <wsdl:operation name="respondOrder">
      <soap:operation soapAction="urn:respondOrder" style="document"/>
      <wsdl:input> <soap:body use="literal"/> </wsdl:input>
   </wsdl:operation>
   <wsdl:operation name="getItemInfoById">
      <soap:operation soapAction="urn:getItemInfoById" style="document"/>
      <wsdl:input> <soap:body use="literal"/> </wsdl:input>
      <wsdl:output> <soap:body use="literal"/> </wsdl:output>
   </wsdl:operation>
   ... ...
</wsdl:binding>
<wsdl:service name="MaterialOrderService">
   <wsdl:port name="MaterialOrderServiceSOAP11port_http"
      binding="ns0:MaterialOrderServiceSOAP11Binding">
      <soap:address
        location="http://171.67.80.217:8080/service/processes/MaterialOrderService"/>
   </wsdl:port>
</wsdl:service>
</wsdl:definitions>
```

Figure 2.12: Excerpt of the WSDL file for the service unit Material Order Service

In WSDL, the abstract definition of ports and messages is separated from the network deployment or data format bindings. This allows the reuse of definitions for messages, which are abstract descriptions of the data being exchanged, and for port types, which are abstract collections of operations. For example, from the PortType section of the WSDL document shown in Figure 2.12, the service operation "respondOrder" is request-only in nature without response message whereas the operation "getItemInfoById" is request-response with both request and response messages. As described in the Types and Message sections, the operation "getItemInfoById" receives one parameter *itemId* and returns a result of type *productInfoType*. The input parameters *accept* and *reject* of the operation "respondOrder" contain an attribute of "maxOccurs" with a value of "unbounded," meaning that multiple elements of *accept* and *reject* are allowed. These specifications stay unchanged when the service unit Material Order Service is deployed in another machine. However, the address of the service location which is specified in the Service section changes according to the actual service deployment on the network.

2.4.2 Service Invocation and System Layout in Application Portlet Units

Each application portlet unit in SC Collaborator is an independent unit, which performs a specific task or business process. The application portlet units are based on Java framework and JavaServer Pages (JSP) technology. The JSP technology enables HTML codes to be embedded with Java codes. The HTML codes in a JSP file specify the layout and display as a regular web page. The embedded Java codes allow various Java-enabled functionalities such as basic computation, application execution, connection to databases, and invocation of web services. Therefore, multiple services can be integrated in a single portlet unit to implement various business processes. For instance, the application portlet unit that helps retailers to manage the purchase orders they have submitted can integrate three different services: (1) service that submits purchase orders to manufacturers, (2) service that monitors the status of each purchase order, and (3) service that triggers

warning notifications when a problem is encountered. The application portlet units in SC Collaborator are compliant with Java Specification Request (JSR) 168 standard [1], a specification that defines a standard programming model for portlet development. Consequently, the portlet units can be packaged and reused by other portal systems, allowing high portability across platforms.

There are two ways to invoke a standardized web service. One method to invoke a web service is by regenerating the implementation classes of the service and importing them into the programs that service invocation is performed. There exist programs that allow users to specify the location of a WSDL document and then produce a set of service implementation Java codes that are consistent with the service specification. Users can compile the Java codes into client classes and import them as normal external library classes. Another method is by specifying the location and operation of the service, initializing the request message, sending the request directly to the deployed service, and parsing the response message to obtain useful information, in the programs that service invocation is performed. Unlike the first method, the second method requires understanding of the schema of the request and response messages and identification of particular service specifications from a WSDL document, which may pose challenges to beginner service consumers. However, the second method does not require compilation of client classes and allows flexible modifications of service invocation. Therefore, the second method is utilized in the SC Collaborator system.

Take the supplier's order management portlet unit in SC Collaborator as an example. The portlet unit allows suppliers to select a particular purchase order they have received, to view the products that are in the purchase order, and to respond to the order electronically with a confirmation number. As illustrated in Figure 2.13, the portlet unit invokes the operation "getIdemIdByOrder" of the Material Order Service to obtain a list of identification numbers of the products included in the purchase order "PO-WM-389."

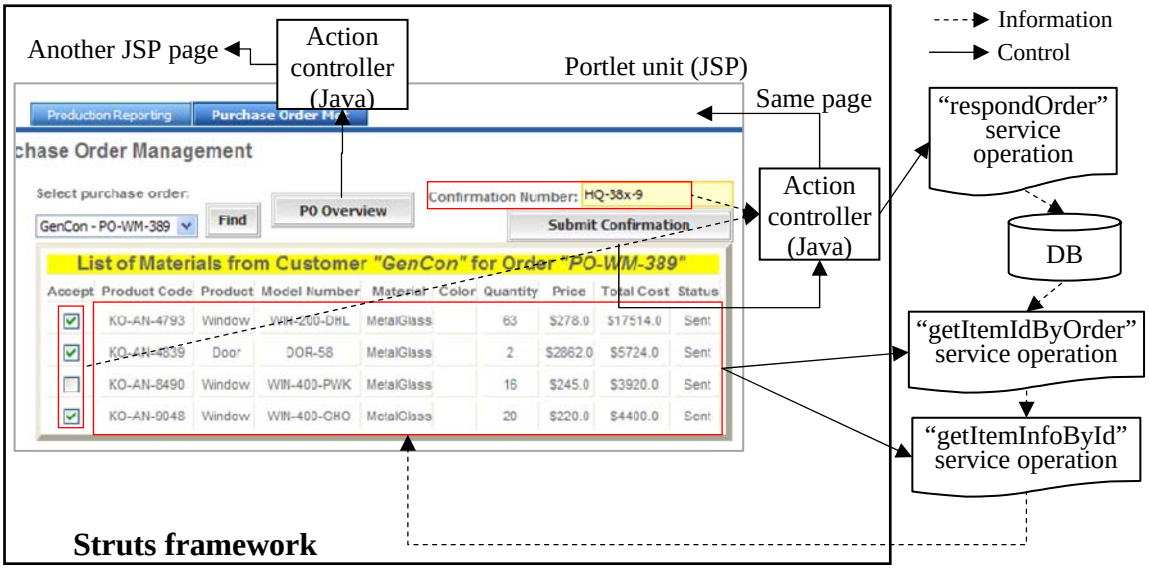


Figure 2.13: Invocation of web services by the order management portlet unit in SC Collaborator

After that, the portlet unit invokes the service operation "getItemInfoById" and obtains the product specification information for each product, which is tabulated in the user interface display. Figure 2.14 shows an excerpt of the JSP codes of the portlet unit. As illustrated in Figure 2.14, invocation of a web service operation requires five pieces of information: (1) target namespace of the service, (2) name of the data type used in the request message, (3) names of the elements in the request message, (4) location of the service on the network, and (5) name of the invoked service operation. As labeled in Figure 2.12 and Figure 2.14, WSDL document of the service operation "getItemInfoById" being invoked provides all these five pieces of information. System administrator can refer to the WSDL documents and modify these service invocation specifications easily to accommodate any change in the service operations being invoked.

```
... ...
<table>
<tr>  <td colspan=10> List of Materials from Customer "<%= buyer %>" for Order "<%=
orderNumber %>" </td> </tr>
<tr>  <td>Accept</td> <td>Product Code</td> <td>Product</td>
   <td>Model Number</td> <td>Material</td> <td>Color</td> <td>Quantity</td>
   <td>Price</td> <td>Total Cost</td> <td>Status</td>
</tr>
```

HTML codes in JSP

Embedded Java codes in JSP

```
<%
// Obtain a list of itemIds
```

Internal variable with value "PO-WM-389" in the example

```
OMFactory fac = OMAbstractFactory.getOMFactory();
OMNamespace omNs = fac.createOMNamespace("http://ws.apache.org/axis2", "eig");
OMElement payload = fac.createOMElement("getItemIdByOrder", omNs);
OMElement value = fac.createOMElement("orderId", omNs);
value.setText(orderNumber);
payload.addChild(value);

ServiceClient serviceClient = new ServiceClient();
Options options = new Options();
options.setTo(new EndpointReference
("http://171.67.80.217:8080/service/processes/MaterialOrderService"));
options.setAction("getItemIdByOrder");
serviceClient.setOptions(options);
OMElement result = serviceClient.sendReceive(payload);
```

Invocation of the service operation "getIdemIdByOrder"

Iterate for every product item, then parse the product ID number

```
Iterator<OMElement> iter = result.getChildElements();
while (iter.hasNext()) {
   String itemId = iter.next().getText();

   // For each item, obtain the product specification information

   OMFactory fac2 = OMAbstractFactory.getOMFactory();
   OMNamespace omNs2 = fac2.createOMNamespace("http://ws.apache.org/axis2", "eig");
   OMElement payload2 = fac2.createOMElement("getItemInfoById", omNs2);
   OMElement value2 = fac2.createOMElement("itemId", omNs2);
   value2.setText(itemId);
   payload2.addChild(value2);

   ServiceClient serviceClient2 = new ServiceClient();
   Options options2 = new Options();
   options2.setTo(new EndpointReference
   ("http://171.67.80.217:8080/service/processes/MaterialOrderService"));
   options2.setAction("getItemInfoById");
   serviceClient2.setOptions(options2);
   OMElement result2 = serviceClient2.sendReceive(payload2);

   Iterator<OMElement> iter2 = result2.getFirstElement().getChildElements();
   String buyer2 = iter2.next().getText();
   String color = iter2.next().getText();
   ... ...
   String status = iter2.next().getText();
   String supplier2 = iter2.next().getText();
%>
<tr> <td> <input type=checkbox name="item" value="<%= itemId %>" /> </td>
   <td><%= productCode %></td> <td><%= product %></td>
   <td><%= modelNumber %></td> <td><%= material %></td>
   <td><%= color %></td> <td><%= quantity %></td>
   <td>$<%= price %></td>
   <td>$<%= Double.parseDouble(price)*Integer.parseInt(quantity) %></td>
   <td><%= status %></td>
</tr>
... ...
```

Invocation of the service operation "getItemInfoById"

① Target namespace of service

② Request message data type name

③ Elements in request message

④ Location of service

⑤ Name of operation

Parse the response message for the product information

Embedded Java codes in JSP

Figure 2.14: Excerpt of the JSP codes for the order management portlet unit

Communication with web service units is performed using Simple Object Access Protocol (SOAP)[2] [102] messaging. SOAP is a W3C standard that provides a protocol for communications between web services. To invoke a web service operation, the embedded Java codes in the application portlet units generate a request message in the SOAP XML format and send it to the service unit through the SOAP. A response message is returned if the service operation being invoked request-response in nature. The response message is parsed in the portlet units for information of interest. Figure 2.15 shows the SOAP request and response messages of the service operation "getItemInfoById."

In SC Collaborator, invocation of web service units can also be performed by the action controllers in the Apache Struts framework. The action controllers are intended to specify the page flow of a portlet unit. Since they are Java-based, they can also be used to perform business logic, application execution, database connection, and service invocation. As illustrated in Figure 2.13, the action controllers can be triggered by button controls in a JSP portlet page. For example, the "PO Overview" button is associated with an action controller which redirects the portlet unit to another portlet page which shows all the purchase orders the supplier has received. The "Submit Confirmation" button triggers an action controller that collects the inputs of the accept checkboxes and the confirmation number, invokes the service operation "respondOrder," and redirects to the same portlet page with updated information.

[2] SOAP was originally designed with backing from Microsoft in 1998. SOAP 1.1 became a W3C standard in 2000. The current version is SOAP 1.2, which was released as a W3C standard in 2003 (first edition) and in 2007 (second edition) respectively.

```
<soapenv:Envelope
  xmlns:soapenv="http://schemas.xmlsoap.org/soap/envelope/"
  xmlns:q0="http://ws.apache.org/axis2"
  xmlns:xsd="http://www.w3.org/2001/XMLSchema"
  xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance">
  <soapenv:Body>
    <q0:getItemInfoById>
      <q0:itemId>KO-AN-4793</q0:itemId>
    </q0:getItemInfoById>
  </soapenv:Body>
</soapenv:Envelope>
```

```
<soapenv:Envelope
  xmlns:soapenv="http://schemas.xmlsoap.org/soap/envelope/">
  <soapenv:Body>
    <getItemInfoByIdResponse xmlns:ns="http://ws.apache.org/axis2">
      <ns:return xmlns:ax21="http://ws.apache.org/axis2/xsd"
        type="productInfoType">
        <ax21:buyer>GenCon</ax21:buyer>
        <ax21:color />
        <ax21:itemId>KO-AN-4793-1</ax21:itemId>
        <ax21:material>MetalGlass</ax21:material>
        <ax21:modelNumber>WIN-200-DHL</ax21:modelNumber>
        <ax21:orderId>PO-WM-389</ax21:orderId>
        <ax21:price>278.0</ax21:price>
        <ax21:product>Window</ax21:product>
        <ax21:productCode>KO-AN-4793</ax21:productCode>
        <ax21:quantity>63</ax21:quantity>
        <ax21:status>Sent</ax21:status>
        <ax21:supplier>Anderson</ax21:supplier>
      </ns:return>
    </getItemInfoByIdResponse>
  </soapenv:Body>
</soapenv:Envelope>
```

Information being parsed by the embedded Java codes in the order management application portlet unit

Figure 2.15: The SOAP request and response messages of the service operation "getItemInfoById"

2.4.3 Service Aggregation and Orchestration Using Business Process Execution Language (BPEL)

In a service oriented portal framework, information, applications and internal system operations are deployed and delivered as web services. These basic web services usually

are not sufficient to perform a business process individually. These web services often need to be aggregated with each other into a workflow. For instance, multiple cross-application activities are required to implement a business process "add purchase order." These activities may include adding a purchase order to the production plan, sending confirmation to the customer, changing the status of the order and the corresponding items, and allocating materials and resources to fulfill the order. Each of these activity components could be separated and deployed as individual web services. A mechanism to combine and coordinate these activity component services is necessary to complete a business process.

There are several research efforts on the mechanisms to invoke, terminate, and combine web-based services. Cheng [21] has developed a simulation access language (SimAL) and framework that integrate legacy project management applications, manage the information flow among them, and allow users to build up scenarios for engineering simulation. Benatallah et al. [12] presents a framework called Self-Serv which consists of a runtime environment that performs dynamic provider selection and orchestrates composite services using SOAP standard. Greenwood et al. [35] introduces a framework namely Web Service Integration Gateway Service (WSIGS) which allows combination of web services and software agents by message encodings translation and exchange using WSDL, SOAP and UDDI standards. Maamar et al. [65] attempts to deploy web services into agents, each of which contains a service chart diagram that defines the underlying web service and is able to interact with peer agents through XML-based conversation messages.

Standards are also available to support composition and orchestration of web services. Web Services Choreography Description Language (WS-CDL) [103] and Web Services Choreography Interface (WSCI) [100] are W3C standards that provide a global, message-oriented view of interactions by describing the collective message exchanges among the interacting web services. Web Services Conservation Language (WSCL) [101] published by W3C helps specify the XML documents being exchanged among web services and the

sequence of these document exchanges. However, these standards only provide an abstract specification of web services composition. Supports for programming and executing these standards are also very limited. In contrast, Business Process Execution Language (BPEL)[3] is an implementation-level standard for web services composition and supported by commercial and open source orchestration engines for execution. The integration and orchestration of the web service units in SC Collaborator using BPEL will be discussed next.

2.4.3.1 Overview of BPEL

BPEL is an executable XML-based language for specifying a business process in which most of the tasks represent interactions between the process and external web services. The language is interpreted and executed by an orchestration engine which realizes the process flow and invokes the connected web services. BPEL is a layer on top of WSDL and XML Schema, with WSDL and XML Schema defining the structural aspects of service interactions, and BPEL defining the behavioral aspects.

The BPEL standard supports two kinds of activity coordination – basic activities and structured activities. Basic activities, also called primitive activities, correspond to atomic actions such as message exchange and service initiation that are being performed within a process. For instance, an *invoke* activity invokes an operation of some web service units. A *receive* activity waits for a message from an external partner. A *reply* activity sends response messages to an external partner. A *wait* activity pauses for a certain period of time. An *assign* activity copies data from one place to another. In a

[3] BPEL was first developed in 2002 by BEA Systems, IBM, and Microsoft. The BPEL 1.0 standard was a merger of Web Services Flow Language (WSFL) [59] and XLANG [92], which were developed in 2001 by IBM and Microsoft respectively. In 2003, the three companies together with SAP and Siebel Systems modified BPEL 1.0 into Business Process Execution Language for Web Services (BPEL4WS) 1.1 [10] and submitted the BPEL4WS 1.1 to Organization for the Advancement of Structured Information Standards (OASIS) for standardization. The current version is Web Services Business Process Execution Language (WS-BPEL) 2.0 [80], which was published as one of the OASIS standards by the BPEL Technical Committee of OASIS in 2007.

BPEL process, partners interact through web service interfaces called port types, and the structure of the relationship at the interface level is specified by a partner link. *Invoke*, *receive*, and *reply* activities are three types of interaction activities defined in the BPEL specification. These interaction activities need to specify the partner link through which the interaction occurs, the operation involved, the port type in the partner link that is being used, and the input and output variables that will be read from or written to.

Structured activities manage the overall process flow, specifying what activities should run and in what order. One can think of structured activities as the underlying programming logic for a BPEL process. There are eight structured activities in BPEL 2.0: *sequence*, *flow*, *if*, *pick*, *while*, *repeat-until*, *scope*, and *for-each*. A *sequence* activity contains one or more activities that are performed sequentially. A *flow* activity allows parallel execution of activities. A *if* activity provides conditional routing between activities. A *pick* activity executes a conditional branch when it is triggered by either a message event or an alarm event. W*hile* and *repeat-until* activities repeats performance of an activity in a structured loop until a certain condition no longer holds true. A *scope* activity groups activities into a block, which is treated as an individual unit. A *for-each* activity iteratively executes an activity according to an internal counter. Structured activities can be nested and combined in arbitrary ways, thus enabling the presentation of complex structures.

2.4.3.2 Service Orchestration Using BPEL

BPEL defines a model and a grammar for describing the behavior of a business process based on interactions between the process and its partners. A BPEL process consists of a set of activities that can be combined through structured operators. The interaction activities – *invoke*, *receive* and *reply* – connects internal or external web service units while other BEPL activities specify the flow and logic among the interaction activities. Therefore, BPEL can integrate individual web service units and orchestrate them to offer specific business functions.

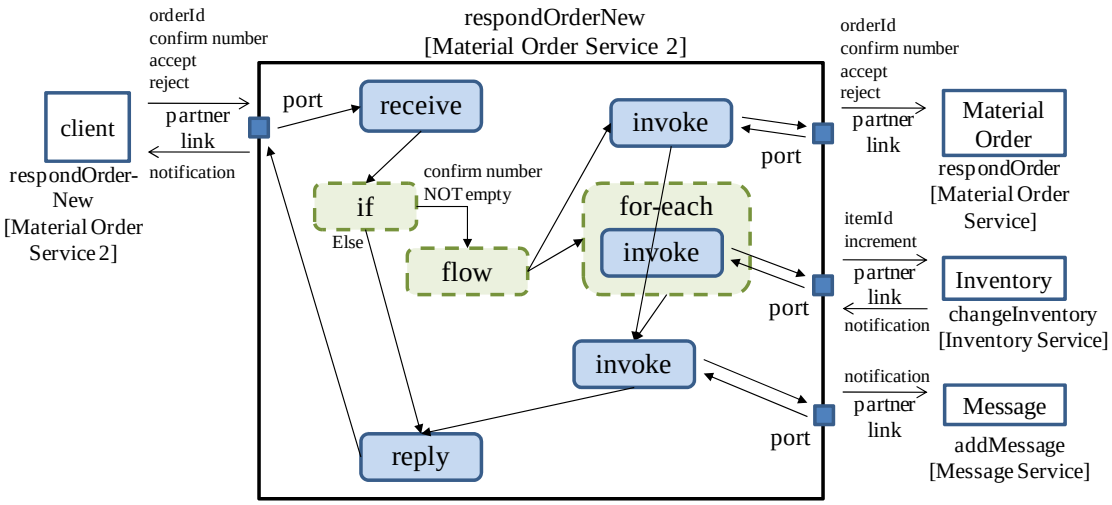


Figure 2.16: Schematic representation of the BPEL activities for the operation "respondOrderNew"

As an example, a BPEL process operation "respondOrderNew" is created to extend the operation "respondOrder" of the service unit Material Order Service using BPEL. Figure 2.16 depicts the behavior of the BPEL process operation "respondOrderNew." The activities with solid lines are BPEL basic interaction activities whereas the activities with dotted lines are structured activities. The service operation "respondOrder" has been described in Section 2.4.1. Both operations "respondOrderNew" and "respondOrder" receive an order identification number, an order confirmation number, a list of identification numbers of the accepted products, and a list of identification numbers of the rejected products, and then update the information of the corresponding purchase order and product items.

Other functionalities can be added to the created operation "respondOrderNew." As illustrated in Figure 2.16, after receiving the input parameters from the partner link "client," the operation "respondOrderNew" checks whether the confirmation number input is empty. If not, the operation performs two tasks concurrently – (1) updating order and product information, and (2) updating the inventory planning information. The former task is done by invoking the operation "respondOrder" of the service unit Material

Order Service through partner link “Material Order.” The latter task is performed by invoking the operation “changeInventory” of the service unit Inventory Service through partner link “Inventory” for each accepted product. The operation “changeInventory” is request-response in nature. It receives input parameters of a product identification number and the increment on product inventory record required to change, and returns a notification to the service consumers. After that, the operation “respondOrderNew” sends a notification to the supplier record by invoking the operation “addMessage” of the service unit Message Service through partner link “Message.” Finally, the operation “respondOrderNew” returns a notification to the customer.

Figure 2.17 shows the BPEL code that defnes an executiable “respondOrderNew” process. As illustrated in Figure 2.17, there are four sections in a BPEL process file.

- The Import section specifies the WSDL documents of the external service units invoked by the BPEL process.
- The PartnerLinks section indicates the role of the partner and the process itself.
- The Variables section describes the name and message type of the variables defined in the process.
- The orchestration logic section defines the flow and implementation details of each activity in the process.

This example illustrates that functionalities provided by basic web service units can be combined and orchestrated in BPEL process service units to provide complex business operations. BPEL process can also invoke and combine other BPEL process service units. In other words, recursive service composition is allowed and service units of different level of complexity can be built based on the basic service units.

```
<bpel:process name="MaterialOrderService2" suppressJoinFailure="yes"
  targetNamespace="http://171.67.80.217:8080/service/processes/MaterialOrderService2"
  xmlns:tns="http://171.67.80.217:8080/service/processes/MaterialOrderService2"
  xmlns:bpel="http://docs.oasis-open.org/wsbpel/2.0/process/executable"
  xmlns:ns="http://ws.apache.org/axis2">
<bpel:import namespace="http://ws.apache.org/axis2" location="InventoryService.wsdl"
  importType="http://schemas.xmlsoap.org/wsdl/" />
<bpel:import namespace="http://ws.apache.org/axis2"
  location="MaterialOrderService.wsdl" importType="http://schemas.xmlsoap.org/wsdl/" />
<bpel:import namespace="http://ws.apache.org/axis2" location="MessageService.wsdl"
  importType="http://schemas.xmlsoap.org/wsdl/" />
<bpel:partnerLinks>
  <bpel:partnerLink name="client" partnerLinkType="tns:MaterialOrderService2"
    myRole="MaterialOrderService2Provider" />
  <bpel:partnerLink name="MaterialOrder" partnerLinkType="tns:MaterialOrderPLT"
    partnerRole="serviceProvider" />
  <bpel:partnerLink name="Inventory" partnerLinkType="tns:InventoryPTL"
    partnerRole="serviceProvider" />
  <bpel:partnerLink name="Message" partnerLinkType="tns:Message"
    partnerRole="serviceProvider" />
</bpel:partnerLinks>
<bpel:variables>
  <bpel:variable name="input" messageType="tns:MaterialOrderService2RequestMessage"/>
  <bpel:variable name="output" messageType="tns:MaterialOrderService2ResponseMessage"/>
  <bpel:variable name="MaterialOrderRequest" element="ns:respondOrder"/>
  <bpel:variable name="InventoryRequest" element="ns:changeInventory"/>
  <bpel:variable name="MessageRequest" messageType="ns:addMessageRequest"/>
</bpel:variables>
<bpel:sequence name="main">
<bpel:receive name="receiveInput" partnerLink="client"
  portType="tns:MaterialOrderService2" operation="respondOrderNew" variable="input"/>
<bpel:if name="If">
  <bpel:condition><![CDATA[$input.payload/tns:confirmationNumber!=""]]></bpel:condition>
  <bpel:sequence>
  <bpel:flow name="Flow"><bpel:sequence name="Sequence">
  <bpel:assign name="Assign">
    <bpel:copy> ... ... </bpel:copy>
  </bpel:assign>
  <bpel:invoke name="respondOrder" partnerLink="MaterialOrder" operation="respondOrder"
    portType="ns:MaterialOrderServicePortType" inputVariable="MaterialOrderRequest" />
  </bpel:sequence><bpel:forEach parallel="no" counterName="Counter" name="ForEach">
    <bpel:startCounterValue><![CDATA[1]]></bpel:startCounterValue>
    <bpel:finalCounterValue> <![CDATA[count($input.payload/tns:accept)]]>
    </bpel:finalCounterValue>
    <bpel:scope>
      <bpel:sequence name="Sequence">
        <bpel:assign validate="no" name="Assign"> ... ... </bpel:assign>
        <bpel:invoke name="updateInventory" partnerLink="Inventory"
          operation="changeInventory" inputVariable="InventoryRequest" />
      </bpel:sequence>
  </bpel:scope></bpel:forEach></bpel:flow>
  <bpel:assign validate="no" name="notifySuccess"> ... ... </bpel:assign>
  <bpel:assign validate="no" name="Assign"> ... ... </bpel:assign>
  <bpel:invoke name="Invoke" partnerLink="Message" operation="addMessage"
    inputVariable="MessageRequest" />
  </bpel:sequence>
<bpel:else>
  <bpel:assign validate="no" name="notifyError"> ... ... </bpel:assign>
</bpel:else>
</bpel:if>
<bpel:reply name="replyOutput" partnerLink="client"/>
</bpel:sequence>
</bpel:process>
```


Figure 2.17: Excerpt of the BPEL code for the service operation “respondOrderNew”

2.4.3.3 Development and Deployment of BPEL Processes

Editing BPEL codes can be challenging, especially when dealing with a large scale service orientation. Eclipse BPEL Visual Designer [32] is used to facilitate the development and validation of BPEL process files. The open source BPEL editor is an eclipse plug-in developed by the Eclipse Foundation. It provides a graphical visualization of BPEL processes, a user-friendly interface for defining the BPEL activities, and a validation engine that check the compliance of BPEL files. Figure 2.18 shows the graphical representation of the aforementioned operation "respondOrderNew" displayed in Eclipse BPEL Visual Designer.

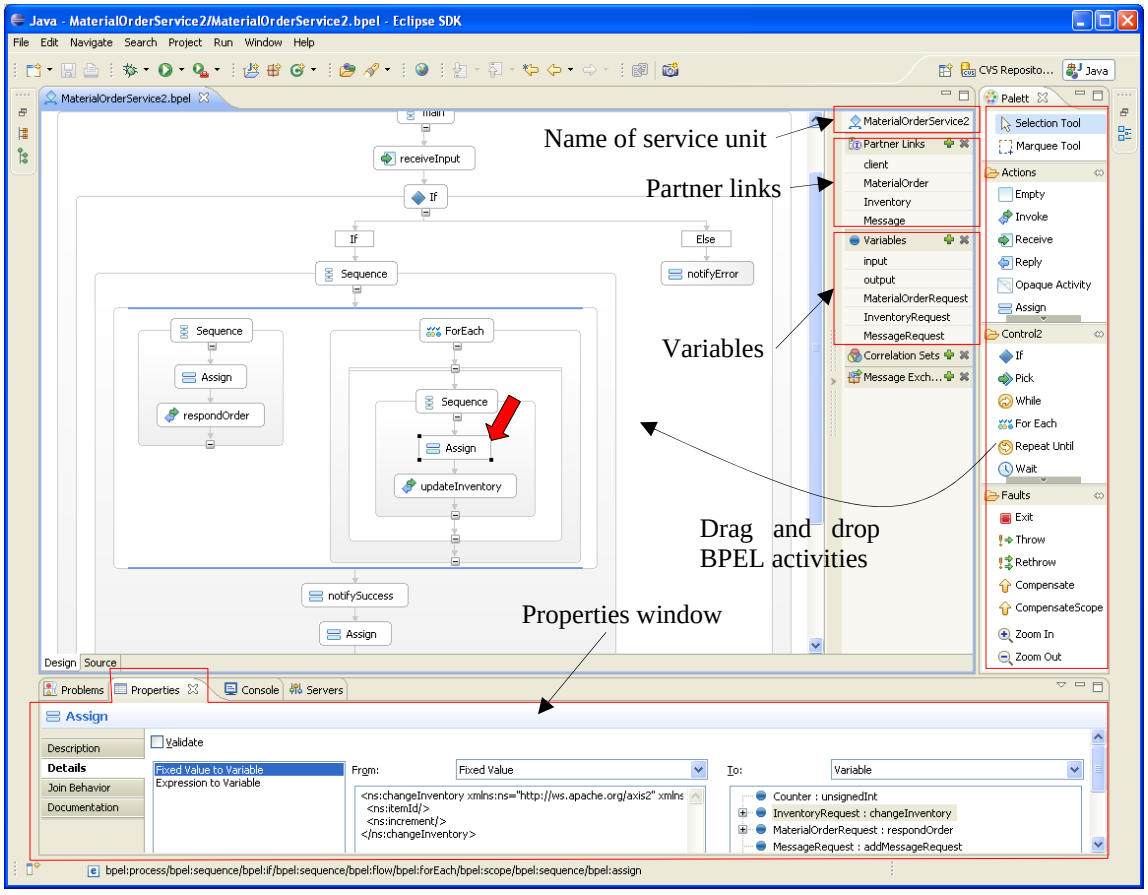


Figure 2.18: Eclipse BPEL Visual Designer

When a BPEL activity is selected in the display in Eclipse BPEL Visual Designer, the Properties window shows a form for entering specification details of the BPEL activity element. The form is dependent on the type of the selected BPEL activities. For example, Figure 2.18 shows the form for the *assign* activity that assigns input values to the request message for the "changeInventory" operation. Users can create BPEL process easily in Eclipse BPEL Visual Designer by simple drag-and-drop of BPEL activities from the column on the right. The BPEL editor also facilitates the definition of partner links and variables in BPEL processes.

A BPEL process file needs to be deployed in a BPEL engine in order to execute the business process specified in the file. The BPEL engine used in SC Collaborator is Apache Orchestration Director Engine (ODE), an open source package developed by the Apache Software Foundation. As illustrated in Figure 2.19, to deploy a BPEL process file in Apache ODE, a deployment package consisting of four types of files is required. The four types of files included in a deployment package are:

- A BPEL process file that describes the behavior and orchestration details of the BPEL process (Figure 2.17),
- A deployment descriptor with file name "deploy.xml" that indicates the name and port of the partner links defined in the BPEL process (Figure 2.20),
- A WSDL document that describes the BPEL process unit (Figure 2.21), and
- WSDL documents that describe the web service units that are invoked in the BPEL process.

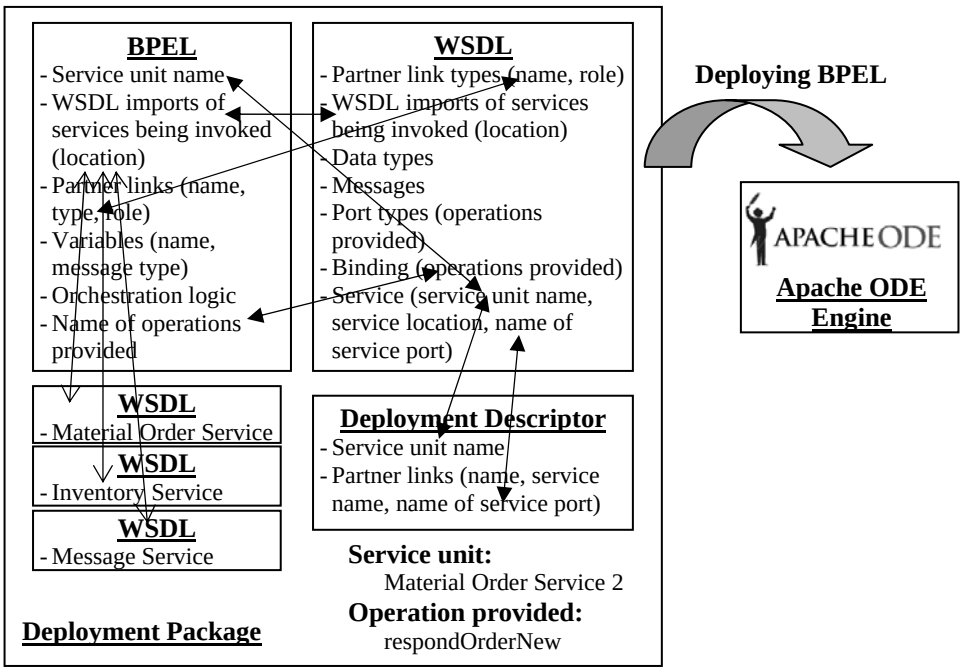


Figure 2.19: Deployment of BPEL process service “Material Order Service 2” with service operation “respondOrderNew”

```
<?xml version="1.0" encoding="UTF-8"?>
<deploy xmlns="http://www.apache.org/ode/schemas/dd/2007/03"
xmlns:MaterialOrderService2="http://171.67.80.217:8080/service/processes/Mate
rialOrderService2" xmlns:axis2="http://ws.apache.org/axis2">
  <process name="MaterialOrderService2:MaterialOrderService2">
    <active>true</active>
    <process-events generate="all"/>
    <provide partnerLink="client">
      <service name="MaterialOrderService2:MaterialOrderService2"
        port="MaterialOrderService2Port"/>
    </provide>
    <invoke partnerLink="MaterialOrder">
      <service name="axis2:MaterialOrderService"
        port="MaterialOrderServiceSOAP11port_http"/>
    </invoke>
    <invoke partnerLink="Inventory">
      <service name="axis2:InventoryService"
        port="InventoryServiceSOAP11port_http"/>
    </invoke>
    <invoke partnerLink="Message">
      <service name="axis2:MessageService"
        port="MessageServiceSOAP11port_http"/>
    </invoke>
  </process>
</deploy>
```

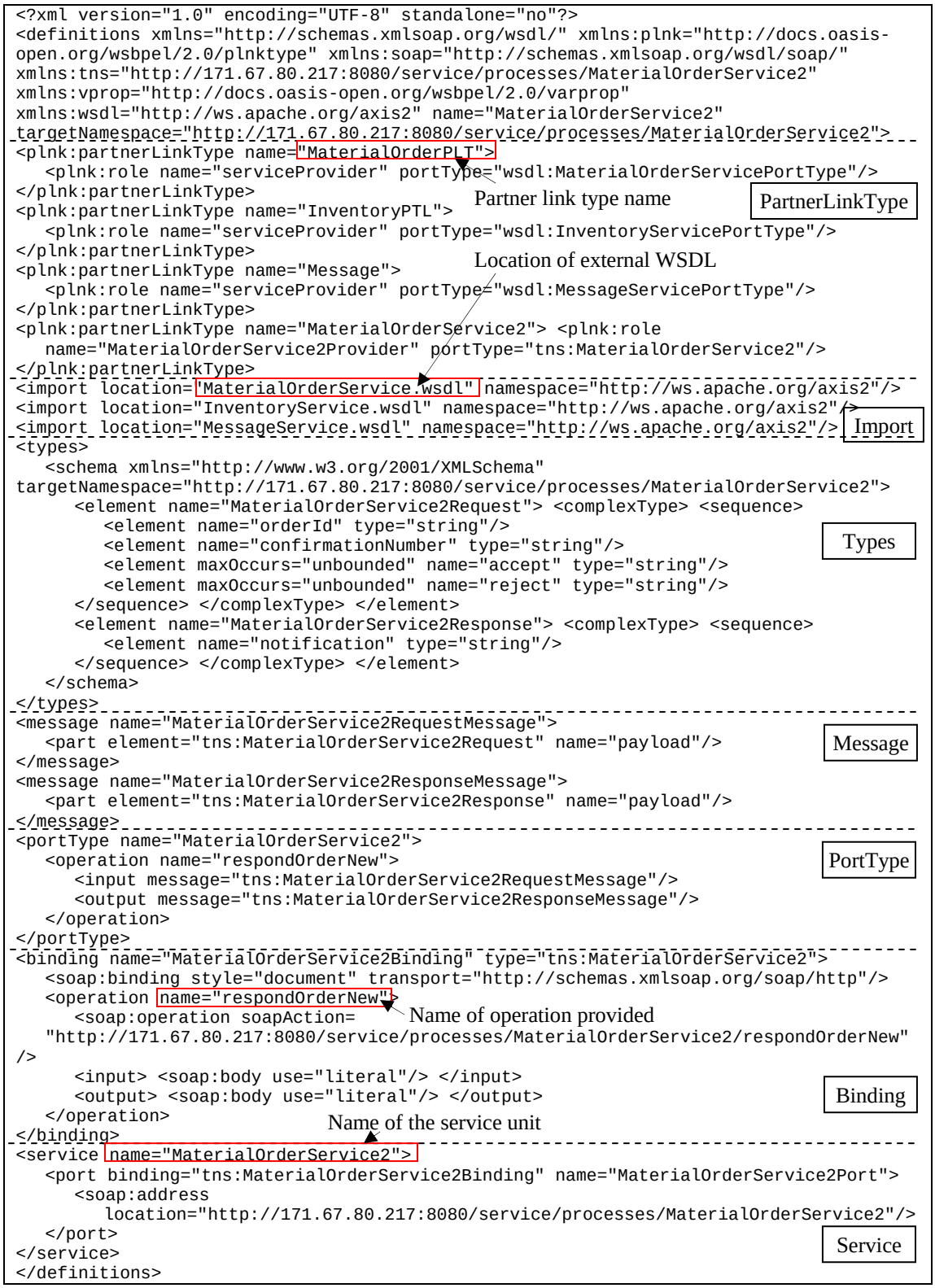
Name of the service unit

Partner link name

For the web service unit provided by the BPEL process itself

For every web service unit that is invoked

Figure 2.20: Deployment descriptor “deploy.xml” for the BPEL process service with operation “respondOrderNew”




```
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<definitions xmlns="http://schemas.xmlsoap.org/wsdl/" xmlns:plnk="http://docs.oasis-
open.org/wsbpel/2.0/plnktype" xmlns:soap="http://schemas.xmlsoap.org/wsdl/soap/"
xmlns:tns="http://171.67.80.217:8080/service/processes/MaterialOrderService2"
xmlns:vprop="http://docs.oasis-open.org/wsbpel/2.0/varprop"
xmlns:wsdl="http://ws.apache.org/axis2" name="MaterialOrderService2"
targetNamespace="http://171.67.80.217:8080/service/processes/MaterialOrderService2">
<plnk:partnerLinkType name="MaterialOrderPLT">
   <plnk:role name="serviceProvider" portType="wsdl:MaterialOrderServicePortType"/>
</plnk:partnerLinkType>
<plnk:partnerLinkType name="InventoryPTL">
   <plnk:role name="serviceProvider" portType="wsdl:InventoryServicePortType"/>
</plnk:partnerLinkType>
<plnk:partnerLinkType name="Message">
   <plnk:role name="serviceProvider" portType="wsdl:MessageServicePortType"/>
</plnk:partnerLinkType>
<plnk:partnerLinkType name="MaterialOrderService2"> <plnk:role
   name="MaterialOrderService2Provider" portType="tns:MaterialOrderService2"/>
</plnk:partnerLinkType>
<import location='MaterialOrderService.wsdl" namespace="http://ws.apache.org/axis2"/>
<import location="InventoryService.wsdl" namespace="http://ws.apache.org/axis2"/>
<import location="MessageService.wsdl" namespace="http://ws.apache.org/axis2"/>
<types>
   <schema xmlns="http://www.w3.org/2001/XMLSchema"
targetNamespace="http://171.67.80.217:8080/service/processes/MaterialOrderService2">
      <element name="MaterialOrderService2Request"> <complexType> <sequence>
         <element name="orderId" type="string"/>
         <element name="confirmationNumber" type="string"/>
         <element maxOccurs="unbounded" name="accept" type="string"/>
         <element maxOccurs="unbounded" name="reject" type="string"/>
      </sequence> </complexType> </element>
      <element name="MaterialOrderService2Response"> <complexType> <sequence>
         <element name="notification" type="string"/>
      </sequence> </complexType> </element>
   </schema>
</types>
<message name="MaterialOrderService2RequestMessage">
   <part element="tns:MaterialOrderService2Request" name="payload"/>
</message>
<message name="MaterialOrderService2ResponseMessage">
   <part element="tns:MaterialOrderService2Response" name="payload"/>
</message>
<portType name="MaterialOrderService2">
   <operation name="respondOrderNew">
      <input message="tns:MaterialOrderService2RequestMessage"/>
      <output message="tns:MaterialOrderService2ResponseMessage"/>
   </operation>
</portType>
<binding name="MaterialOrderService2Binding" type="tns:MaterialOrderService2">
   <soap:binding style="document" transport="http://schemas.xmlsoap.org/soap/http"/>
   <operation name="respondOrderNew">
      <soap:operation soapAction=
   "http://171.67.80.217:8080/service/processes/MaterialOrderService2/respondOrderNew"
/>
      <input> <soap:body use="literal"/> </input>
      <output> <soap:body use="literal"/> </output>
   </operation>
</binding>
<service name="MaterialOrderService2">
   <port binding="tns:MaterialOrderService2Binding" name="MaterialOrderService2Port">
      <soap:address
         location="http://171.67.80.217:8080/service/processes/MaterialOrderService2"/>
   </port>
</service>
</definitions>
```

Figure 2.21: WSDL document for the process service with operation “respondOrderNew”

While the deployment descriptor file can be easily created, it can be time-consuming to create and edit the WSDL document that describes a BPEL process. Eclipse BPEL Visual Designer facilitates the generation of the WSDL document. When a BPEL process file is created in Eclipse BPEL Visual Designer, an empty WSDL document is generated and linked to the BPEL process file. When the BPEL process file is changed, the BPEL editor automatically alters the linked WSDL document and makes sure that both the WSDL and BPEL files are consistent with each other. The WSDL document for the BPEL process unit Material Order Service 2 shown in Figure 2.21 is the WSDL document generated by Eclipse BPEL Visual Designer.

The BPEL file, deployment descriptor file, WSDL document, and external WSDL documents are related to each other with some overlaps of information, as illustrated in Figure 2.19. After deployment, the BPEL process acts as a standardized web service and can be invoked by standardized SOAP messaging. As a result, the operation "respondOrderNew" can replace the operation "respondOrder" with only minimal changes of the JSP codes of the application portlet units. The actual service implementation can be encapsulated and modified in a flexible manner.

2.5 Discussions of the SC Collaborator System

A collaborative system that is designed to manage construction supply chains needs (1) low cost, (2) ability to integrate external systems and information, (3) ease of installation and configuration, (4) ease to be connected and integrated, and (5) customizable access to information and applications. All of these requirements are taken into consideration when designing and implementing the SC Collaborator system.

- *Low cost*: The SC Collaborator system framework is developed leveraging open source tools. These tools can be freely downloaded and easily installed. Furthermore, these tools are widely supported in various open source

communities. Therefore, SC Collaborator provides an economical solution with low cost for system installation and maintenance.

- *Ability to integrate external systems and information*: The connectivity to the extensible computing layer enables SC Collaborator to integrate with external systems and information. Since the application portlet units are based on the Java framework, the SC Collaborator system can connect to databases through JDBC, and to systems through protocols such as TCP/IP and JRMP (Java Remote Method Protocol). If the systems and databases of trading partners are wrapped into web services, connectivity and integration are even easier. SC Collaborator can also obtain files and information from online sources such as web sites. This allows dynamic responses to changes of online information. The scope of integration in SC Collaborator is therefore not constrained to a local machine or to a communication network that a user belongs to; instead, any information, applications and systems that are online and available on the web can potentially be integrated in SC Collaborator.

- *Ease of installation and configuration*: The SC Collaborator system can be easily installed and reconfigured. The modular system architecture of SC Collaborator allows flexible installation of the system components. Configuration on the system, users, and layout can be conveniently modified using the administrative portlet units provided on the portal user interface. System layout and service invocation can also be conveniently altered in the JSP codes of application portlet units. In addition, system functionality can be changed flexibly because the internal information, applications and operations are encapsulated and deployed as separate web service units, which can be integrated and modified easily. Therefore, a lot of time and effort can be saved on installation and configuration.

- *Ease to be connected and integrated*: Ease to be connected and integrated is fulfilled by leveraging Apache Axis2, Apache Struts, and the web portal user interface. Many programming languages such as Java and commercial software

such as Microsoft Excel have developed the infrastructure to invoke web services through SOAP messaging. As internal system operations can be exposed to external systems via standardized web services protocol, information and applications residing in the SC Collaborator system can be integrated in external software applications. For example, a construction material supplier uses a home-grown inventory management system in its warehouse. Suppose the supplier is also one of the users of a SC Collaborator system which has been installed to support collaborations with clients and suppliers regarding material procurement and delivery. The inventory management system can be configured so that it downloads the material orders from the SC Collaborator system every hour, and then checks for any time conflicts and updates the production planning schedule in an appropriate manner.

- *Customizable access to information and applications*: Accessibility to system layouts and operations in SC Collaborator can be assigned to users according to the roles, user groups, and organization the user belongs to. The access control can also be customized to individual users. As a result, internal information, applications and system operations in SC Collaborator are protected for trading partners. This ensures that the right information and operations are delivered to the right person at the right time.

2.6 Scenario Examples

To illustrate the SC Collaborator system for construction industry applications, two example scenarios are described in the following sections. These examples demonstrate the potential of SC Collaborator to facilitate communication among construction project participants, and to integrate distributed web applications and systems for construction project management.

2.6.1 Procurement Interactions

The first example is an e-Procurement scenario among interior designers, contractors and suppliers. Many studies have shown the values of electronic procurement (e-Procurement) in supply chain management [43, 85]. In addition to the obvious savings in transaction cost and time, e-Procurement increases responsiveness to orders, offers product standardization, and enhances inventory management. However, it usually takes time to configure and establish the communication channels between buyers and sellers. Due to its service oriented architecture, SC Collaborator allows easy and quick integration of system users. When there is a new supplier, the system administrator simply needs to create an account in SC Collaborator for the supplier and add the address of the supplier's web services to the system. The communication between trading partners is then achieved through the standardized web services protocol.

This scenario demonstrates the integration of external applications (Microsoft Excel) and information (production planning schedule) for e-Procurement in SC Collaborator. Figure 2.22 shows the workflow of activities involved in this example scenario. In this scenario, suppliers publish their product information on company online catalogs on the Internet or an Extranet. The catalogs can be password protected so that only business partners can access the published information. An interior designer working with a general contractor company **GenCon** connects to the catalogs and selects the items (such as furniture items) the designer needs (Figure 2.23). As the catalogs are incorporated with Autodesk i-drop[4] technology, the designer can drag and drop the items from online catalogs directly to architectural design software Autodesk Architectural Desktop (ADT). As illustrated in Figure 2.23, embedded item information is also dropped to the architectural drawings.

[4] Autodesk i-drop technology allows users to drag and drop contents from web pages to the drawing interface in computer-aided design (CAD) software programs developed by Autodesk, Inc. The i-drop indicator software that enables Autodesk i-drop technology can be downloaded at http://usa.autodesk.com/adsk/servlet/index?siteID=123112&id=2753219&linkID=9240618.

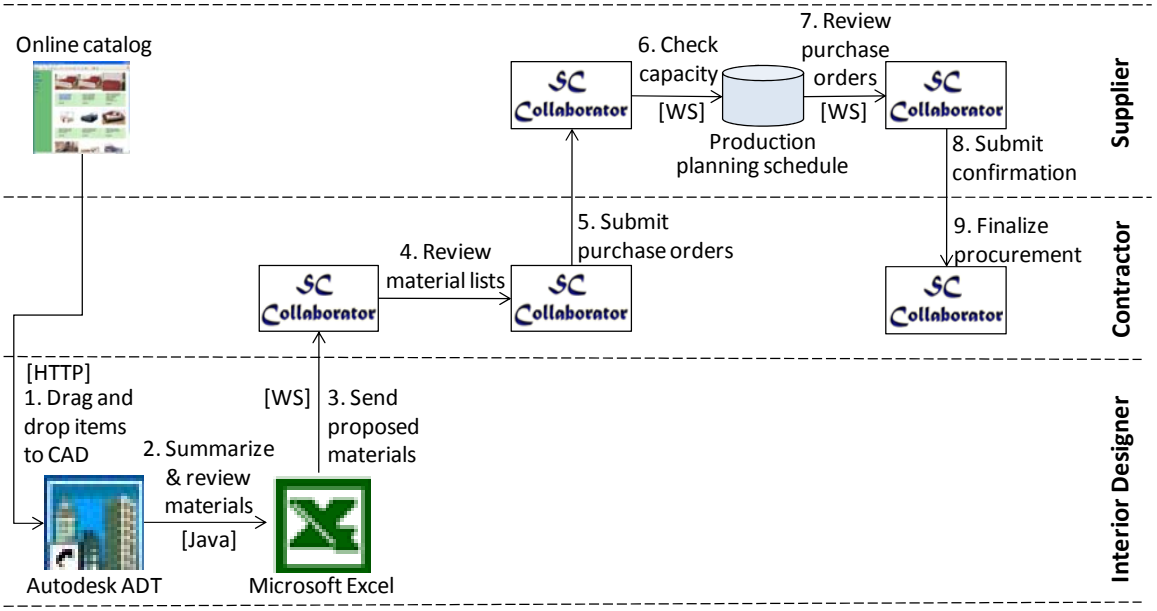


Figure 2.22: Workflow in the e-Procurement scenario

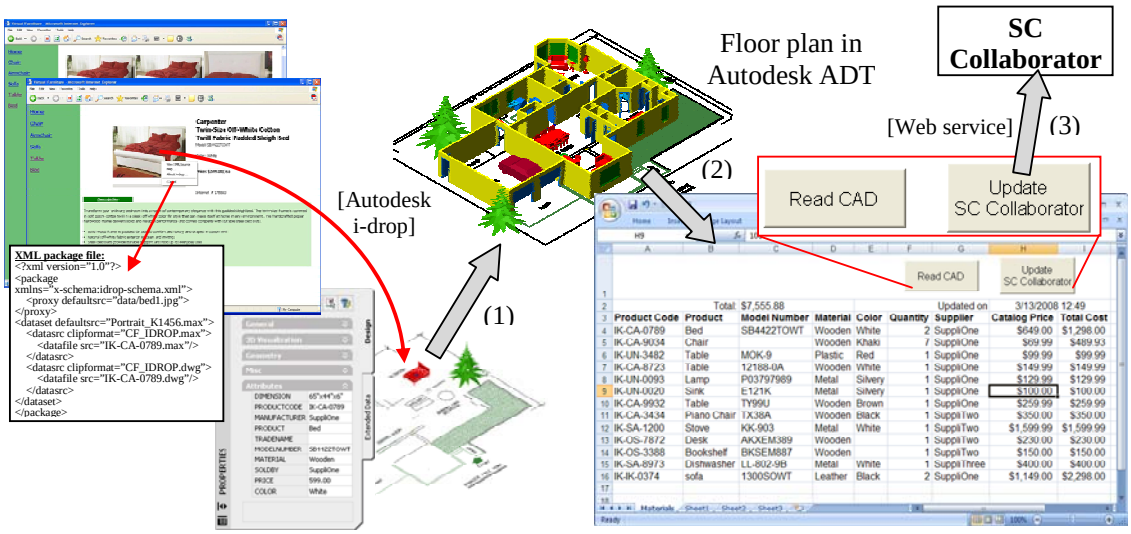


Figure 2.23: Integrating online purchasing with CAD and procurement services: (1) designers dragging items from supplier's online catalogs to CAD drawings, (2) extracting the embedded item information to a spreadsheet in Microsoft Excel, (3) and sending the suggested item list to SC Collaborator for contractor to review

After selecting and adding the items to the architectural drawings, the designer extracts the item information from Autodesk ADT to Microsoft Excel for final checking and submission (Figure 2.23). The procurement is submitted to SC Collaborator via standardized web services protocol for the general contractor to review. The procurement officer in **GenCon** can log into the SC Collaborator system and evaluate the material lists proposed by the designer through the portlet unit shown in Figure 2.24. Each product item is hyperlinked to a separate window that displays the product information and timestamps. Items that have not been included in any purchase order can be selected and grouped together for procurement. By providing an order number, an electronic purchase order can be easily generated and sent to the designated suppliers for confirmation.

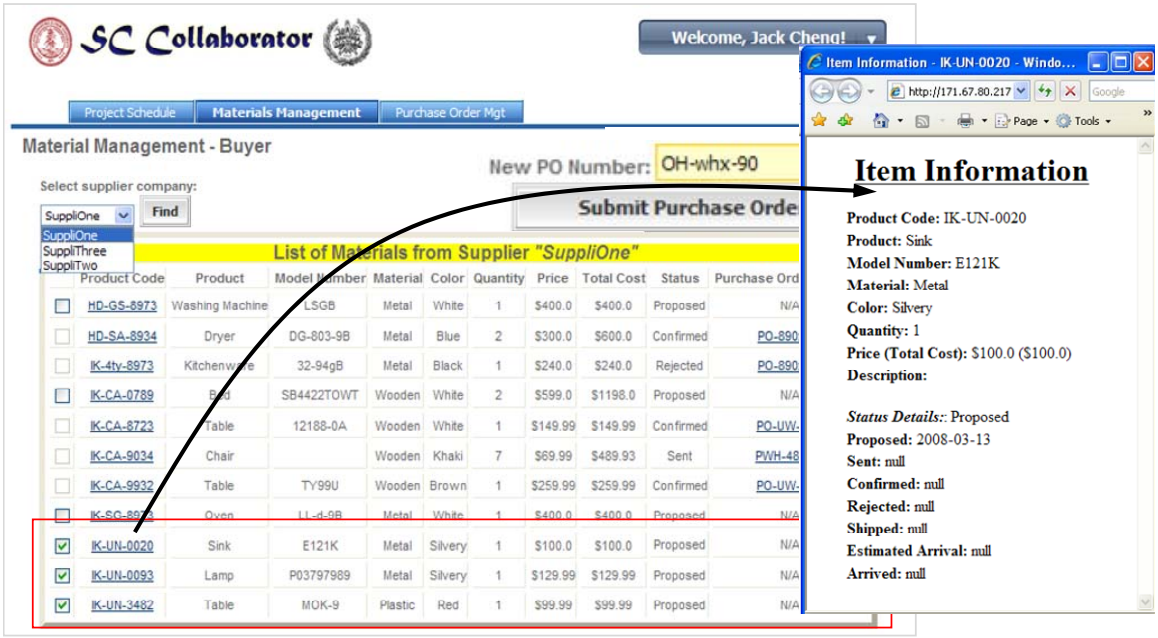


Figure 2.24: Contractor's layout for review of procurement item list and submission of electronic purchase orders

The suppliers log into the SC Collaborator system and manage the purchase orders they receive, as illustrated in Figure 2.25. In this scenario, the portlet unit for suppliers to manage purchase orders is modified to integrate external information and systems useful for the decision making process. Before making decisions, the suppliers need to check the product availability in their inventory and the capacity of their production units. For each supplier in this scenario, this information is stored in production management systems deployed as web services. Queries are sent to the production management systems and results are displayed in the SC Collaborator system.

The information displayed in the portlet unit is provided by separate web service units that connect to the external systems as well as the internal database in SC Collaborator (Figure 2.26). Changes of the locations or operations of the production management systems do not affect the system functioning and layout in the portlet unit due to the abstraction using web service units. After considering the inventory information and production schedule, the furniture supplier can confirm the feasibility to deliver the requested products and select the items that they decide to offer. As shown in Figure 2.25, the supplier decides to offer only two of the requested items and responds to **GenCon** electronically with a confirmation number. The contractor **GenCon** can obtain the instantaneously updated item status and purchase order information from the SC Collaborator system (Figure 2.27).

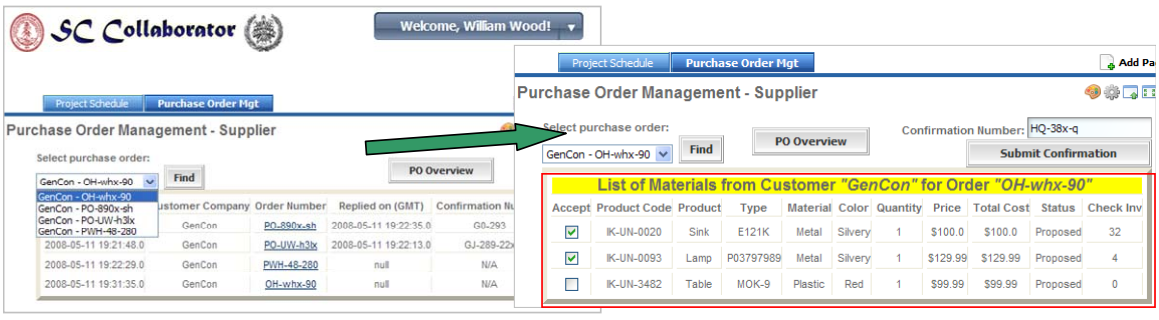


Figure 2.25: Supplier's layout for managing received purchase orders

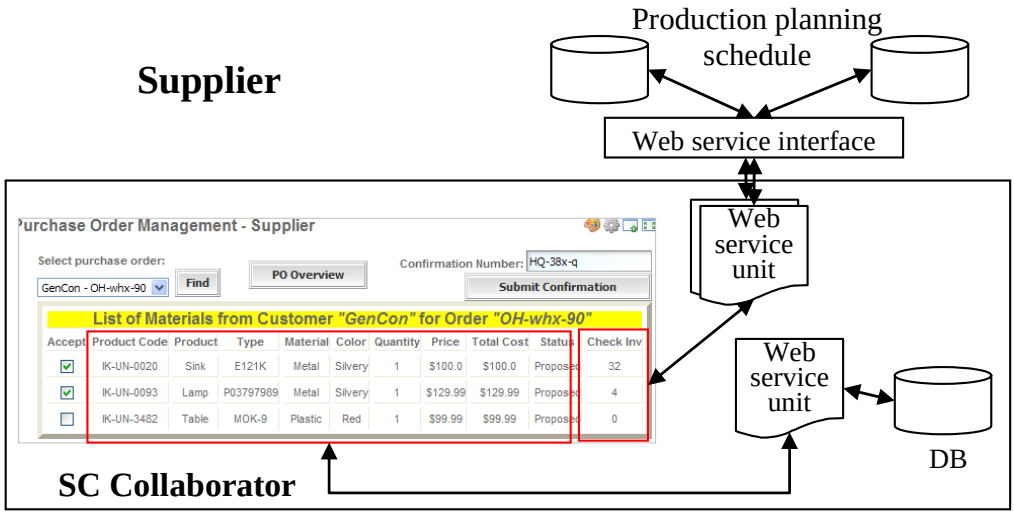


Figure 2.26: Connection to internal and external information and applications in the portlet unit that suppliers manage and evaluate received purchase orders

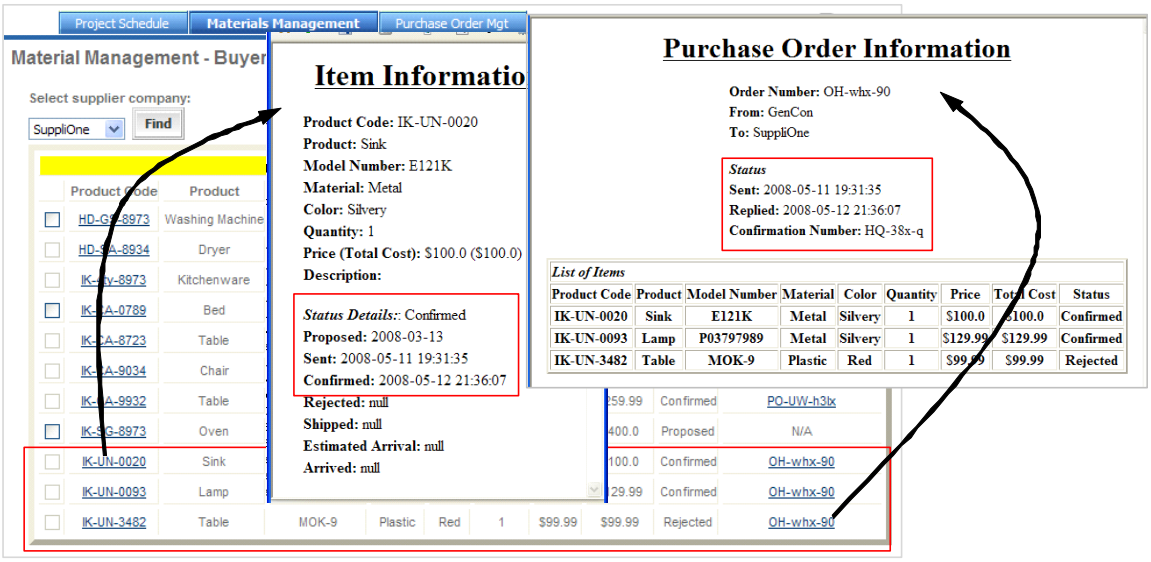


Figure 2.27: Contractor's layout showing updated item status and purchase order information

2.6.2 Project Rescheduling

The second scenario is based on data collected from a completed construction project of a supermarket of 11,500 square meters in Boras, Sweden (Figure 2.28). The project started in April 2007 and finished in April 2008. In this project, the main contractor hired 21 subcontractors. Since the project was heavily dependent on subcontractors, communication and collaboration among the general contractor and subcontractors were crucial to the success of the project.

Figure 2.28: Floor plan and finished layout of the supermarket in Boras, Sweden

One of the major problems in the project reported by the general contractor was the schedule delay by the subcontractors, which causes the project manager to reschedule almost every day. Turnkey-type of contracts were used in the project. In other words, material procurement, delivery and installation were performed by the subcontractors themselves. The general contractor was not involved in any of these activities. Therefore, poor communication and coordination among the general contractors and subcontractors could prevent the project manager from gathering all the necessary information for making the right decisions in schedule change, hindering the rescheduling and project planning processes.

To limit the scope, the period between May 2007 and August 2007 was extracted for testing purposes. In this period, the construction site was divided into five areas (i.e. major parts 1, 2, 3, entry area, and loading area) in most processes such as ground works, piling works and foundation works. There were 38 activities in total in this period, involving five subcontractors. Figure 2.29 shows a portion of the project schedule. Figure 2.29 also illustrates some of the activity dependencies in the period. This implies the interdependencies and constraints of the site areas as well as the subcontractors. This scenario focuses on the suppliers of a concrete works subcontractor, **Muniak**.

Information such as material delivery and activity start time is crucial for project rescheduling. The SC Collaborator system provides a platform for integrating this information from suppliers, subcontractors and general contractor. The flows of information and interactions are as follows (Figure 2.30). In the scenario, production status information and expected delivery time information were reported to corresponding subcontractors by the suppliers (Figure 2.31). By sharing the current status and future forecast of production, suppliers could let customers be aware of any potential production problems ahead of time and be able to mitigate the problems. Sharing of current delivery status and expected delivery time allowed the contractors to plan for the on-site product verification and storage and to evaluate their schedule feasibility. General contractor and subcontractors could monitor the production and

delivery information provided by their suppliers in the SC Collaborator system (Figure 2.32). The latest time the suppliers updated their information was also recorded in the system so that the contractors knew how up-to-date the information was.

If the subcontractors anticipated any need for change of the activity start time or finish time, due to changes in material delivery time or unexpected delay in installation, the subcontractors could adjust the scheduled start, finish and every scheduled delivery time (Figure 2.33). The adjustment information was sent to the suppliers and the general contractor. This information may change the suppliers' decisions about the size of production for the next production period and the expected delivery time. This information may also help the general contractor alter the task sequence and resource allocation. Consequently, the information provided by the participants and the decisions made by the participants were highly interdependent on each other.

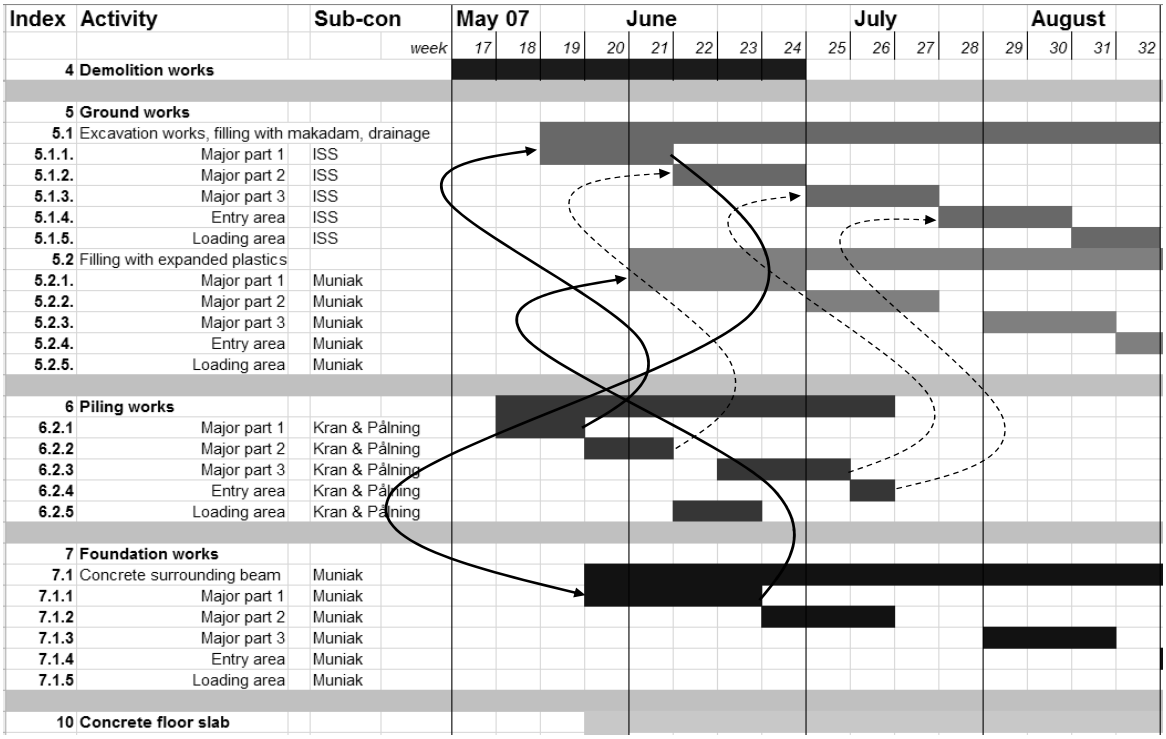


Figure 2.29: An excerpt of the project schedule between May 2007 and August 2007

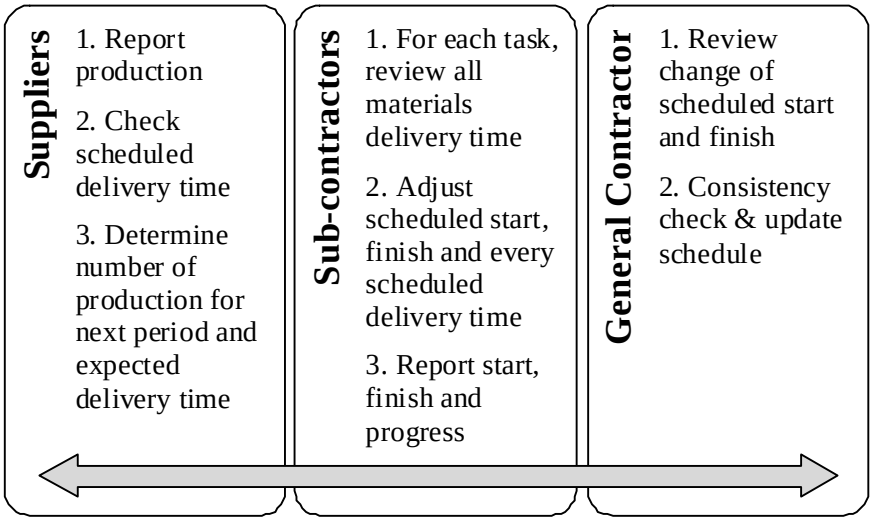


Figure 2.30: Information flows and interactions in the rescheduling process

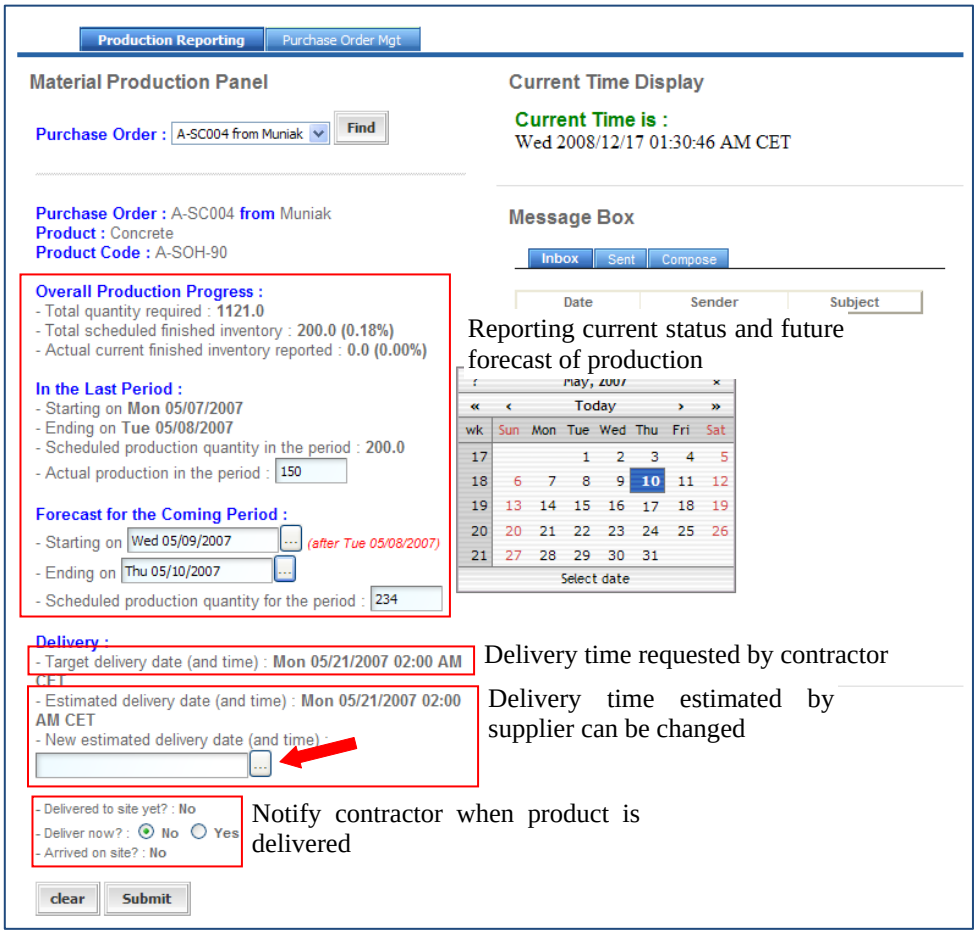
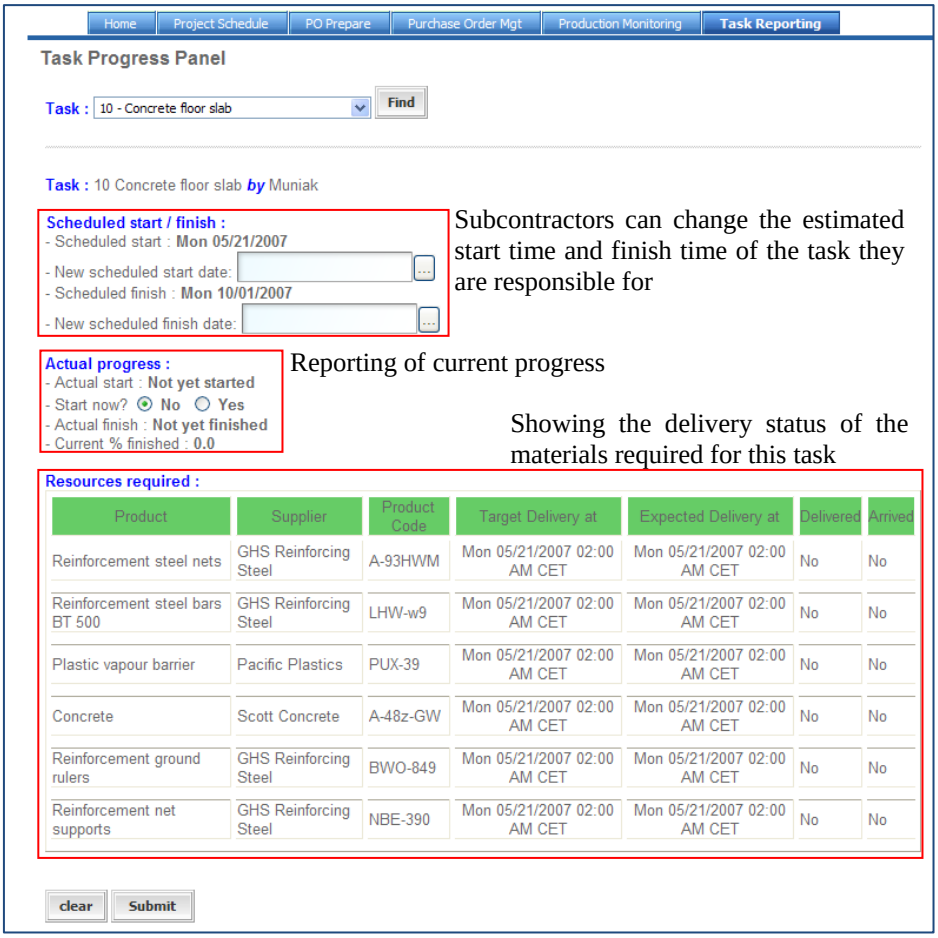


Figure 2.31: Supplier's layout for production reporting

PO Number	Product Code	Product	Total Quantity	Reported Finished Qty	Reported Period Ends	Last Reported on	Target Delivery at	Expected Delivery at	Delivered	Arrived
A-SC004	A-48z-GW	Concrete	2081	0.00	N/A	N/A	Sun 05/20/2007 10:30 PM PST	Sun 05/20/2007 10:30 PM PST	No	No
A-SC004	A-SOH-90	Concrete	1121	0.00	N/A	N/A	Sun 05/20/2007 10:30 PM PST	Sun 05/20/2007 10:30 PM PST	No	No
A-SC004	GOP93	Sandwich concrete elements (Siroc)	430	280.00	Fri 05/11/2007	Tue 05/15/2007 10:43 AM PST	Sun 05/20/2007 10:30 PM PST	Sun 05/20/2007 10:30 PM PST	No	No

Figure 2.32: Subcontractor's layout for monitoring material production and delivery



Product	Supplier	Product Code	Target Delivery at	Expected Delivery at	Delivered	Arrived
Reinforcement steel nets	GHS Reinforcing Steel	A-93HWM	Mon 05/21/2007 02:00 AM CET	Mon 05/21/2007 02:00 AM CET	No	No
Reinforcement steel bars BT 500	GHS Reinforcing Steel	LHW-w9	Mon 05/21/2007 02:00 AM CET	Mon 05/21/2007 02:00 AM CET	No	No
Plastic vapour barrier	Pacific Plastics	PUX-39	Mon 05/21/2007 02:00 AM CET	Mon 05/21/2007 02:00 AM CET	No	No
Concrete	Scott Concrete	A-48z-GW	Mon 05/21/2007 02:00 AM CET	Mon 05/21/2007 02:00 AM CET	No	No
Reinforcement ground rulers	GHS Reinforcing Steel	BWO-849	Mon 05/21/2007 02:00 AM CET	Mon 05/21/2007 02:00 AM CET	No	No
Reinforcement net supports	GHS Reinforcing Steel	NBE-390	Mon 05/21/2007 02:00 AM CET	Mon 05/21/2007 02:00 AM CET	No	No

Figure 2.33: Subcontractor's layout for activity review and adjustment

Transparency among the suppliers, subcontractors and general contractor is important for construction supply chain management. The general contractor reported that they had no idea about the situations and problems of materials and therefore could only keep pushing the subcontractors, while several subcontractors in the project even did not have all the information from their suppliers. The SC Collaborator system allows instantaneous sharing and analysis of information, adding values to the entire supply chain. Different cases of collaboration and information transparency were tested using the SC Collaborator system. It showed that the benefits of information sharing in this scenario can be significant. For example, there was a material production and delivery delay of one week (five working days) starting from Day 1 of Week 20 for a sandwich concrete element called Siroc. The element was required for the activity "7.1.1 foundation works – concrete surrounding beam – major part 1." The activity required two more materials – 1,121 m^3 of concrete and 2,388 m^2 of form material (wood). The form material was delivered to the construction site every working day. There were several constraints that had to be satisfied: every delivery must be confirmed at least three working days before the delivery time. In addition, product type, configuration, amount, and delivery time cannot be changed after confirmation.

Figure 2.34 is a plot of the inventory on site of the form material over time. The area under each curve multiplied by per-unit per-day holding cost represents the total inventory holding cost of the form material due to delivery delay of the material Siroc, which happened in Day 1 of Week 20. If the Siroc supplier notified the subcontractor **Muniak** of the delay at least three days earlier, **Muniak** could contact the supplier of the form material immediately and delay the delivery for one week. The activity 7.1.1 could also be postponed, allowing the general contractor and other subcontractors to modify the project schedule and reallocate resources. If **Muniak** knew the delay one day earlier than delivery time, the inventory holding cost it would incur was more than double the cost it would incur if it knew two days earlier. If the Siroc supplier did not notify **Muniak** of the delay, either due to unwillingness to report or lack of communication channels, the inventory holding cost could be tremendous. Therefore, although information sharing

between trading partners looks simple, it can aid decision making and add significant values to each supply chain member.

People often are not aware of the changes in the materials or schedules and do not react to the changes promptly, leading to time lags of the information flowing among project participants. The time lags can accumulate along a supply chain and result in significant impacts. Therefore, message notifications and automated responses can support efficient supply chain management. In this scenario, for instance, basic service units were integrated and orchestrated into a composite service unit to facilitate automated response and notification upon changes of material delivery. When a supplier changed the estimated delivery time of a product item using the production reporting application portlet unit (Figure 2.31), the composite service operation "changeDeliveryEstiamte" is triggered.

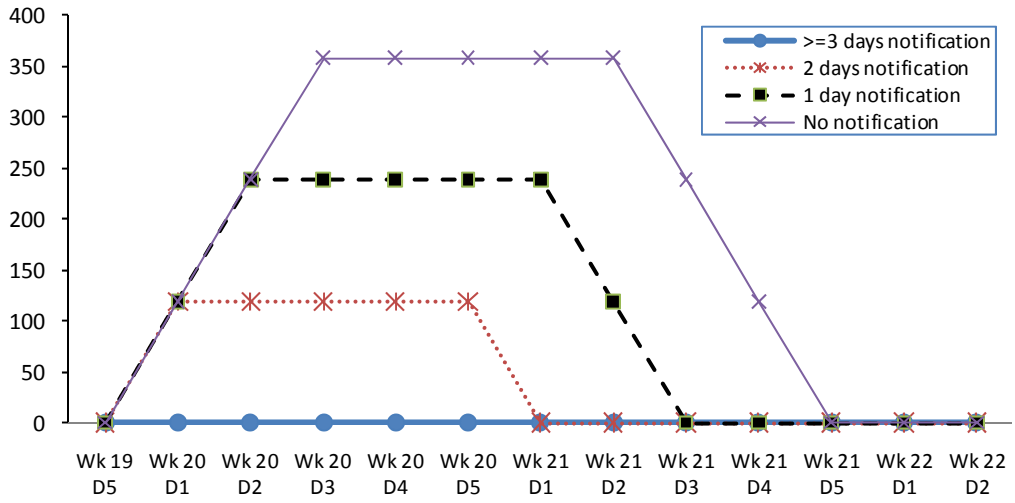


Figure 2.34: Inventory (in m^2) of form material (wood) under different supply delay conditions

As illustrated in Figure 2.35, the operation combines the functionality of various basic service operations from the Material Order Service, Message Service, and Project Schedule Service. First, the operation notifies the buyer of the change in item delivery time and checks the impact of the change to the affected task. If the impact is high and the start time of the affected task needs to be changed (postponed in most cases), the operation "changeDeliveryEstimate" modifies the task schedule, alters the target delivery time of the other product items involved in the affected task, and notifies the general contractor, subcontractors, and suppliers impacted. This shows that business tasks can be customized and automated conveniently in a service oriented framework such as SC Collaborator.

2.7 Summary

This chapter describes a prototype service oriented portal-based system, SC Collaborator, designed for construction supply chain integration and collaboration. Open standards and open source technologies are leveraged for the system implementation. The SC Collaborator system provides a single point of access to distributed information, applications and services among scattered supply chain members. It is modular, flexible, secure, and easy to install and reconfigure, which make the SC Collaborator system a desirable means for companies in the construction industry. The system also allows interoperation among applications because programs written in different languages and operating on different systems can be integrated via standardized web services protocol.

The system consists of four major components. The communication layer allows users to connect to the system using web browsers, wireless devices, and web services. The portal-based user interface manages the system configuration and layout. The business applications layer performs deployment, invocation, and orchestration of web service units. The back-end database stores and provides the information that supports the

system and various application operations. Based on the characteristics of construction supply chains and the study in literatures, we have summarized five desirable sytem features for construction supply chain integration and collaboration as described in Section 1.2. The SC Collaborator system fulfills all these five system features.

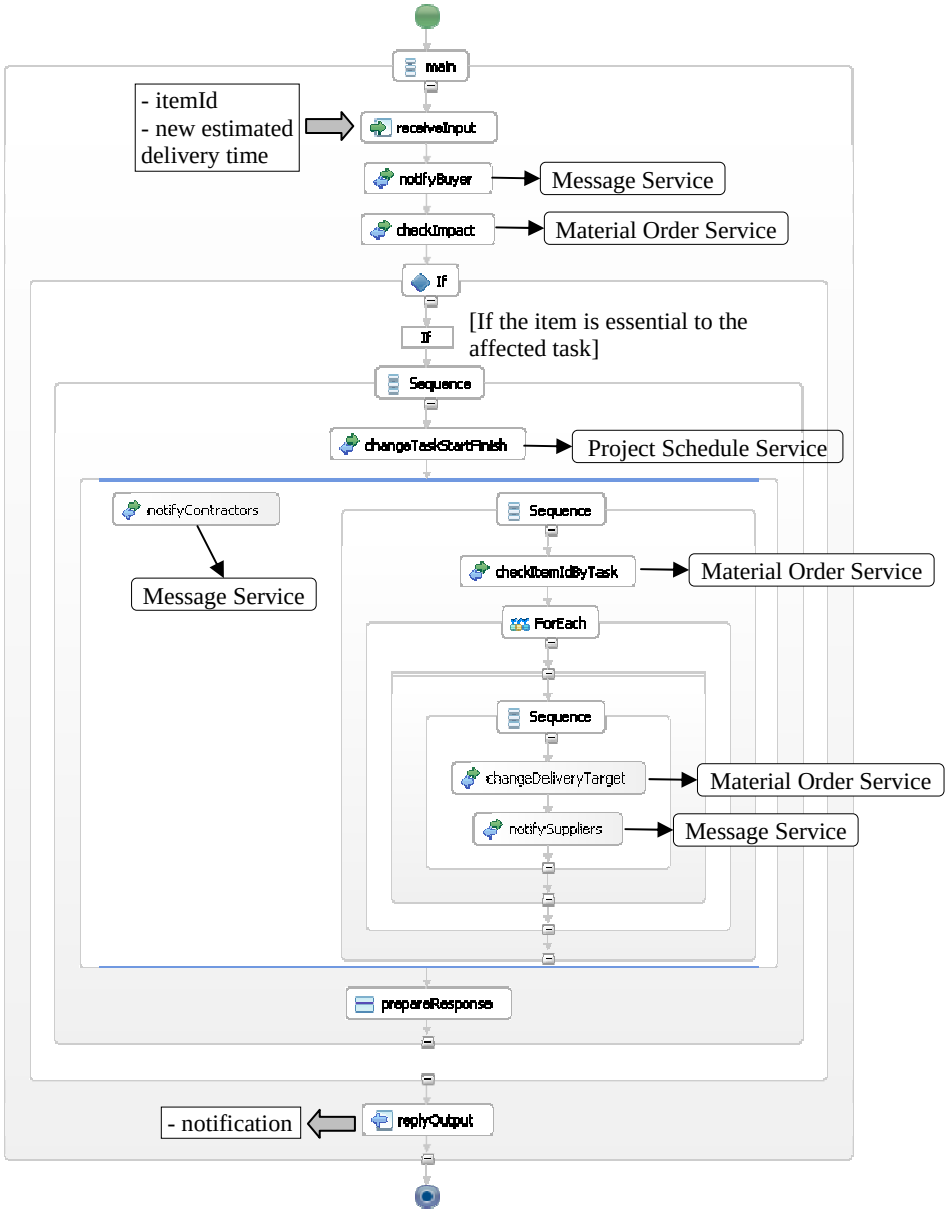


Figure 2.35: BPEL process for the operation “changeDeliveryEstimate”

Two example scenarios have been presented to illustrate the potential of the SC Collaborator system to extend functionality and to integrate partners in construction projects. The first one is an e-Procurement scenario which involves designers, contractors and suppliers. In this scenario, online catalogs, architectural design software, SC Collaborator, and production and inventory planning systems are integrated to facilitate the procurement process in construction projects. The second one is a scenario based on a real construction project of a supermarket in Boras, Sweden. The rescheduling problem among general contractor, subcontractors and material suppliers has been studied. The importance of transparency in an integrated construction supply chain which can be enabled by the SC Collaborator system has been illustrated in the chapter.

Chapter 3

Supply Chain Modeling and Performance Monitoring

3.1 Introduction

The planning and management of supply chains require properly specifying the participating members and identifying the relationships among them. This task is especially challenging in the construction industry because construction supply chains are complex in structure and often composed of a large number of participants who work together in a project-based temporary manner. Construction projects typically involve tens and hundreds of companies, supplying materials, components, and a wide range of construction services [28]. Modeling the structure of participants involved in a construction supply chain can help understand the complexity and the organization in a supply chain [74]. Supply chain network models also facilitate the identification of bottlenecks and provide the basis for supply chain re-configuration and re-engineering.

There are very few standard methods or frameworks for representing and modeling supply chain structures. Supply chain structures are commonly recorded as tables that

enlist the members of a supply chain, or represented as network diagrams that show the supply chain members as well as the links between them. Lambert and Cooper [52] proposed a mapping of supply chain structures using three primary attributes: members of the supply chain, structural dimensions, and types of business processes between the members. However, these methods do not provide a direct migration from the modeling of supply chain structures to the modeling of the business operations.

There are two commonly used supply chain modeling frameworks that provide guidelines to systematically map the relationships of companies and specify the operations involved in a supply chain. The Supply Chain Model framework introduced by the Global Supply Chain Forum (GSCF) is built on eight key business processes that are both cross-functional and cross-organizational in nature [51]. As illustrated in Figure 3.1, the eight processes are customer relationship management, supplier relationship management, customer service management, demand management, order fulfillment, product development and commercialization, manufacturing flow management, and returns management. Each process is managed by a cross-functional team, including representatives from logistics, production, purchasing, finance, marketing, and research and development. The Supply Chain Model framework provides a granular framework to model the cross-departmental interactions in every process along a supply chain. However, the majority of construction companies are small and medium enterprises (SMEs). According to a study on the construction industry in United Kingdom [28], for example, about 83% of the private contracting companies employ three or less workers while 98% of the companies employ 24 or less workers. Construction companies often do not have a clear boundary between business functional units. Employees in construction companies usually work on a project basis instead of a business functional basis. Therefore, the Supply Chain Model framework that describes the interactions across internal business functional units is not suitable for modeling construction supply chains.

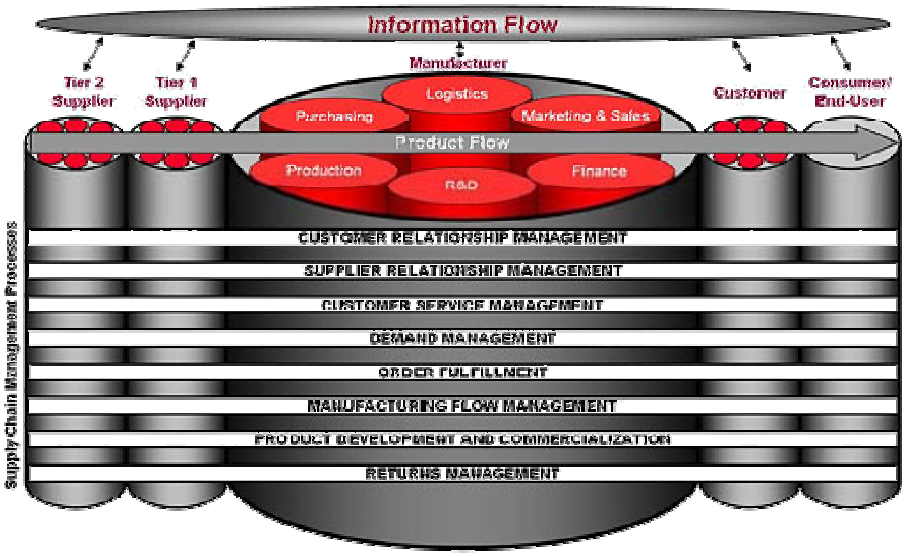


Figure 3.1: The Supply Chain Model framework [51] introduced by the Global Supply Chain Forum (GSCF)

The other framework is the Supply Chain Operations Reference (SCOR) modeling framework established by the Supply Chain Council for supply chain standardization, measurement, and improvement [91]. The SCOR modeling framework is based on five key supply chain processes – Plan, Source, Make, Deliver, and Return. The SCOR modeling framework is hierarchically structured into four levels, with increasing details at each level. Construction supply chains often do not have a standard and well structured configuration. Members may not be involved in both the material flows and the information flows of the procurement, manufacturing, and distribution activities in construction supply chains. Since the SCOR framework is generic and can be used to model supply chains of various types and scales, the framework is suitable for modeling various construction supply chains of different complexity. The material flows and information flows in a supply chain are represented separately in the SCOR framework. Therefore, the SCOR framework is employed for modeling construction supply chains in this study.

The SCOR framework has been widely used to model supply chain network structures and operations for strategic planning purposes [42]. However, the SCOR framework is

seldom leveraged for the design and implementation of information systems for supply chain management. Furthermore, while performance monitoring is critical to the measurement and improvement of supply chains, there have been little efforts focused on performance monitoring systems for construction supply chain management. This chapter discusses the modeling of construction supply chains using the SCOR framework. Furthermore, this chapter describes the development of a supply chain performance monitoring system by incorporating the SCOR models into the service oriented SC Collaborator framework described in Chapter 2.

The supply chain models for a demonstration application presented in this chapter are developed using a retrospective case study of the mechanical, electrical and plumbing (MEP) processes in a student center construction project. There are altogether 524 distinct process-based performance metrics recommended in SCOR [91]. Since the MEP case example is focused on the procurement and delivery processes, the metrics selected in this study are the process cycle times, documentation accuracy, and product conditions upon arrival. A model-based service oriented approach is adopted in the development of the performance monitoring system. First, the supply chain models are transformed into process execution files by leveraging Business Process Modeling Notation (BPMN) [78] and Business Process Execution Language (BPEL) [80]. The BPEL process execution files are then incorporated in the monitoring system, which is built on SC Collaborator.

This chapter is organized as follows. Section 3.2 briefly describes the SCOR framework. Section 3.3 presents the MEP processes in the construction project we studied and illustrates the modeling of the MEP supply chains using the SCOR framework. Section 3.4 demonstrates the implementation of the prototype supply chain performance monitoring system and discusses the usage of performance metrics. Section 3.4 also presents a service oriented approach to implementation of a system framework based on SCOR models. Specially, the conversion of supply chain models into BPEL executable files and the incorporation of the BPEL files in the service oriented system SC Collaborator are illustrated in Section 3.4. Section 3.5 shows the system with the

construction project example. Section 3.6 summarizes the chapter and discusses the limitations and potentials.

3.2 Supply Chain Operations Reference (SCOR) Model

The Supply Chain Operations Reference (SCOR) modeling framework was initially developed by Supply Chain Council in 1996. The current version is the SCOR model version 9.0, which was released in 2008 [91]. The framework provides a systematic approach to describe, characterize, and evaluate complex supply chain processes. Standardization of business processes is necessary to allow the communication and integration between business partners of the supply network [38]. The SCOR model is a process reference model for standardization purposes. The model attempts to capture business operations including (1) customer interactions, from order entry through paid invoice, (2) product transactions, from supplier's supplier to customer's customer, and (3) market interactions, from the understanding of aggregate demand to the fulfillment of each order [91].

The SCOR modeling framework is based on five basic management processes in supply chains – Plan, Source, Make, Deliver, and Return – to meet planned and actual demand (Figure 3.2). Plan includes processes that balance resources to establish plans that best meet the requirements of a supply chain and its sourcing, production, delivery, and return activities. Source includes processes that manage the procurement, delivery, receipt, and transfer of raw material items, subassemblies, products, and services. Make includes processes that transform products to a finished state. Deliver includes processes that provide finished goods and services, including order management, transportation management, and distribution management. Return includes post-delivery customer support and processes that are associated with returning or receiving returned products.

Figure 3.2: SCOR Level 1 modeling [91]

The SCOR framework allows users to model supply chain structures and relationships in a progressive and systematic manner. There are four levels of model development in the SCOR framework (Figure 3.3). Level 1 modeling provides a broad definition of the scope and content for the SCOR model (Figure 3.2). Level 2 modeling divides the five basic management processes into process categories, which allow companies to describe the configuration of their supply chains. Table 3.1 shows the Level 2 process categories described in the SCOR framework. Level 2 models conceptually specify the relationship and interactions among supply chain members. The conceptual specification can be extended to describe the process workflow through Level 3 modeling.

Level 3 modeling provides companies with the information for detailed planning and setting goals. The SCOR framework offers a guideline of the inputs and outputs for each Level 3 process element. As an example, Figure 3.4 shows a Level 3 process "S1.1 Schedule Product Deliveries." As shall be discussed in Section 3.4.1, Level 3 processes provide the basis for defining the supply chain performance metrics. The Level 3 processes for process type Source, Make, and Deliver are illustrated in Table 3.2, Table 3.3, and Table 3.4 respectively.

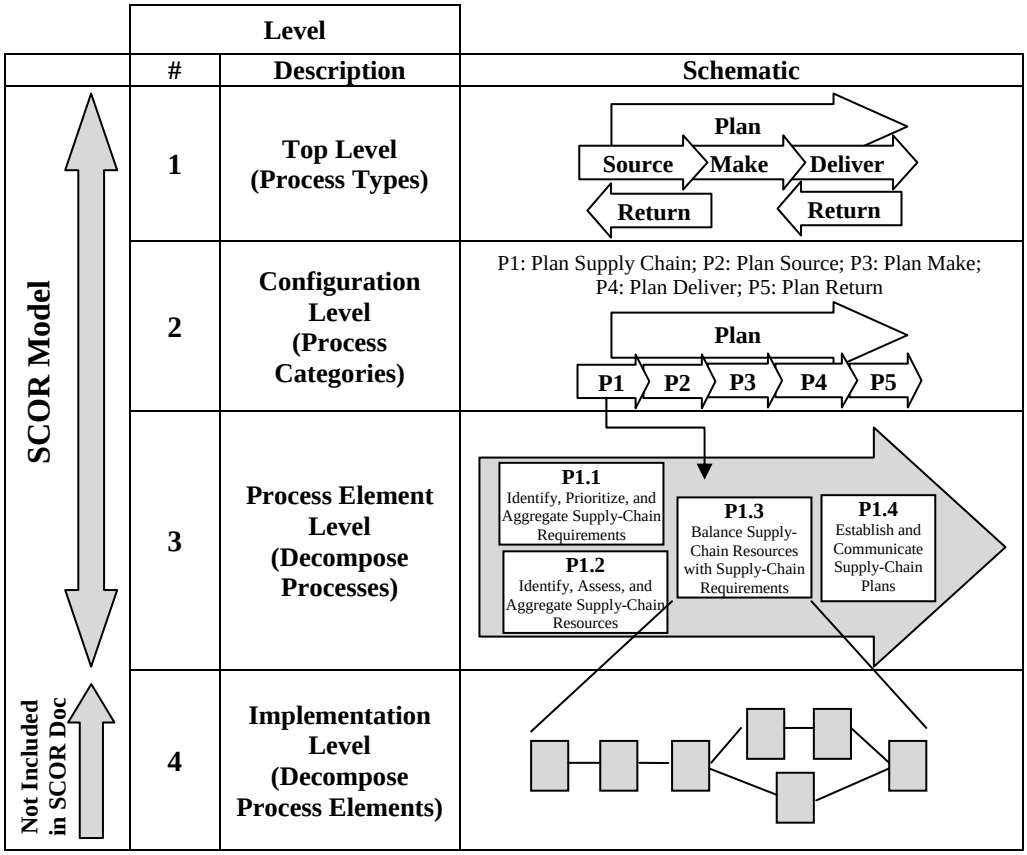


Figure 3.3: Four levels of SCOR business processes [91]

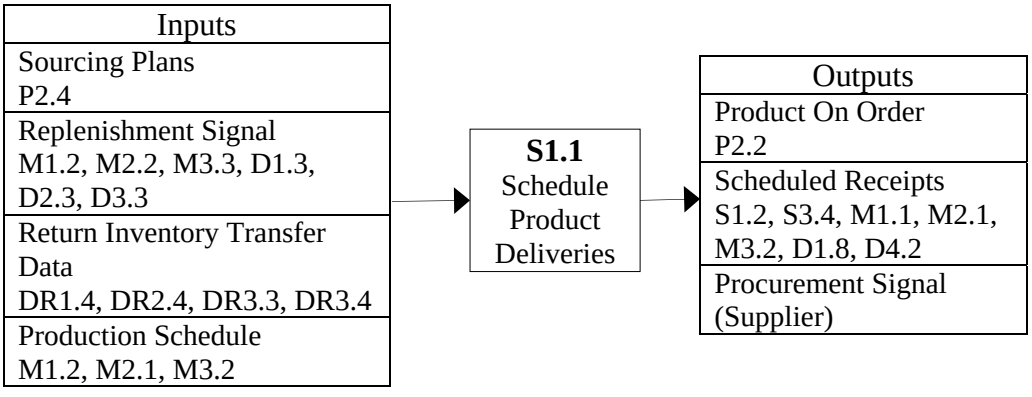


Figure 3.4: Inputs and outputs for Level 3 process “S1.1 Schedule Product Deliveries”

Table 3.1: SCOR Level 2 process categories

Level 1 Process Type	**Level 2 Process Category**
PLAN	P1: Plan Supply Chain P2: Plan Source P3: Plan Make P4: Plan Deliver P5: Plan Return
SOURCE	S1: Source Stocked Product S2: Source Make-to-Order Product S3: Source Engineer-to-Order Product
MAKE	M1: Make-to-Stock M2: Make-to-Order M3: Engineer-to-Order
DELIVER	D1: Deliver Stocked Product D2: Deliver Make-to-Order Product D3: Deliver Engineer-to-Order Product D4: Deliver Retail Product
RETURN	SR1: Source Return Defective Product SR2: Source Return Maintenance, Repair, Operations (MRO) Product SR3: Source Return Excess Product DR1: Deliver Return Defective Product DR2: Deliver Return Maintenance, Repair, Operations (MRO) Product DR3: Deliver Return Excess Product

Table 3.2: SCOR Level 3 process elements for “Source”

S1: Source Stocked Product	**S2: Source Make-to-Order Product**	**S3: Source Engineer-to-Order Product**
S1.1: Schedule Product Deliveries S1.2: Receive Product S1.3: Verify Product S1.4: Transfer Product S1.5: Authorize Supplier Payment	S2.1: Schedule Product Deliveries S2.2: Receive Product S2.3: Verify Product S2.4: Transfer Product S2.5: Authorize Supplier Payment	S3.1: Identify Sources of Supply S3.2: Select Final Supplier(s) and Negotiate S3.3: Schedule Product Deliveries S3.4: Receive Product S3.5: Verify Product S3.6: Transfer Product S3.7: Authorize Supplier Payment

Table 3.3: SCOR Level 3 process elements for "Make"

M1: Make-to-Stock	M2: Make-to-Order	M3: Engineer-to-Order
M1.1: Schedule Production Activities	M2.1: Schedule Production Activities	M3.1: Finalize Engineering
M1.2: Issue Product	M2.2: Issue Product	M3.2: Schedule Production Activities
M1.3: Produce and Test	M2.3: Produce and Test	M3.3: Issue Product
M1.4: Package	M2.4: Package	M3.4: Produce and Test
M1.5: Stage Product	M2.5: Stage Product	M3.5: Package
M1.6: Release Product to Deliver	M2.6: Release Finished Product to Deliver	M3.6: Stage Product
M1.7: Waste Disposal	M2.7: Waste Disposal	M3.7: Release Product to Deliver
		M3.8: Waste Disposal

Table 3.4: SCOR Level 3 process elements for "Deliver"

D1: Deliver Stocked Product	D2: Deliver Make-to-Order Product	D3: Deliver Engineer-to-Order Product	D4: Deliver Retail Product
D1.1: Process Inquiry and Quote	D2.1: Process Inquiry and Quote	D3.1: Obtain and Respond to RFP/RFQ	D4.1: Generate Stocking Schedule
D1.2: Receive, Enter and Validate Order	D2.2: Receive, Configure, Enter and Validate Order	D3.2: Negotiate and Receive Contract	D4.2: Receive Product at the Store
D1.3: Reserve Inventory and Determine Delivery Date	D2.3: Reserve Resources and Determine Delivery Date	D3.3: Enter Order, Commit Resources and Launch Program	D4.3: Pick Product from Backroom
D1.4: Consolidate Orders	D2.4: Consolidate Orders	D3.4: Schedule Installation	D4.4: Stock Shelf
D1.5: Build Loads	D2.5: Build Loads	D3.5: Build Loads	D4.5: Fill Shopping Cart
D1.6: Route Shipments	D2.6: Route Shipments	D3.6: Route Shipments	D4.6: Checkout
D1.7: Select Carriers and Rate Shipments	D2.7: Select Carriers and Rate Shipments	D3.7: Select Carriers and Rate Shipments	D4.7: Deliver and/or install
D1.8: Receive Product from Source or Make	D2.8: Receive Product from Source or Make	D3.8: Receive Product from Source or Make	
D1.9: Pick Product	D2.9: Pick Product	D3.9: Pick Product	
D1.10: Pack Product	D2.10: Pack Product	D3.10: Pack Product	
D1.11: Load Product and Generate Shipping Docs	D2.11: Load Product and Generate Shipping Docs	D3.11: Load Product and Generate Shipping Docs	
D1.12: Ship Product	D2.12: Ship Product	D3.12: Ship Product	
D1.13: Receive and Verify Product by Customer	D2.13: Receive and Verify Product by Customer	D3.13: Receive and Verify Product by Customer	
D1.14: Install Product	D2.14: Install Product	D3.14: Install Product	
D1.15: Invoice	D2.15: Invoice	D3.15: Invoice	

Level 4 modeling focuses on implementation. Since SCOR Level 4 models are unique to each company, the specific elements at this level are not defined within the SCOR framework. In Level 4 modeling, users need to design the implementation details of each Level 3 process to meet their own needs. Through the four levels of development, the SCOR models can be extended to capture and represent complex interactions among supply chain partners. Therefore, the SCOR framework is a useful tool for modeling construction supply chains, which usually involve many organizations and are complex in nature. The application of the SCOR framework to model construction supply chains is illustrated in the next section.

3.3 Modeling of Construction Supply Chains Using SCOR Framework: A Case Example

In this chapter, a construction project of a two-storey high school student center is used as a case example (Figure 3.5). Specifically, the mechanical, electrical and plumbing (MEP) supply chains of the project have been studied retrospectively and modeled based on the information from the documents provided by and the interviews conducted with the general contractor, subcontractors, and suppliers. The buyer-supplier relationships in a construction project can differ from project to project, organization to organization, and product to product. However, similar patterns are observed in the buyer-supplier interactions and configuration of supply chains among various organizations and products in the MEP processes of the project. Although the supply chain modeling is demonstrated only with the MEP supply chains, the framework can be potentially applied and extended to other kinds of supply chains in construction projects of various scales and types.

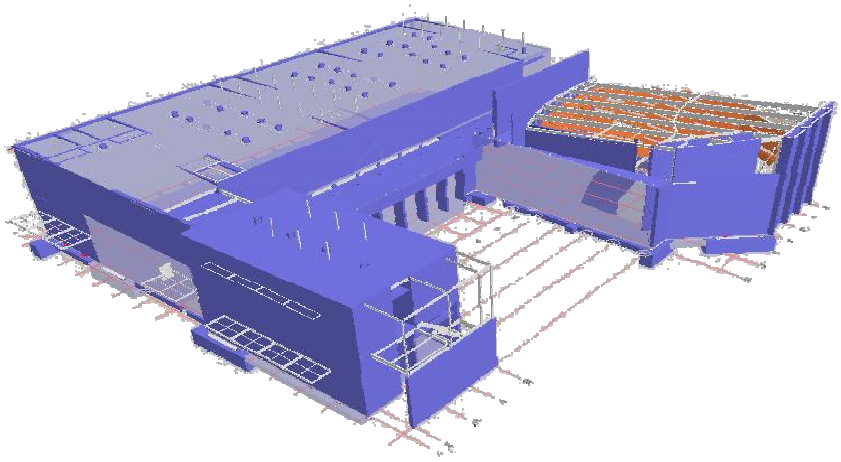
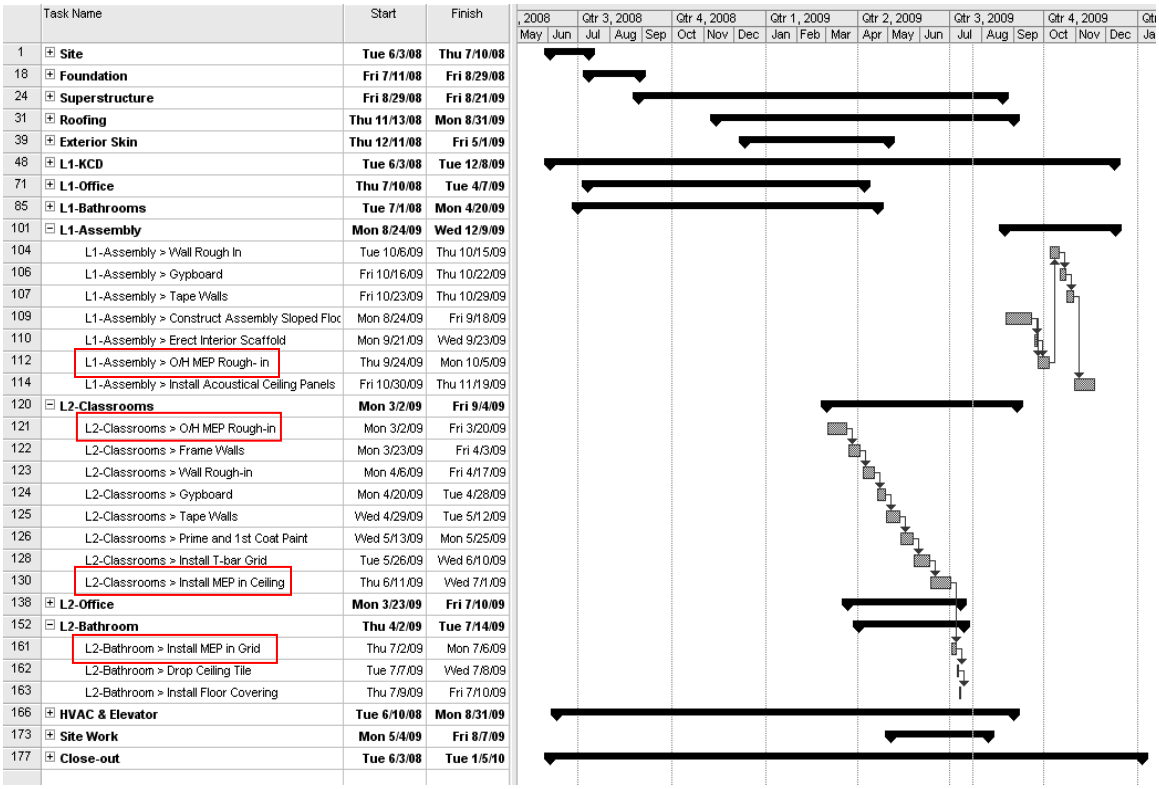


Figure 3.5: 3D model of the two-storey high school student center

3.3.1 Case Example

The student center in the example construction project is a two-storey building with a 650 fixed-seat auditorium, a 350 seat dining hall with a full commercial kitchen and server, three bathrooms, and eight sophisticated science classrooms. The construction project started in May 2008 and was planned to finish by December 2009. To minimize the impact of the construction on student activities on campus, the construction site was kept to minimal. The stocking space on site was limited in size and needed to change locations occasionally over the project time. Early delivery of materials leading to long-time stocking was not recommended in order to free up the construction site space and to avoid double material handling. Therefore, the general contractor heavily emphasized Just-in-Time material delivery in the project.

There are 170 tasks in the project, and 47 of them are on the critical paths. Since many MEP activities are essential for enabling other critical tasks, the MEP activities are usually on the critical path. For example, as shown in Figure 3.6, the MEP activities for the assembly hall on Level 1, the classrooms on Level 2, and the bathroom on Level 2 are on a critical path. In addition, MEP activities are interior work and often start at the late stage of the project. Therefore, there is little schedule buffer for problems in the MEP activities. The performance and timeliness of the MEP components delivery are important to the on-schedule project delivery. In fact, the project once experienced a serious potential for prolonging project completion time due to the material delays of several electrical products.



	Task Name	Start	Finish
1	**Site**	**Tue 6/3/08**	**Thu 7/10/08**
18	**Foundation**	**Fri 7/11/08**	**Fri 8/29/08**
24	**Superstructure**	**Fri 8/29/08**	**Fri 8/21/09**
31	**Roofing**	**Thu 11/13/08**	**Mon 8/31/09**
39	**Exterior Skin**	**Thu 12/11/08**	**Fri 5/1/09**
48	**L1-KCD**	**Tue 6/3/08**	**Tue 12/8/09**
71	**L1-Office**	**Thu 7/10/08**	**Tue 4/7/09**
85	**L1-Bathrooms**	**Tue 7/1/08**	**Mon 4/20/09**
101	**L1-Assembly**	**Mon 8/24/09**	**Wed 12/9/09**
104	L1-Assembly > Wall Rough In	Tue 10/6/09	Thu 10/15/09
106	L1-Assembly > Gypboard	Fri 10/16/09	Thu 10/22/09
107	L1-Assembly > Tape Walls	Fri 10/23/09	Thu 10/29/09
109	L1-Assembly > Construct Assembly Sloped Floc	Mon 8/24/09	Fri 9/18/09
110	L1-Assembly > Erect Interior Scaffold	Mon 9/21/09	Wed 9/23/09
112	L1-Assembly > O/H MEP Rough- in	Thu 9/24/09	Mon 10/5/09
114	L1-Assembly > Install Acoustical Ceiling Panels	Fri 10/30/09	Thu 11/19/09
120	**L2-Classrooms**	**Mon 3/2/09**	**Fri 9/4/09**
121	L2-Classrooms > O/H MEP Rough-in	Mon 3/2/09	Fri 3/20/09
122	L2-Classrooms > Frame Walls	Mon 3/23/09	Fri 4/3/09
123	L2-Classrooms > Wall Rough-in	Mon 4/6/09	Fri 4/17/09
124	L2-Classrooms > Gypboard	Mon 4/20/09	Tue 4/28/09
125	L2-Classrooms > Tape Walls	Wed 4/29/09	Tue 5/12/09
126	L2-Classrooms > Prime and 1st Coat Paint	Wed 5/13/09	Mon 5/25/09
128	L2-Classrooms > Install T-bar Grid	Tue 5/26/09	Wed 6/10/09
130	L2-Classrooms > Install MEP in Ceiling	Thu 6/11/09	Wed 7/1/09
138	**L2-Office**	**Mon 3/23/09**	**Fri 7/10/09**
152	**L2-Bathroom**	**Thu 4/2/09**	**Tue 7/14/09**
161	L2-Bathroom > Install MEP in Grid	Thu 7/2/09	Mon 7/6/09
162	L2-Bathroom > Drop Ceiling Tile	Tue 7/7/09	Wed 7/8/09
163	L2-Bathroom > Install Floor Covering	Thu 7/9/09	Fri 7/10/09
166	**HVAC & Elevator**	**Tue 6/10/08**	**Mon 8/31/09**
173	**Site Work**	**Mon 5/4/09**	**Fri 8/7/09**
177	**Close-out**	**Tue 6/3/08**	**Tue 1/5/10**

Figure 3.6: Project schedule showing only the tasks on the critical path

Managing the MEP supply chains in the project was more challenging than many project participants had anticipated. The MEP components in the project were large in number and supplied by many different companies. In addition, the project is expected to achieve LEED Platinum Certification from the U.S. Green Building Council. Therefore, many of the MEP (especially electrical) components were designed and specified by the architects. Only a small portion of the electrical components are standard products that can be delivered in a short period of time after procurement. The electrical subcontractor and several other subcontractors did not anticipate and were surprised by the complexity of the material supply management in a project of this scale.

3.3.2 SCOR Level 2 Modeling

Figure 3.7 shows the major interactions between the MEP subcontractors (buyers) and the suppliers in the project. The flowchart represents a typical material planning, procurement, and delivery management process for various products in construction projects. The interactions start from the selection of suppliers and the request for submittals and quotes. If the owners or architects do not specify the suppliers, the quotes are used by the subcontractors to evaluate and to select the suppliers. The submittals, which normally include shop drawings, product data, samples, manuals, and reports, are then submitted to the engineers through the general contractor for approval. The submittals may be approved as it is, approved with minor revisions needed, undecided with major revisions needed and resubmission needed, and rejected. For the latter two cases, the subcontractors need to revise the submittals and resubmit them to the engineers. The revision and resubmission process can be iterative and could take weeks to months in the planning phase.

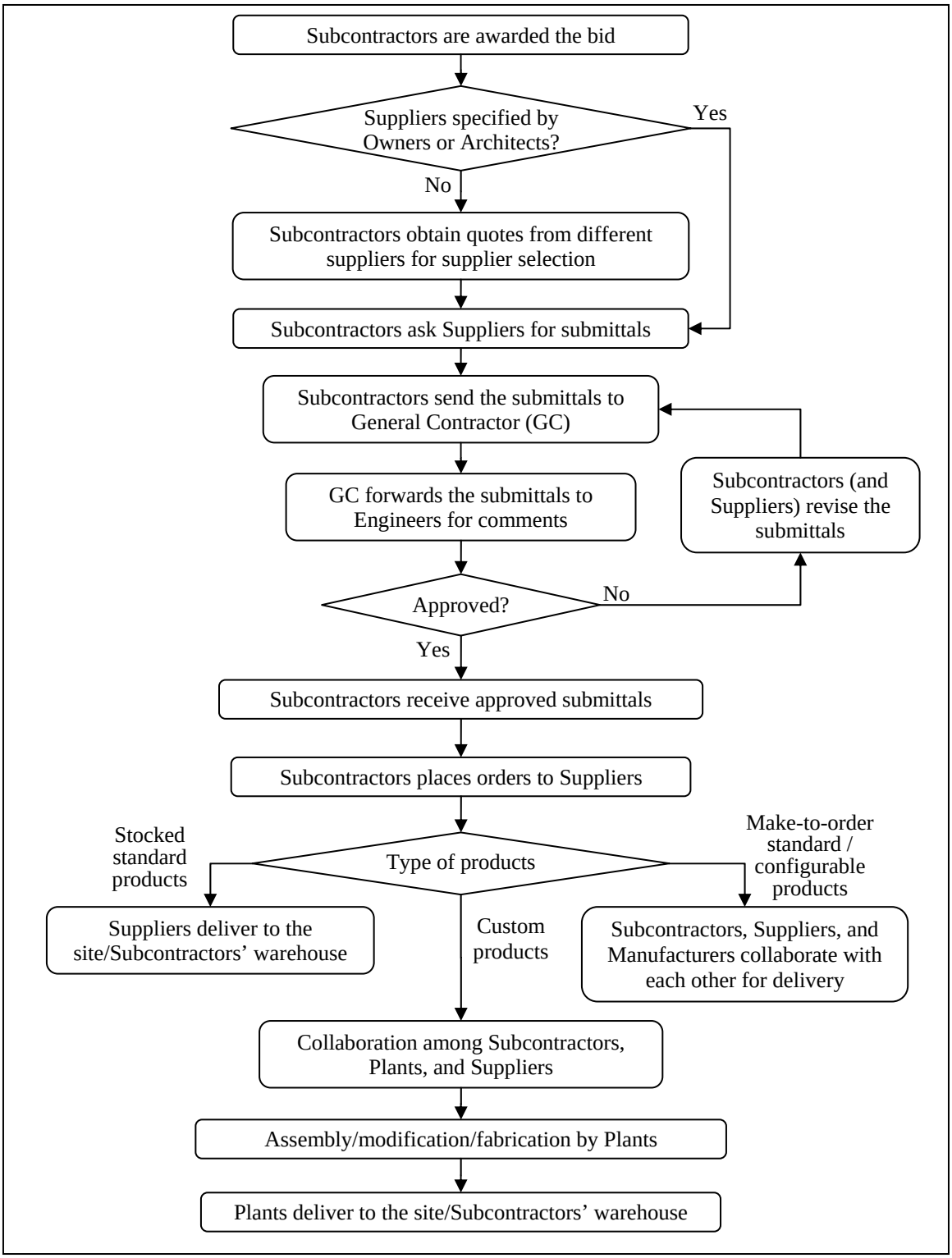


Figure 3.7: Flow chart of a typical material planning, procurement, and delivery management process in construction projects

In the material procurement and delivery management phase in the student center construction project, the interactions along the MEP supply chains show three major patterns according to the nature of products. For high-demand standard commodity products such as wires, tubing, bolts, and nuts that subcontractors purchase from distributors (suppliers), the suppliers usually keep stocks of such products to meet anticipated orders. Therefore, the suppliers usually can deliver the products in a short time once they receive the purchase orders. The second type is standard and configurable products that have low turnover rate and/or high inventory cost, for instance, light fixtures and switchgears. Products of this type are produced only after customers' purchase orders are received, or so-called "made-to-order." The third type is products that are specially designed, engineered, and customized by the owners, architects, engineers, or subcontractors. One example is customized ductwork. Close interactions and collaborations among the subcontractors, the plants, and the suppliers are often required in the design, engineering, sourcing, and delivery processes. In the following subsections, the high-level SCOR Level 2 modeling of the information flows and material flows for these three types of products is illustrated. The supply chain models are then extended to create supply chain process maps with greater details through the SCOR Level 3 and Level 4 modeling in Section 3.3.3.

3.3.2.1 Stocked Standard Products

Some standard products such as wires and tubing are maintained in a finished goods state and kept in stocks in suppliers' inventory prior to the receipt of a customer order. These products usually have high demand and low inventory cost. Suppliers procure according to sales forecast, so products are produced before the suppliers receive order. Supply chains of this type are inventory driven. Unsatisfied orders usually become lost sales as alternative suppliers can often be found.

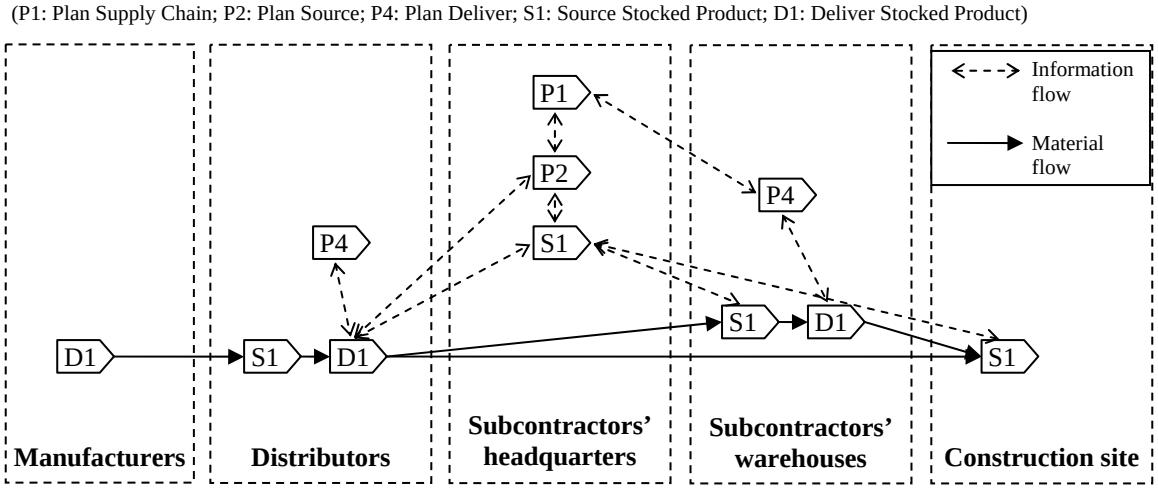


Figure 3.8: SCOR Level 2 model for a typical construction supply chain for stocked standard products

Construction supply chains for stocked standard products involve foremen in the construction site, subcontractors, distributors, and manufacturers. Figure 3.8 shows the SCOR Level 2 model for this type of supply chains. The dotted lines and the solid lines represent the information flows and the material flows respectively. The information flows start from the subcontractors' headquarters, where purchase orders are sent. There are two alternative material flow paths. Products are often delivered to the construction site at the time designated by the subcontractors. In some cases, subcontractors hope to better control the material delivery time and practice just-in-time delivery on site. These subcontractors prefer the suppliers first delivering the products to the subcontractors' warehouses and manage the products themselves.

3.3.2.2 Make-to-order Standard / Configurable Products

Products of this type include products that are built to a specific design and the products that are manufactured, assembled, or configured from standard parts or subassemblies. Suppliers prefer make-to-order due to various reasons. Suppliers of products such as

light fixtures usually do not keep stocks of their products because they often publish a wide variety of products in catalogs and it is hard for them to anticipate the demand for each specific design. Moreover, some products such as switchgears have a high inventory cost and depreciation rate, making it risky to keep stock for uncertain anticipated demand. Many suppliers also like to keep the flexibility to slightly configure and customize their products based on the requirements of a particular customer order. For these reasons, manufacture, assembly, or configuration of these make-to-order standard / configurable products begins only after the receipt and validation of a firm customer order.

Similar to the stocked standard products, members of construction supply chains for make-to-order standard / configurable products include foremen in the construction site, subcontractors, distributors, and manufacturers. Figure 3.9 shows the SCOR Level 2 model for a typical construction supply chain for make-to-order standard / configurable products. Normally, the products can be delivered directly from the manufacturers to either the construction site or the subcontractors' warehouses. On the other hand, procurement directly to manufacturers is not allowed in general. Distributors serve as a middleman between subcontractors and manufacturers, coordinating the procurement, production, and delivery in the supply chain. Besides the distributors, some subcontractors also communicate actively with their manufacturers to check the production and to schedule the delivery (the communication channels are shown as the information links with asterisks in Figure 3.9). By communicating directly with the manufacturers, subcontractors can be less vulnerable to supply chain risk because they can notice any material delay or shortage and mitigate the impact at an early stage.

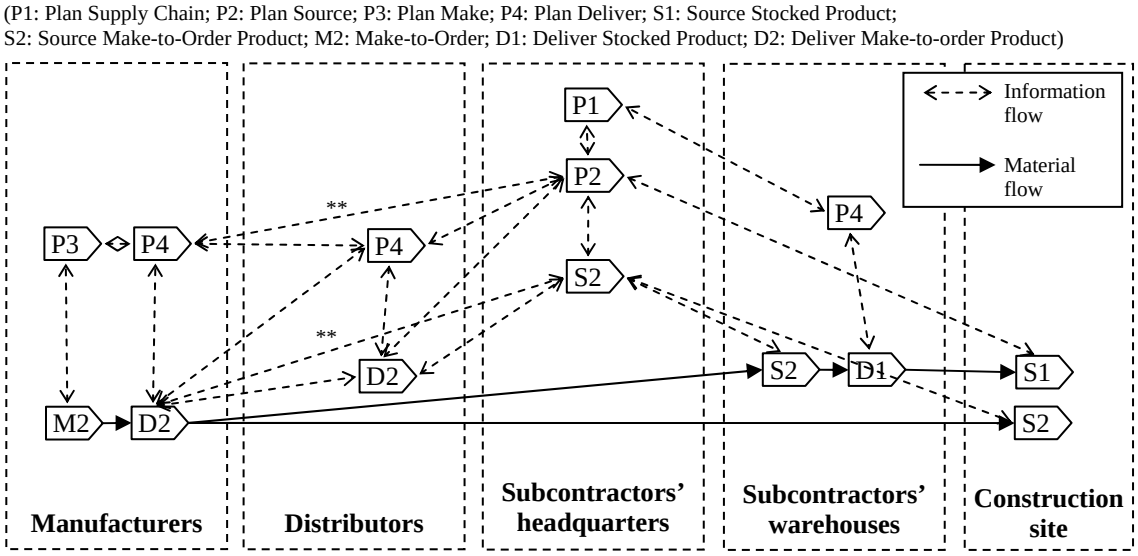


Figure 3.9: SCOR Level 2 model for a typical construction supply chain for make-to-order standard / configurable products

3.3.2.3 Custom Products

While make-to-order standard / configurable products include standard products built only in response to a customer order or products configured according to a customer order, custom products include products that are designed, developed, and manufactured in response to a specific customer request. HVAC systems and customized ductworks are examples of custom products. While some standardized ducts can be made-to-order or made-to-stock, ductwork systems with special configurations and dimensions need to be designed and engineered before production.

Members of supply chains for custom MEP products usually consist of foremen in the construction site, subcontractors, plants, and material suppliers. A plant represents a business unit for the engineering and production of the custom products. A plant can be a third party company, a department of a supplier, or a subsidiary of a subcontractor. Suppliers, plants, and subcontractors collaborate with each other in the negotiation,

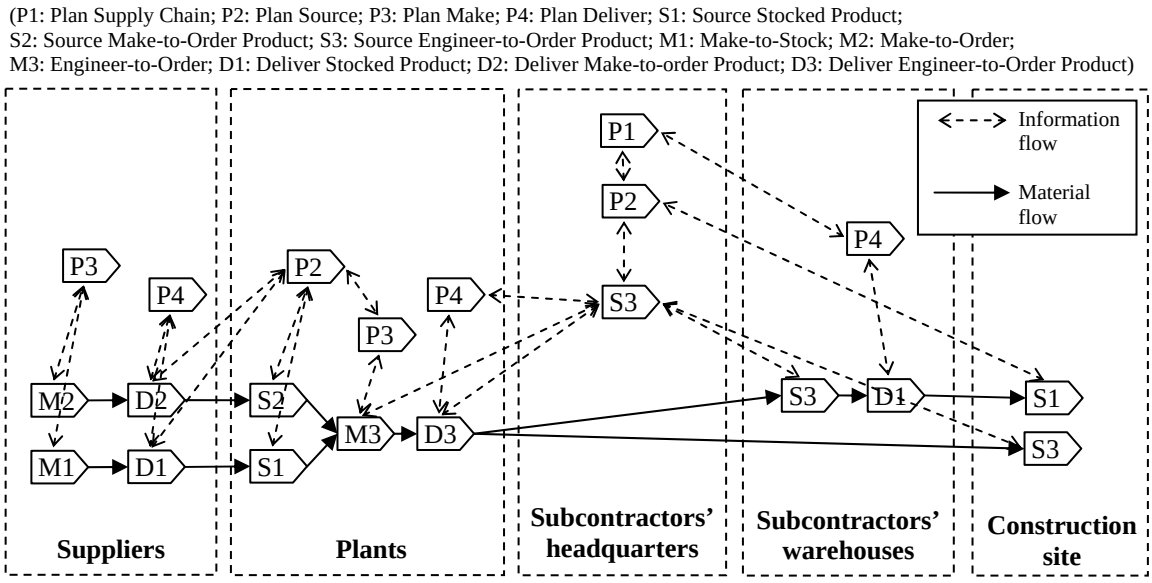


Figure 3.10: SCOR Level 2 model for a general construction supply chain for custom products

design, procurement, production, and delivery processes. Architects and engineers who have specialized requirements may also be involved in the negotiation, design, and production processes. Final and detailed design often starts after the receipt and validation of a customer order. Therefore, supply chains of this type of products are driven by customer requirements and specifications and often take a long time to complete. Figure 3.10 shows the SCOR Level 2 model for a general construction supply chain for custom products.

3.3.3 SCOR Level 3 and Level 4 Modeling

While SCOR Level 2 models provide an overview of the information flows and material flows along a supply chain, SCOR Level 3 and 4 models specify the business processes involved in the supply chain. A Level 3 model links different SCOR Level 3 supply chain processes into a process map whereas a Level 4 model specifies the necessary

business operations to implement a particular SCOR Level 3 process. As an example, Figure 3.11 depicts the SCOR Level 3 model for a typical construction supply chain for stocked standard products. Similarly, SCOR Level 3 models can be constructed for make-to-order standard / configurable products and for custom products. A Level 3 model usually is a complex map of processes, making it difficult to be developed on paper. The complexity of a Level 4 model may vary, but the configuration in a Level 4 model for a particular Level 3 process may change occasionally. Therefore, a user-friendly digital graphical representation should be used to facilitate the creation, modification, and manipulation of the SCOR Level 3 and Level 4 models. Business process modeling notation (BPMN) [78], supported by several open source and commercial graphical tools, offers such a standard graphical representation for business processes modeling.

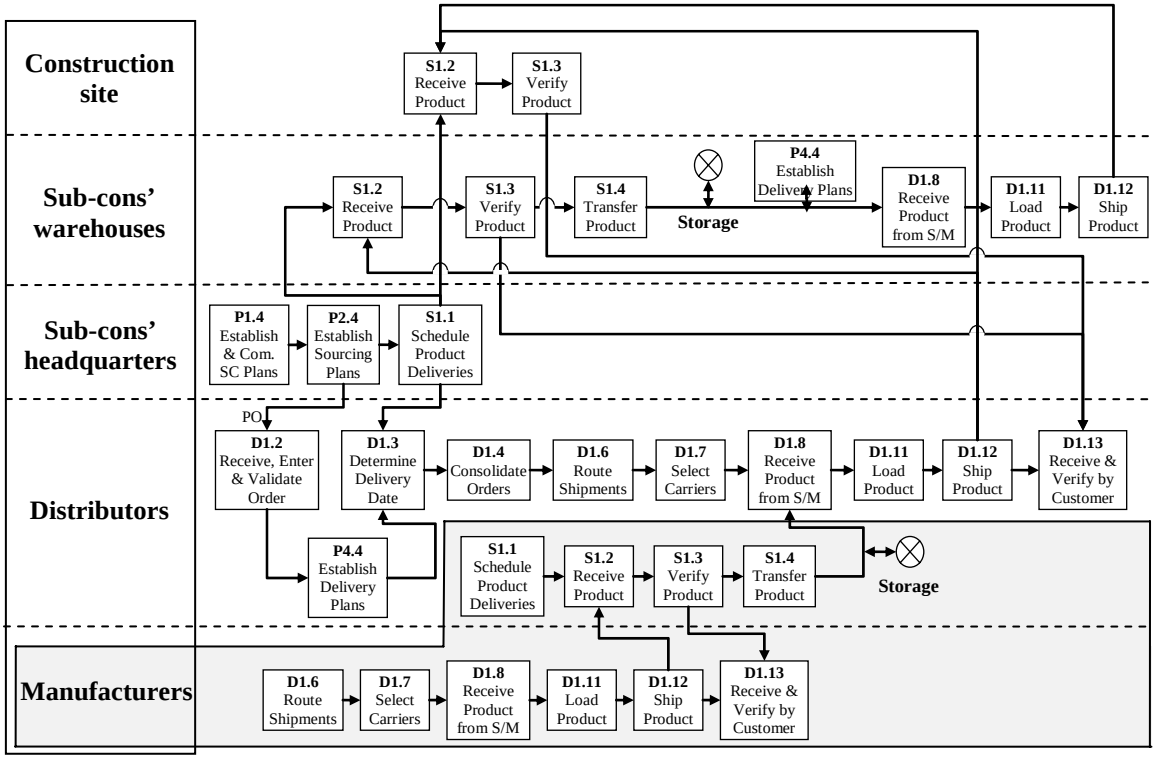


Figure 3.11: SCOR Level 3 model for a typical construction supply chain for stocked standard products

3.3.3.1 Business Process Modeling Notation (BPMN) Models

BPMN [78] is an Object Management Group (OMG) standard for business process modeling. This graph-oriented modeling language provides a visual modeling notation to specify business processes in a diagram. The primary objective of BPMN is to bridge the gap between process design and process implementation. BPMN is targeted both as a high level process specification for business users and as a low level process description details for implementers. The business users should be able to easily read and understand a BPMN business process diagram. On the other hand, the process implementer can add further details to a business process diagram in order to represent the process suitable for a physical implementation. As a result, BPMN models can help define process interactions and facilitate communication in the process design and analysis phase. BPMN models can also act as a blueprint for the subsequent implementation.

There are various standards such as IDEF0 [96] and UML [77] for process modeling. In this study, BPMN is used for SCOR Level 3 and Level 4 modeling because BPMN models can easily be converted into executable languages such as Business Process Execution Language (BPEL) [80]. Efforts spent on the development of SCOR Level 3 and Level 4 models in BPMN can thus be leveraged for system execution, which will be demonstrated in Section 3.4.2. In addition, the modeling in BPMN is made by simple diagrams with a small set of graphical elements. BPMN models can make complex system architecture understandable and facilitate the understanding of the flows and the processes between different organizations. Moreover, BPMN modeling is user-friendly due to the support of several open source and commercial graphical BPMN tools. This research uses an open source BPMN modeling tool developed by Eclipse Foundation, called Eclipse BPMN Modeler [31] (Figure 3.12).

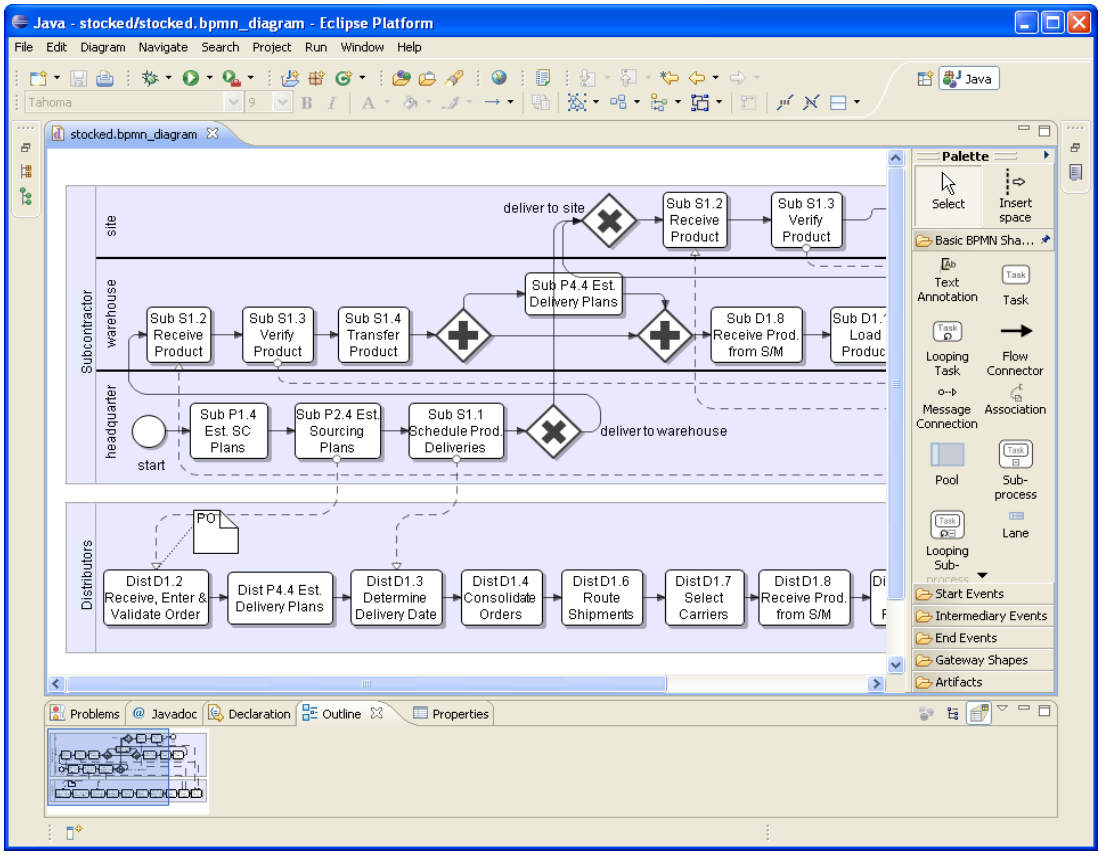


Figure 3.12: Snapshot of Eclipse BPMN Modeler

There are four basic categories of elements in BPMN models – flow objects, connecting objects, swimlanes, and artifacts (Figure 3.13). Flow objects consist of three core elements – events, gateways, and activities. An event is denoted as a circle and represents something that happens. An event can associate with other elements such as a message envelope or a clock to perform a complex event. Every process has only one start event and one end event. A gateway determines forking and merging of paths depending on the conditions expressed. An activity element can be a task which represents a single unit of work or a sub-process which has its own self-contained sequence flows and start and end events. Connecting objects represent linkages between flow objects, with sequence flows linking flow objects in the same pool and message flows linking flow objects in different pools. Swimlanes consist of pool and lane

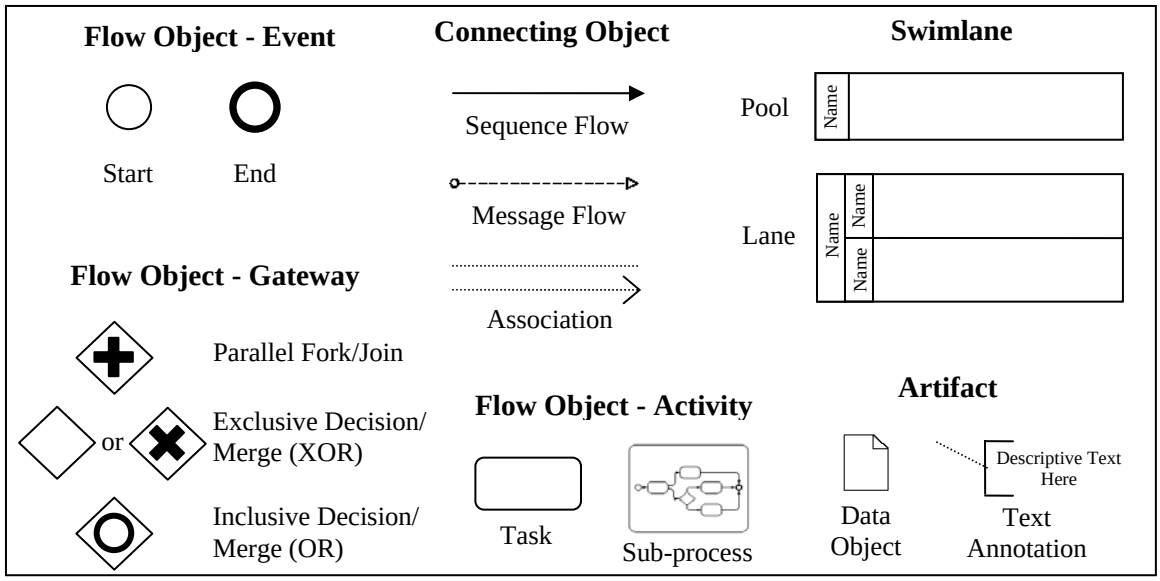


Figure 3.13: Core components in BPMN standard

elements. A pool represents a major participating company in a process, whereas a lane represents a division of a company. Nevertheless, pool and lane elements are interchangeable and different companies can also be separated by lanes in the same pool.

3.3.3.2 BPMN Model for SCOR Level 3 Modeling

The SCOR Level 3 model for a typical supply chain for stocked standard products shown in Figure 3.11 can be represented using BPMN (Figure 3.14). The sourcing activities of distributors, highlighted in Figure 3.11, are not included in the BPMN representation because it is assumed that there is no backlog and that a subcontractor only procures stocked standard products from the suppliers with sufficient inventory. Therefore, the supply chain from a subcontractor's perspective is independent of the sourcing activities of distributors. The SCOR Level 3 models for make-to-order standard / configurable products and for custom products are shown in Figure 3.15 and Figure 3.16, respectively. Different pools are used to represent the subcontractor, the distributors, the manufacturers, the plants, and the suppliers. The subcontractor's headquarter, warehouse, and the construction site are separated by lanes.

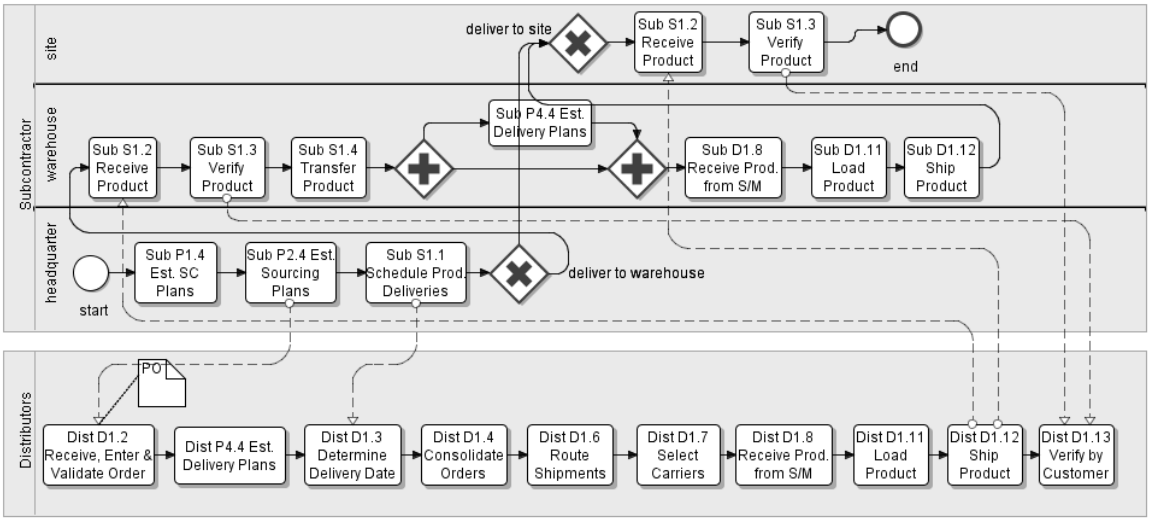


Figure 3.14: BPMN representation of the SCOR Level 3 model for stocked standard products

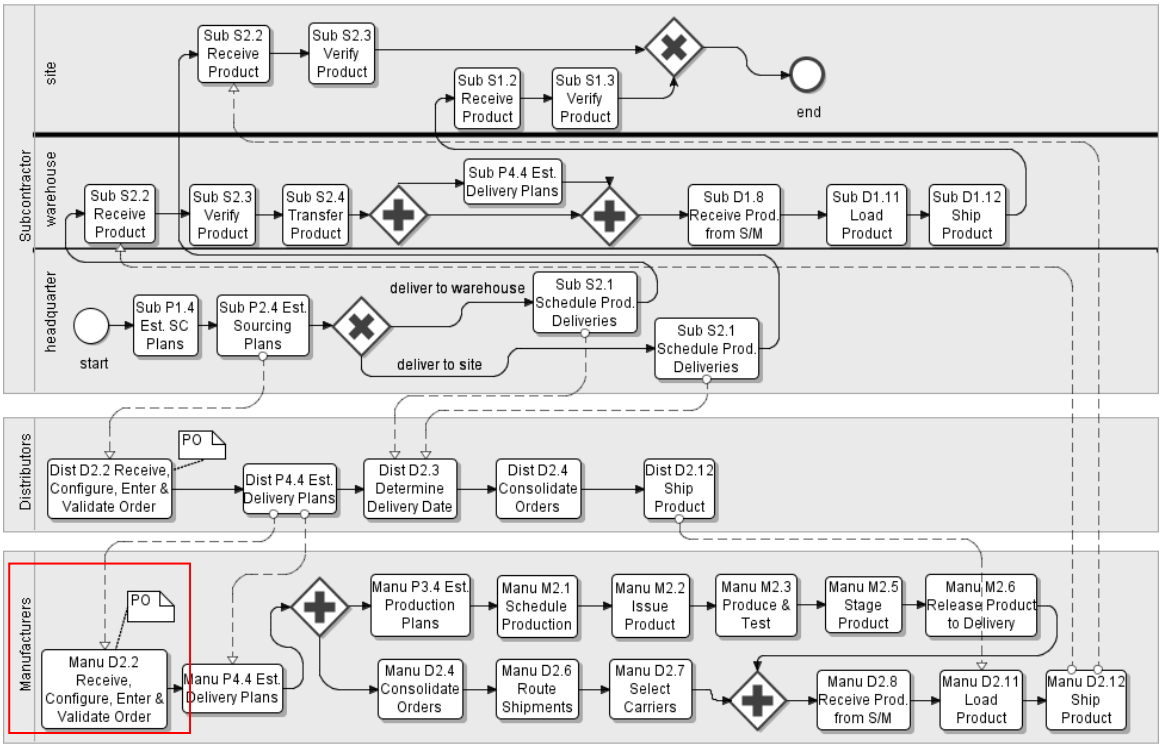


Figure 3.15: BPMN representation of the SCOR Level 3 model for make-to-order standard / configurable products

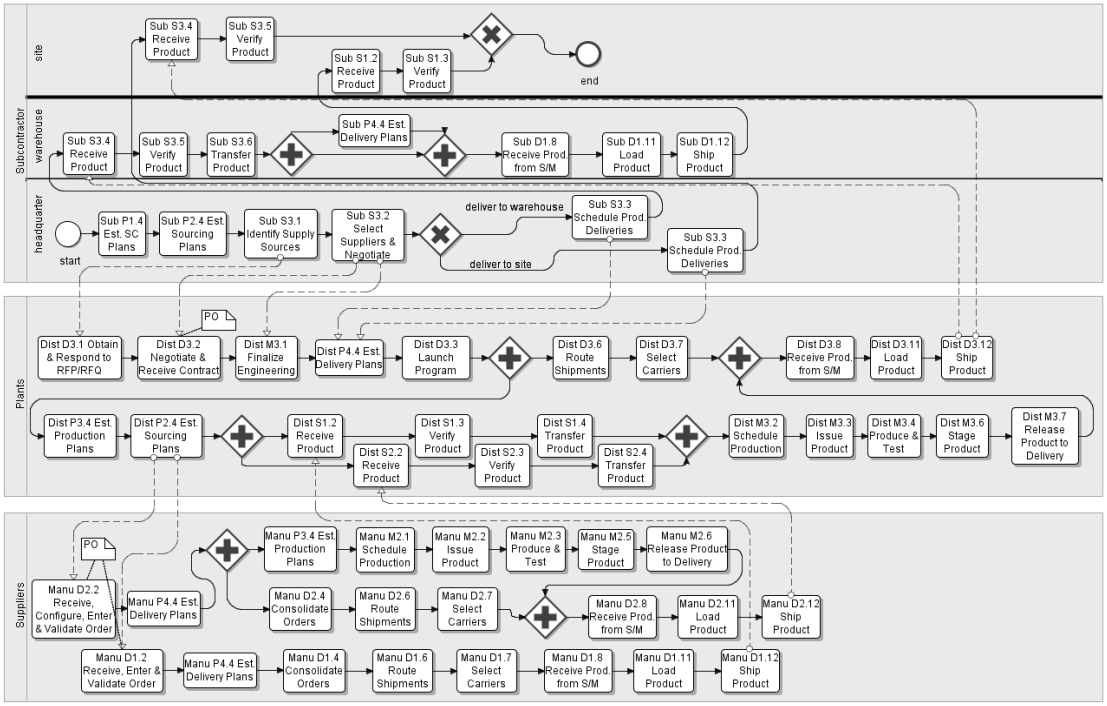


Figure 3.16: BPMN representation of the SCOR Level 3 model for custom products

3.3.3.3 BPMN for SCOR Level 4 Modeling

The complexity of the implementation for different Level 3 processes can vary. Figure 3.17 illustrates the BPMN representation of a SCOR Level 4 model for the fairly complex Level 3 process “Manu D2.2 Receive, Configure, Enter & Validate Order” performed by manufacturers, which is shown in Figure 3.15. When performing the Level 3 process, as described in the Level 4 process model, the manufacturer processes the purchase order received and checks the order consistency and validity. If the order is not valid, the manufacturer will return the order and ask for clarification; otherwise, the manufacturer will check its inventory status and production plan concurrently. After evaluating the order, the manufacturer will either send a confirmation message if the order is accepted, or notify a rejection on the purchase order otherwise.

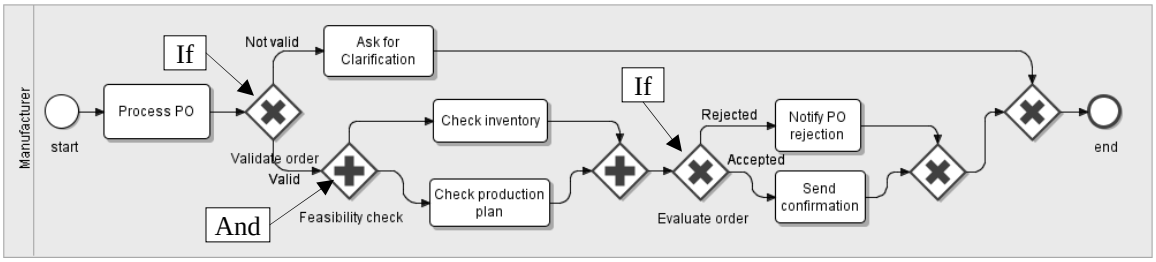


Figure 3.17: BPMN graphical representation of the process "Manu D2.2 Receive, Configure, Enter & Validate Order" in Figure 3.15

These processes and their arrangements depicted in Figure 3.17 are only one of the many possible configurations. In fact, SCOR Level 4 models are specific to company and product. The SCOR documents do not provide the detailed process components, process structures, and implementation. Users need to define the Level 4 models to fit their own needs and situations.

3.4 Supply Chain Performance Monitoring

The SCOR framework is commonly used to describe the network structure of a supply chain for strategic planning. The use of the SCOR models in the development of information systems for supply chain integration and management is herein proposed and demonstrated. This section presents a development framework that leverages SCOR Level 3 and Level 4 models to build a supply chain performance monitoring system for construction projects.

In the construction industry, consumers increasingly place a higher value on quality than on loyalty to suppliers, and price is often not the only determining factor in making choices [76]. Performance management is a common means to improve quality level and to maintain a high quality. Performance monitoring and measurement is at the heart of the performance management processes [15]. It is often said that a business can only

manage what it measures. The lack of performance measurement systems is one of the major obstacles to effective supply chain management [55]. In the construction industry, various researchers have developed conceptual frameworks and systems for the monitoring and measurement on the performance at the project level [22, 46, 106]. However, studies on the performance monitoring and measurement systems of supply chains in construction projects are lacking. Supply chain performance monitoring and measurement systems allow project participants to identify any bottleneck in a supply chain and offer the basis for supply chain process evaluation and improvement. Therefore, a performance monitoring system can help contractors to evaluate suppliers' information for use in future projects.

Building a supply chain performance monitoring system is a non-trivial task because it involves understanding and integration across organizational boundaries. Traditionally, supply chain performance is measured in the form of scorecards or reports through interviews or questionnaires. These approaches are labor-intensive in the data collection processes and often provide information with time lags. Nowadays the Internet provides a means to instantaneously share and integrate distributed information and applications at low cost. Monitoring supply chain performance and sharing the data across company boundaries can now be performed conveniently over the web. This section describes the use of the Internet and web services technologies for the development of a web-enabled performance monitoring system for construction supply chains.

The system development framework, as illustrated in Figure 3.18, adopts a model-based service oriented approach. At the beginning of the system design phase, the supply chain network and its members are identified and modeled through the SCOR Level 1 and Level 2 modeling framework. Process maps of internal and external supply chain operations are then produced through SCOR Level 3 and Level 4 modeling and represented in the BPMN standard. Performance metrics for each SCOR Level 3 process are specified, with the aid of the SCOR guidelines. Whenever necessary, the SCOR

Level 4 BPMN models are modified to measure and record the specified performance metrics.

In the system implementation phase, the SCOR Level 3 and Level 4 models are then converted into web services execution language BPEL files. Implementation details such as port types of the connected web services are added to the BPEL files, which are finally incorporated to the SC Collaborator system.

We can reuse the modeling techniques in Section 3.3 for the supply chain network modeling and the process modeling in the system development framework. The following sections describe the incorporation of performance metrics in a BPMN process model and the conversion of the system implementation of BPMN process models in SC Collaborator.

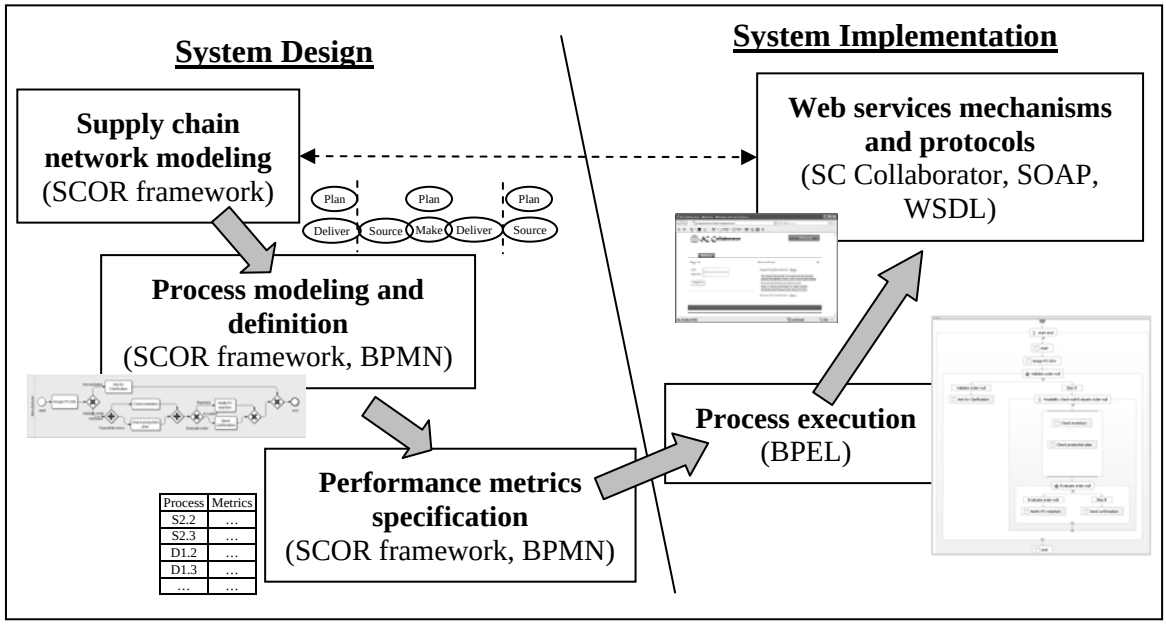


Figure 3.18: Development framework for service oriented supply chain performance monitoring systems using the SCOR framework, open standards, and open source technologies

3.4.1 Supply Chain Performance Metrics

What to measure and how to measure should be clearly defined when developing a performance monitoring and measurement system. Various performance metrics for supply chain management have been suggested, investigated, and analyzed in literature [36-39, 48, 54]. Gunasekaran et al. [38] emphasizes performance metrics related to suppliers, delivery performance, customer-service, and inventory and logistics costs in a supply chain. Kleijnen and Smits [48] analyzes performance metrics in fill rate, confirmed fill rate, response delay, stock level, delivery delay, and sales/inventory ratio. Gunasekaran and Kobu [36] reviews recently published literature on performance measurement in supply chains and summarizes 27 key performance indicators for supply chain management. In this research, we refer to the guidelines for supply chain performance metrics in the SCOR framework [91].

The SCOR document suggests 524 distinct performance metrics that are divided into five categories: supply chain reliability (RL), responsiveness (RS), agility (AG), costs (CO), and asset management (AM). Reliability measures the accuracy and conditions of the products, documentation, packaging, etc. in the delivering process. Responsiveness refers to the speed at which a supply chain provides products to the customer. Agility measures the flexibility and adaptability of a supply chain to respond to the changes in markets. Costs correspond to the costs associated with operating the supply chain. Asset management measures the effectiveness in managing assets to support supply chain operations. The performance metrics are hierarchically structured in three levels. For example, as illustrated in Figure 3.19, the performance metric “Receive, Configure, Enter & Validate Order Cycle Time” belongs to “RS 2.3 Delivery Cycle Time” on Level 2, which belongs to “RS 1.1 Order Fulfillment Cycle Time” on Level 1 in the Supply Chain Responsiveness category.

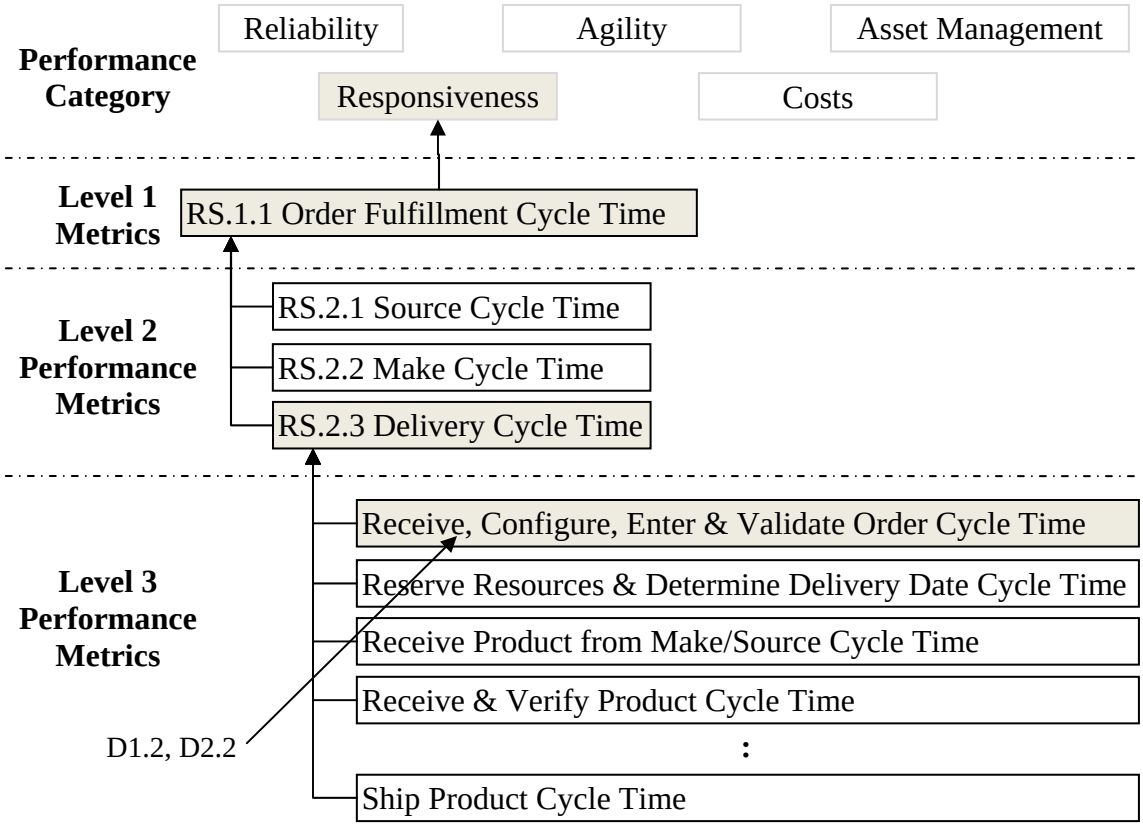


Figure 3.19: Performance metrics hierarchically structured in the SCOR guidelines

Level 3 performance metrics are related to SCOR Level 3 processes. For example, the performance metric "Receive, Configure, Enter & Validate Order Cycle Time" measures the average time associated with reserving resources and determining a delivery date in the SCOR Level 3 processes "D1.2 Receive, Configure, Enter & Validate Order" and "D2.2 Receive, Configure, Enter & Validate Order." Therefore, we can select the supply chain performance metrics in a process-based approach after the SCOR Level 3 modeling. Selection of performance metrics is specific to the characteristics of the project and the needs of the stakeholders. One approach is to first decide one or two performance categories of interest, and then selects the performance metrics in the categories of interest in each SCOR Level 3 supply chain process.

For the case example, since timeliness was emphasized in the MEP processes in the student center construction project, performance metrics in the Supply Chain Responsiveness category are selected for most of the processes. Metrics in the Supply Chain Reliability category are also selected because unreliable and incomplete order fulfillment can delay the material delivery. For demonstration purpose, the selected metrics include mainly process cycle time, timeliness of product arrival, product conditions upon arrival, and documentation accuracy. Table 3.5 enlists some of the supply chain performance metrics used in the student center construction case example.

Task elements can be added at the beginning and/or at the end of a SCOR Level 4 model to measure and record the performance values. To measure the cycle time of the process "D2.2 Receive, Configure, Enter & Validate Order," for example, a task is added after the start event to record the starting time of every instance of the process and a task is added right before the end event to calculate the time spent on the instance, as illustrated in Figure 3.20. The time spent is the cycle time for an instance of the D2.2 process. The performance value of "Receive, Configure, Enter & Validate Order Cycle Time" for a particular organization or a particular product type can be obtained by taking the average of the cycle time of the D2.2 process instances.

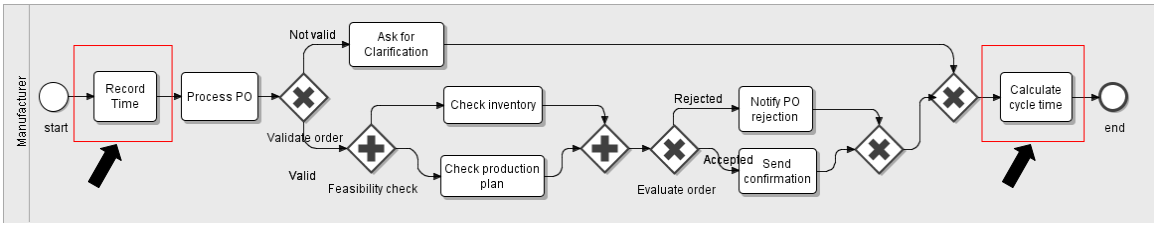


Figure 3.20: Level 4 BPMN model for the process "Manu D2.2 Receive, Configure, Enter & Validate Order" with addition of two tasks to calculate the cycle time

Table 3.5: Examples of supply chain performance metrics used in the case example

SCOR Supply Chain Processes	SCOR Performance Metrics
P1.4 Establish & Communicate Supply-Chain Plans	• (RS) Establish Supply Chain Plans Cycle Time
P2.4 Establish Sourcing Plans	• (RS) Establish Sourcing Plans Cycle Time
P3.4 Establish Production Plans	• (RS) Establish Production Plans Cycle Time
P4.4 Establish Delivery Plans	• (RS) Establish Delivery Plans Cycle Time
S1.1 S2.1 S3.3 Schedule Product Deliveries	• (RS) Schedule Product Deliveries Cycle Time • (RS) Average Days per Schedule Change • (CO) Quantity per shipment
S1.2 S2.2 S3.4 Receive Product	• (RL) % Orders/ Lines Received On-Time • (RL) % Orders/ Lines Received with Correct Shipping Documents • (RS) Receiving Product Cycle Time
S1.3 S2.3S3.5 Verify Product	• (RL) % Orders/ Lines Received Defect Free • (RL) % Orders/ lines Received with Correct Content • (RS) Verify Product Cycle Time
M1.1 M2.1 Schedule Production Activities	• (RS) Schedule Production Activities Cycle Time • (AM) Capacity Utilization
M2.2 M3.3 Issue Sourced/ In-Process Product	• (RS) Issue Sourced/In-Process Product Cycle Time • (CO) Quantity per Shipment
M2.3 Produce and Test	• (RL) Yield • (RS) Produce and Test Cycle Time • (AM) Capacity Utilization
D1.1 D2.1 Process Inquiry and Quote	• (RS) Process Inquiry & Quote Cycle Time
D1.2 D2.2 Receive, Configure, Enter and Validate Order	• (RS) Receive, Configure, Enter & Validate Order Cycle Time
D1.3 D2.3 Reserve Inventory and Determine Delivery Date	• (RL) % of Orders Delivered In Full • (RS) Reserve Inventory & Determine Delivery Date Cycle Time
D1.8 D2.8 D3.8 Receive Product from Source or Make	• (RL) % correct material documentation • (RS) Receive Product from Source or Make Cycle Time

3.4.2 System Implementation

The SCOR Level 3 and Level 4 BPMN models developed in Section 3.3.3 are deployed in the SC Collaborator system framework. Each of these models is deployed as a separate process service unit to be integrated in the system. The process service units are implemented using Business Process Execution Language (BPEL) [80], an implementation-level standard for web services orchestration. The SCOR Level 3 and Level 4 BPMN models are converted to BPEL processes, which are deployed in an orchestration engine for execution. After deployment, a Web Service Description Language (WSDL) [104] document that describes the deployed BPEL process units is available for each of the deployed SCOR Level 3 and Level 4 BPEL processes. The WSDL documents provide information on how to invoke the process units.

Figure 3.21 illustrates the relationship among different components in the SCOR-based SC Collaborator system framework. There are three types of service units – SCOR Level 3 process units, SCOR Level 4 process units, and fundamental web service units.

- As discussed in Section 3.3.3, SCOR Level 3 models can be categorized for (1) stocked standard products, (2) make-to-order standard / configurable products, and (3) custom products. Each role in the Level 3 model is deployed as a BPEL process unit. Each SCOR Level 3 process node in the Level 3 models links to a SCOR Level 4 process unit. For example, as represented in Figure 3.21, the SCOR Level 3 process unit of the Subcontractor role for stocked products links to the SCOR Level 4 process units of “D2.2” and “P4.4.” WSDL documents of the Level 4 process units are needed for service invocation.

- The SCOR Level 4 BPEL process units integrate the fundamental web service units to perform various SCOR Level 3 processes. The process units refer to the WSDL documents of the fundamental service units for service invocation.

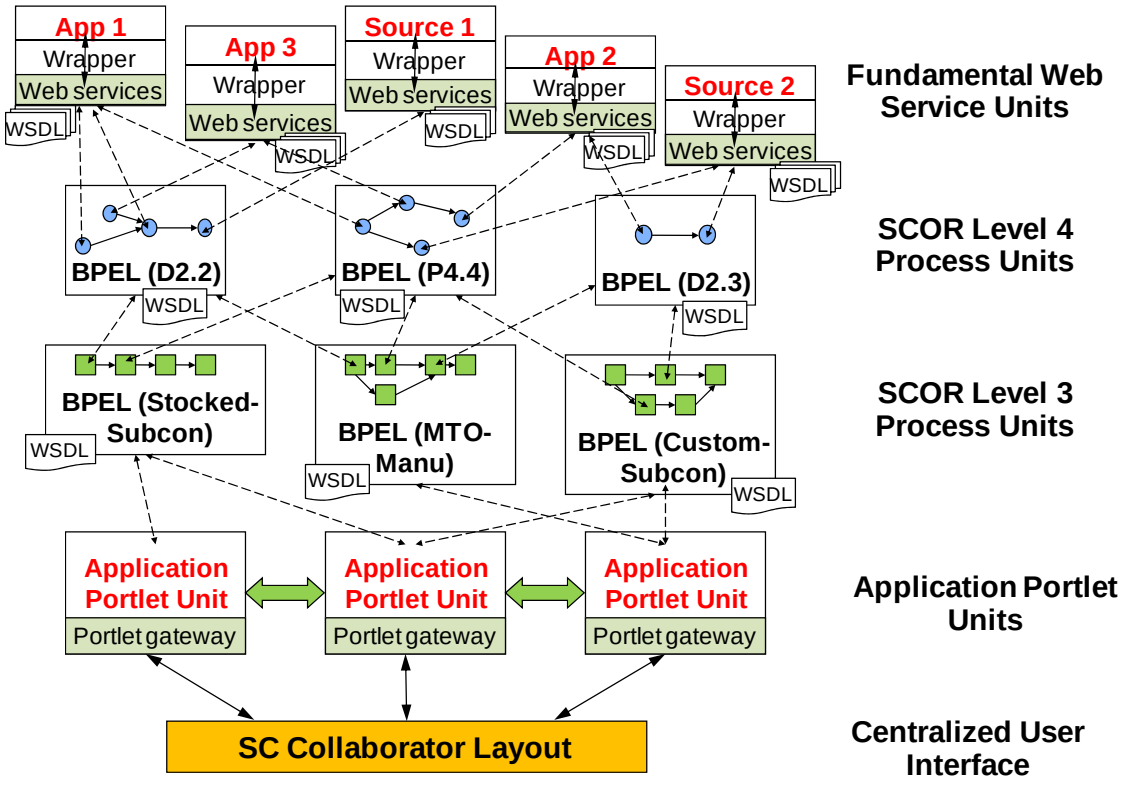


Figure 3.21: Incorporating SCOR Level 3 and Level 4 models in SC Collaborator

- Fundamental web service units include both the internal and external web service units that are available to invocation. These web service units may perform various operations such as offering data or system functionality, running an application, or modifying information. The implementation and deployment of web service units in SC Collaborator are discussed in Section 2.4. Each of these web service units is associated with a WSDL specification document.

Figure 3.22 shows the procedures to implement a SCOR-based SC Collaborator system framework based on SCOR Level 3 and Level 4 models. First, SCOR Level 4 BPMN models are converted into BPEL skeleton files, which capture the process flows described in the BPMN models. The skeleton files form the basis to develop complete, executable BPEL process files. BPEL deployment packages are then created by combining the BPEL process files with the WSDL documents that describe the Level 4

BPEL processes. The deployment packages are then deployed by Apache ODE engine [9], an open source BPEL execution engine developed by the Apache Software Foundation. Similarly, SCOR Level 3 BPMN models are converted into BPEL skeleton files. Referring to the deployed SCOR Level 4 process units, complete Level 3 BPEL process files are created. After that, deployment packages are built and deployed using Apache ODE engine. Finally, both the SCOR Level 3 and Level 4 process units can be invoked by application portlet units in SC Collaborator for system operations and layouts. The details of the procedures are presented in the following sections.

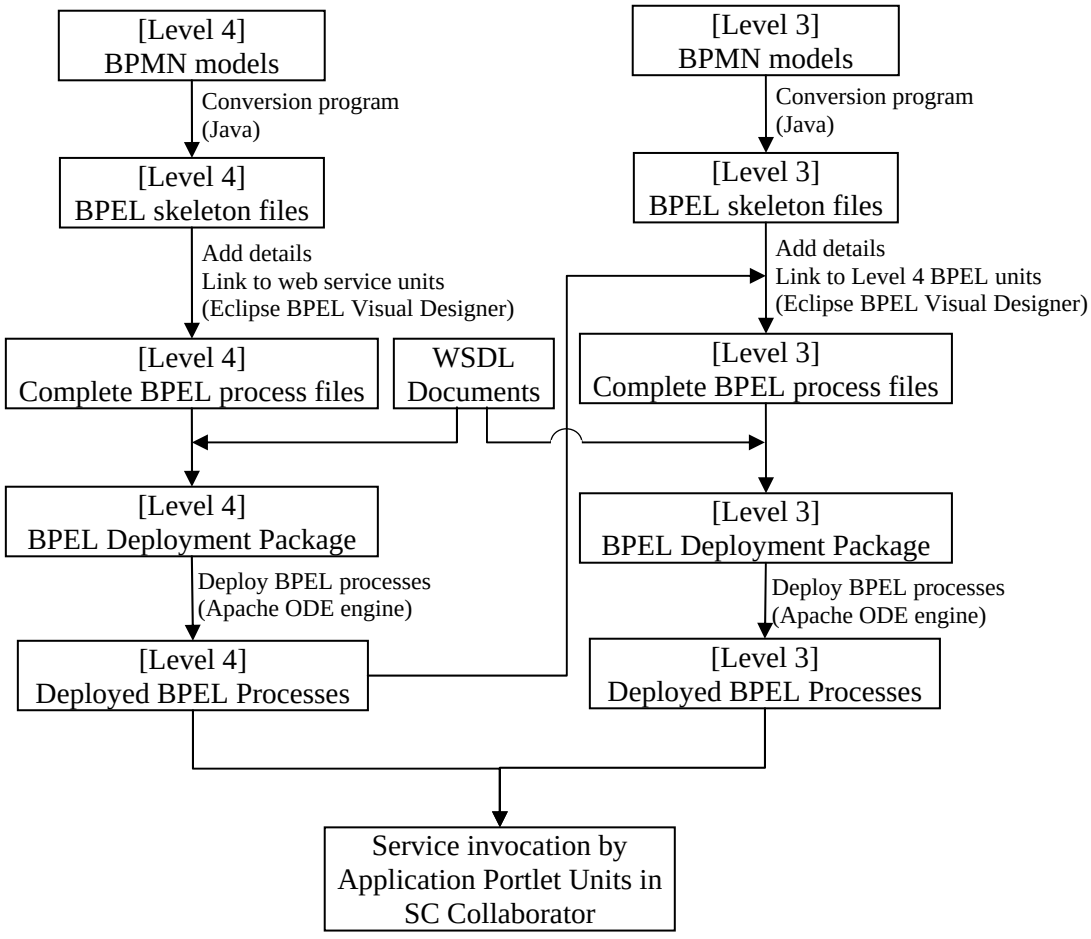


Figure 3.22: Procedures to incorporate the SCOR models to the service oriented SC Collaborator system framework

3.4.2.1 Conversion of BPMN Models into BPEL Skeleton Files

BPMN models cannot be executed directly due to its high level of abstraction. However, BPMN models can be easily converted into BPEL [80]. The converted BPEL files capture the process flow and logic specified in the BPMN models. However, to make the converted BPEL files executable, specifications of the BPEL activities and the partner links have to be added.

BPMN models are stored and transferred using XML Metadata Interchange (XMI) format. XMI is a standard developed by OMG for exchanging metadata information via Extensible Markup Language (XML). To convert BPMN models into BPEL files, XMI output of the BPMN models are exported, and then parsed to extract the process definitions and sequences. Figure 3.23 shows the XMI representation of the BPMN model for the SCOR Level 3 process "Manu D2.2 Receive, Configure, Enter & Validate Order," which is depicted in Figure 3.20. In the XMI output, every event, gateway, activity, or artifact object is represented as an individual <vertices> element, while every connecting object is represented as a <sequenceEdges> element. As illustrated in Figure 3.23, an XMI file indicates the linkages between the flow objects (events, gateways and activities) represented in a BPMN model.

A Java conversion program has been built to parse XMI files and to create a BPEL skeleton file for every BPMN model. The program instantiates a Java class `Process` for every extracted <vertices> element. Every `Process` instance has (1) a process name, (2) a process type, and (3) a list of succeeding `Process` instances. The *name* attribute of a <vertices> element is used as the process name. The *activityType* attribute of a <vertices> element is converted and used as the process type. The conversions between *activityType* attribute values and the BPEL process type are listed in Table 3.6. The *outgoingEdges* and *incomingEdges* attributes of <vertices> elements are matched to each other to regenerate the sequences and relationships of the flow objects. As illustrated in Figure 3.23, for example, the *outgoingEdges* attribute of <vertices> element "start"

```
<?xml version="1.0" encoding="UTF-8"?>
<bpmn:BpmnDiagram xmi:version="2.0"
   xmlns:xmi="http://www.omg.org/XMI"
   xmlns:bpmn="http://stp.eclipse.org/bpmn"
   xmi:id="_7eIVwYYMEd6DcYMaJrJywg" iD="_7eIVwIYMEd6DcYMaJrJywg">
   <pools xmi:type="bpmn:Pool" xmi:id="_7fUokYYMEd6DcYMaJrJywg"
     iD="_7fUokIYMEd6DcYMaJrJywg" name="Manufacturer">
     <vertices xmi:type="bpmn:Activity"
       xmi:id="_ED9jIYYNEd6DcYMaJrJywg" iD="_ED9jIIYNEd6DcYMaJrJywg"
       outgoingEdges="_ZJwbsYYOEd6DcYMaJrJywg" name="start"
       activityType="EventStartEmpty"/>
     <vertices xmi:type="bpmn:Activity"
       xmi:id="_7fUok4YMEd6DcYMaJrJywg" iD="_7fUokoYMEd6DcYMaJrJywg"
       outgoingEdges="_oin4kYYNEd6DcYMaJrJywg"
       incomingEdges="_ZJwbsYYOEd6DcYMaJrJywg" name="Record Time"
       activityType="Task"/>
                :
     <vertices xmi:type="bpmn:Activity"
       xmi:id="_Xy4vYYYOEd6DcYMaJrJywg" iD="_Xy4vYIYOEd6DcYMaJrJywg"
       incomingEdges="_Xy4vaoYOEd6DcYMaJrJywg" name="end"
       activityType="EventEndEmpty"/>
     <sequenceEdges xmi:type="bpmn:SequenceEdge"
       xmi:id="_ZJwbsYYOEd6DcYMaJrJywg" iD="_ZJwbsIYOEd6DcYMaJrJywg"
       source="_ED9jIYYNEd6DcYMaJrJywg"
       target="_7fUok4YMEd6DcYMaJrJywg"/>
     <sequenceEdges xmi:type="bpmn:SequenceEdge"
       xmi:id="_oin4kYYNEd6DcYMaJrJywg" iD="_oin4kIYNEd6DcYMaJrJywg"
       source="_7fUok4YMEd6DcYMaJrJywg"
       target="_oiUWkYYNEd6DcYMaJrJywg"/>
             :
     <sequenceEdges xmi:type="bpmn:SequenceEdge"
       xmi:id="_r2D_QYYNEd6DcYMaJrJywg" iD="_r2D_QIYNEd6DcYMaJrJywg"
       name="Not validated" source="_oiUWkYYNEd6DcYMaJrJywg"
       target="_r16OQYYNEd6DcYMaJrJywg"/>
   </pools>
</bpmn:BpmnDiagram>
```

Vertex ID

Edge ID

Vertex ID

Edge ID

Edge ID

Vertex IDs

Figure 3.23: XMI representation of the SCOR Level 4 BPMN model for the process "Manu D2.2 Receive, Configure, Enter & Validate Order," which is shown in Figure 3.20

matches the *incomingEdges* attribute of the succeeding <vertices> element "Process PO." The unique IDs of these two elements are specified in the <sequenceEdges> element linking the <vertices> elements. As an example, the `Process` class instance for the <vertices> element highlighted in Figure 3.23 has a value of (process name = "start", process type = "empty", succeeding = ["Process@19821f"]), where "Process@19821f" is the internal ID for the `Process` class instance with process name "Process PO."

Table 3.6: Conversion table from BPMN elements to BPEL elements

BPMN element type	"activityType" attribute value	Converted BPEL activity
Event	EventStartEmpty	<bpel:empty>
Event	EventEndEmpty	<bpel:empty>
Activity	Task, or *null*	<bpel:empty>
Gateway	GatewayDataBasedExclusive	<bpel:if>, <bpel:elseif>, <bpel:else>
Gateway	GatewayDataBasedInclusive	<bpel:if>
Gateway	GatewayParallel	<bpel:flow>

After parsing all the <vertices> elements in an XMI file, the Java conversion program generates a linked list of instances of the class `Process` internally. The linked list is then converted into a BPEL skeleton file with the corresponding BPEL activity tags. The internally generated linked list and the BPEL skeleton file of the SCOR Level 4 model for "Manu D2.2 Receive, Configure, Enter & Validate Order" are shown in Figure 3.24 and Figure 3.25, respectively. As illustrated in Figure 3.25, whenever there is an "if" process instance or a "flow" process instance, the elements in the resulted BPEL skeleton will move a level down. The conversion program finally adds an <bpel:process> tag as the beginning element of the XML-based BPEL skeleton file.

SCOR Level 3 BPMN models can also be converted to BPEL skeleton files using the conversion program using the same approach. Each lane in the SCOR Level 3 BPMN model generates a single BPEL skeleton file. Figure 3.26 shows the BPEL skeleton file for the "Subcontractor" lane in the SCOR Level 3 model for stocked standard products, which is shown in Figure 3.14.

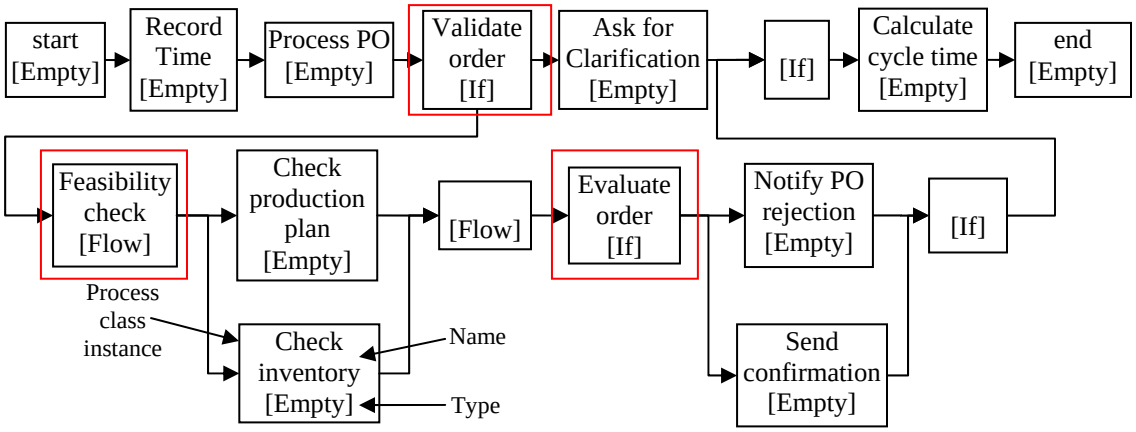


Figure 3.24: The linked list of "Process" class instances after parsing the SCOR Level 4 model for the process "Manu D2.2 Receive, Configure, Enter & Validate Order"

```
<?xml version="1.0" encoding="UTF-8"?>
<bpel:process exitOnStandardFault="yes" name="Manu D2.2"
  suppressJoinFailure="yes" xmlns:bpel="http://docs.oasis-
  open.org/wsbpel/2.0/process/executable">
  <bpel:sequence>
    <bpel:empty name="start"/>
    <bpel:empty name="Record Time"/>
    <bpel:empty name="Process PO"/>
    <bpel:if name="Validate order">
      <bpel:sequence>
        <bpel:flow name="Feasibility check">
          <bpel:empty name="Check inventory"/>
          <bpel:empty name="Check production plan"/>
        </bpel:flow>
        <bpel:if name="Evaluate order">
          <bpel:empty name="Notify PO rejection"/>
          <bpel:elseif>
            <bpel:empty name="Send confirmation"/>
          </bpel:elseif>
        </bpel:if>
      </bpel:sequence>
      <bpel:elseif>
        <bpel:empty name="Ask for Clarification"/>
      </bpel:elseif>
    </bpel:if>
    <bpel:empty name="Calculate cycle time"/>
    <bpel:empty name="end"/>
  </bpel:sequence>
</bpel:process>
```

Figure 3.25: BPEL skeleton file converted from the linked list of "Process" class instances depicted in Figure 3.24

```
<?xml version="1.0" encoding="UTF-8"?>
<bpel:process exitOnStandardFault="yes" name="Stocked-Subcontractor"
  suppressJoinFailure="yes" xmlns:bpel="http://docs.oasis-
  open.org/wsbpel/2.0/process/executable">
  <bpel:sequence>
    <bpel:empty name="start"/>
    <bpel:empty name="Sub P1.4 Est. SC Plans"/>
    <bpel:empty name="Sub P2.4 Est. Sourcing Plans"/>
    <bpel:empty name="Sub S1.1 Schedule Prod. Deliveries"/>
    <bpel:if name="Deliver Warehouse">
      <bpel:sequence>
        <bpel:empty name="Sub S1.2 Receive Product"/>
        <bpel:empty name="Sub S1.3 Verify Product"/>
        <bpel:empty name="Sub S1.4 Transfer Product"/>
        <bpel:flow name="Inventory">
          <bpel:empty name="Sub P4.4 Est. Delivery Plans"/>
          <bpel:empty/>
        </bpel:flow>
        <bpel:empty name="Sub D1.8 Receive Prod. from S/M"/>
        <bpel:empty name="Sub D1.11 Load Product"/>
        <bpel:empty name="Sub D1.12 Ship Product"/>
      </bpel:sequence>
    </bpel:if>
    <bpel:empty name="Sub S1.2 Receive Product"/>
    <bpel:empty name="Sub S1.3 Verify Product"/>
    <bpel:empty name="end"/>
  </bpel:sequence>
</bpel:process>
```

Figure 3.26: BPEL skeleton file converted from the “Subcontractor” lane in the SCOR Level 3 BPMN model for stocked standard products, which is shown in Figure 3.14

3.4.2.2 Completing BPEL Process Files

The generated BPMN skeleton file only describes the process flow represented in BPMN model. The process flow serves as a backbone for the orchestration logic section of a BPEL process file. Detailed specification of the BPEL activities and the PartnerLinks and Variables sections need to be added before the BPEL process can be deployed. Eclipse BPEL Visual Designer [32], an open source BPEL editor developed by the Eclipse Foundation, is used to facilitate the addition of implementation and connection details to BPEL skeleton files.

To obtain a complete SCOR Level 4 BPEL process file, a new BPEL process file is created in Eclipse BPEL Visual Designer. The BPEL codes in the generated Level 4 skeleton file are then copied to the new empty BPEL process file. Specifications of the BPEL activities, partner links, and variables are then defined using the user interface provided in Eclipse BPEL Visual Designer. Creation of a new BPEL process file in Eclipse BPEL Visual Designer generates a WSDL document that is linked to the BPEL process file. The WSDL document is modified automatically by the BPEL editor whenever the linked BPEL process file is changed. Therefore, consistency between the WSDL and BPEL files can be guaranteed.

Consider the SCOR Level 4 model for the process "Manu D2.2 Receive, Configure, Enter & Validate Order" as an example. Figure 3.27 shows the Eclipse BPEL Visual Designer displaying a new BPEL file with the BPEL codes from the skeleton file, which are shown in Figure 3.25. When a BPEL activity is selected in the display in the BPEL editor, the Properties window shows a form for entering specification details of the selected BPEL activity. The form is dependent on the type of the selected BPEL activities. For instance, when the *empty* BPEL activity "Check inventory" is selected, the Properties window shows an option to replace the *empty* activity by a *invoke, receive, reply,* or *assign* activity, as illustrated in Figure 3.27.

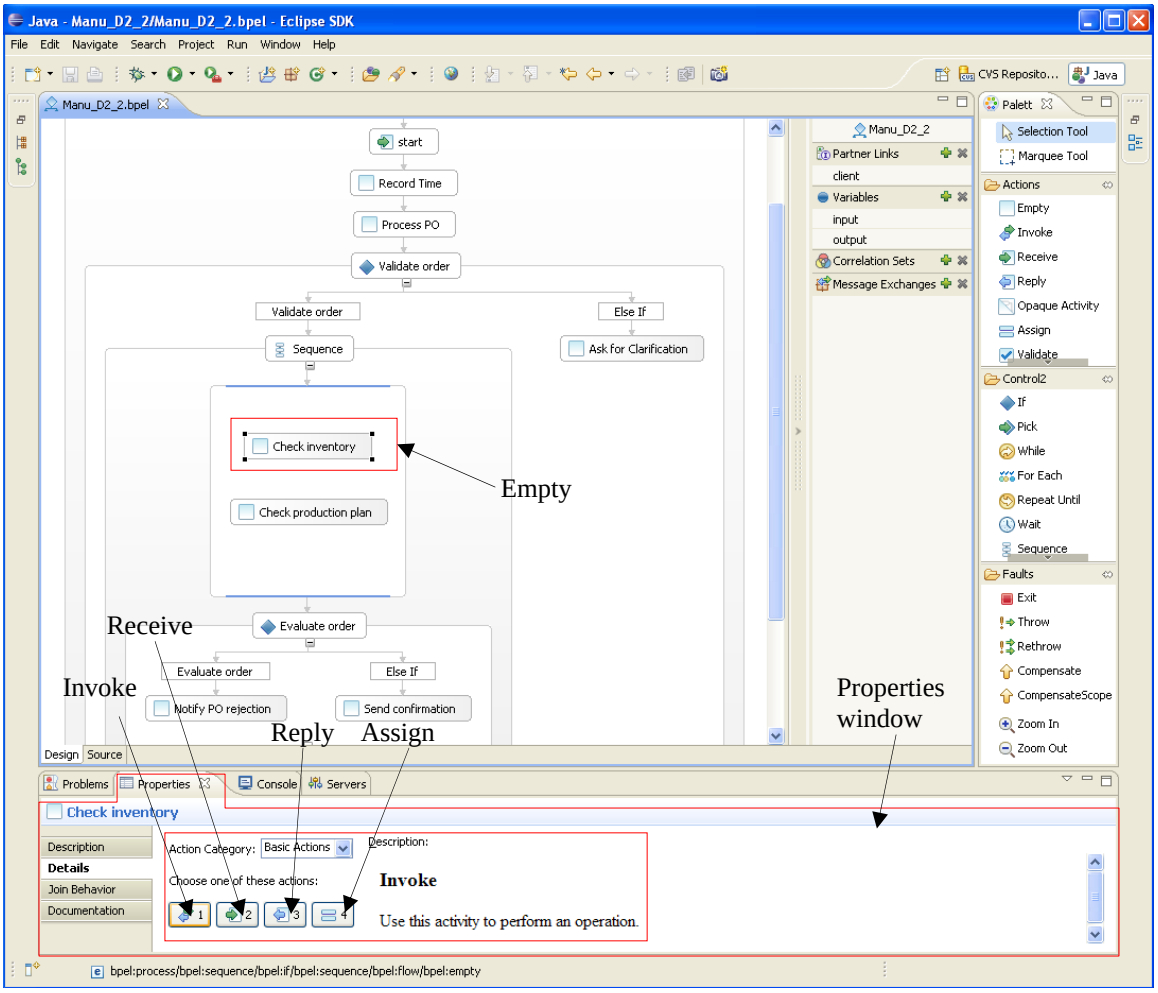


Figure 3.27: Eclipse BPEL Visual Designer for completing the BPEL process file

For *receive*, *reply* and *invoke* activities, the *partnerLink*, *portType*, *operation*, and *variable* attributes should be defined. Take the activity "Check inventory" as an example. It is replaced by an *invoke* BPEL activity using the interface in Eclipse BPEL Visual Designer. As illustrated in Figure 3.28, when the replaced "Check inventory" activity is selected, the Properties window allows creation of a partner link that will be associated with the activity. After naming the newly created partner link as "Inventory," WSDL document of the service unit Inventory Service is then imported to the BPEL editor. The editor can extract the specification from the imported WSDL file such as the service port type and the data structure of the request and response messages. Users can

associate the service unit Inventory Service to the newly created partner link "Inventory" and assign the partner link to the activity "Check inventory," as demonstrated in Figure 3.28. Finally, the operation "checkInventory" of the service unit Inventory Service is selected. This automatically generates the variables with data structure consistent to the request and response messages of the operation "checkInventory," and assigns the variables as well as the operation to the BPEL activity "Check inventory." The BPEL codes added at the back-end are shown in Figure 3.29.

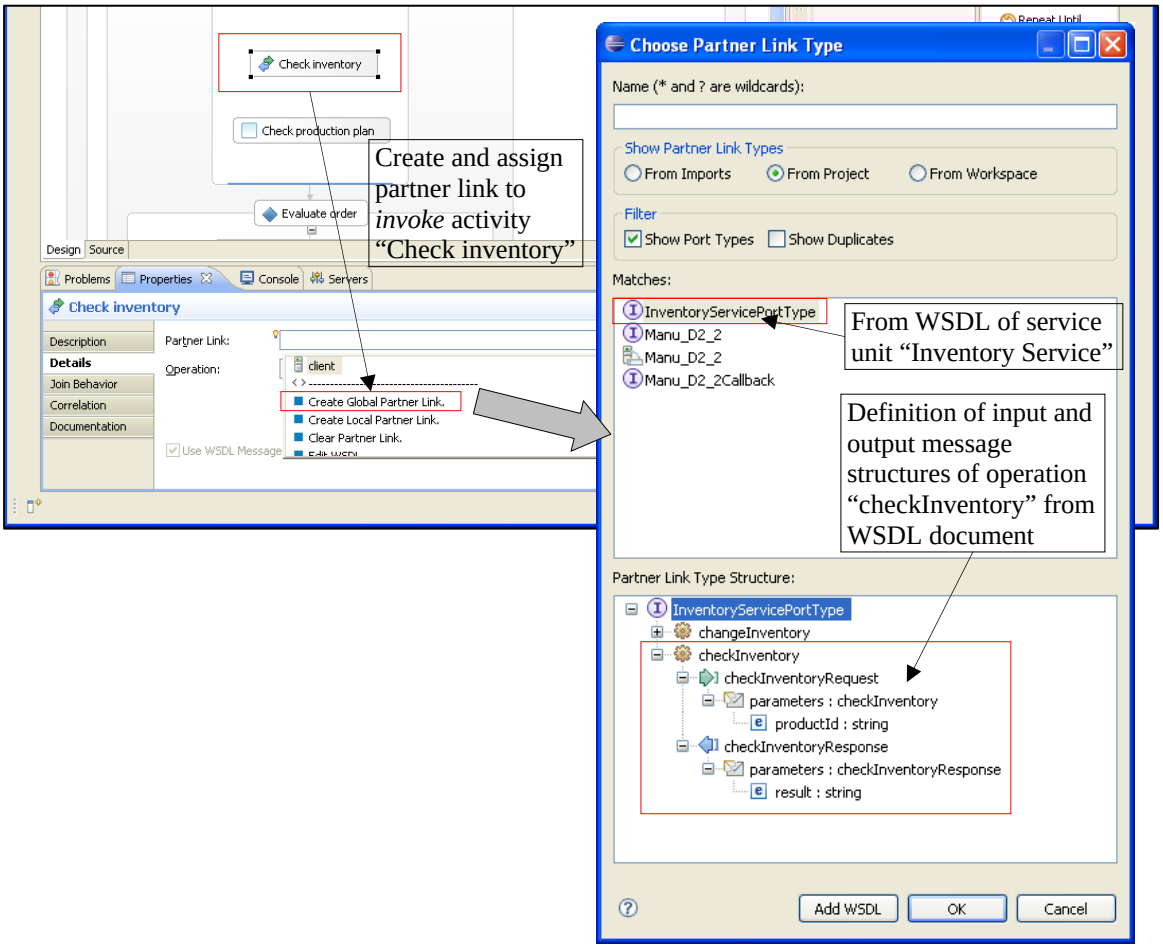


Figure 3.28: Creating and assigning partner link to an *invoke* activity "Check inventory"

```
        :
<bpel:partnerLink name="Inventory" partnerLinkType="tns:InventoryPLT"
   partnerRole="ServiceProvider" />
        :
<bpel:variable name="InventoryResponse"
   messageType="ns:checkInventoryResponse" />
<bpel:variable name="InventoryRequest"
   messageType="ns:checkInventoryRequest" />
        :
<bpel:invoke name="Check inventory" partnerLink="Inventory"
   operation="checkInventory" portType="ns:InventoryServicePortType"
   inputVariable="InventoryRequest"
   outputVariable="InventoryResponse" />
        :
```

Figure 3.29: Specification details for the “Check inventory” activity added to the BPEL process file

Eclipse BPEL Visual Designer also allows a user-friendly interface for checking, modifying and managing the specification details of each component in a BPEL process file. As illustrated in Figure 3.30, for example, the created partner link “Inventory” and variables “InventoryResponse” and “InventoryRequest” are listed in the user interface display. When the partner link is selected, the Properties window shows the partner role and available service operations of the service unit associated with the partner link. Similarly, the definition of partner link, operation, input variable, and output variable for the activity “Check inventory” can be conveniently viewed and changed using the Properties window in the user interface, as shown in Figure 3.31.

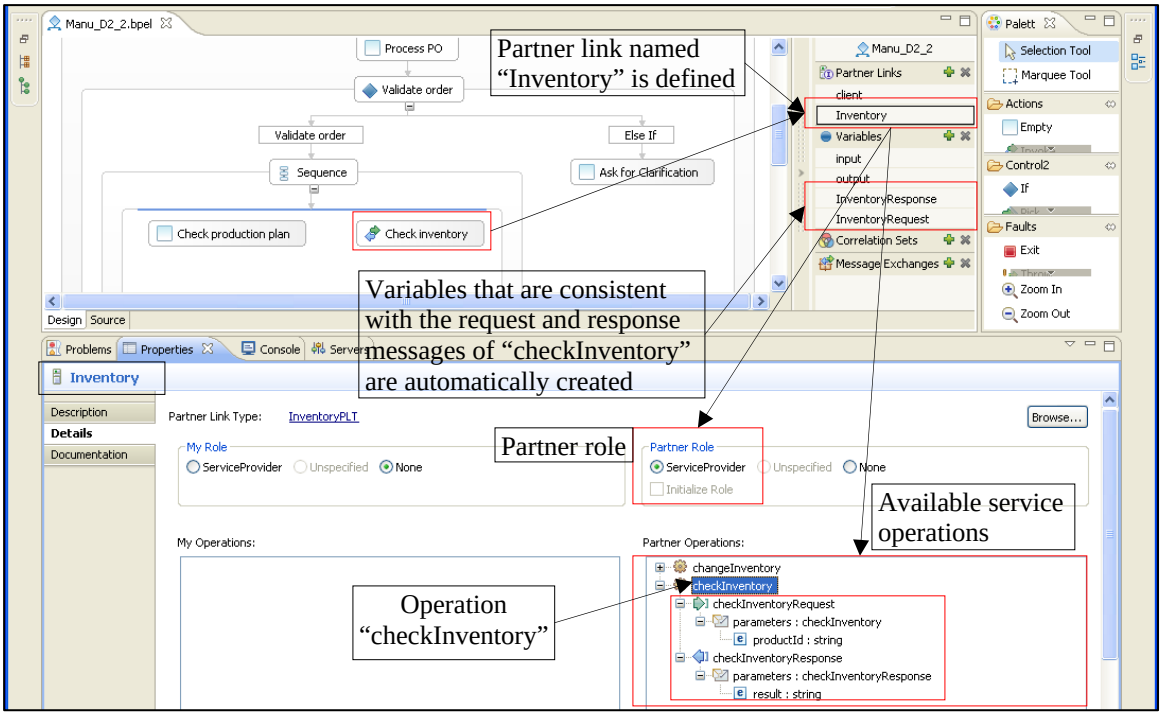


Figure 3.30: Displaying the definition of the partner link "Inventory"

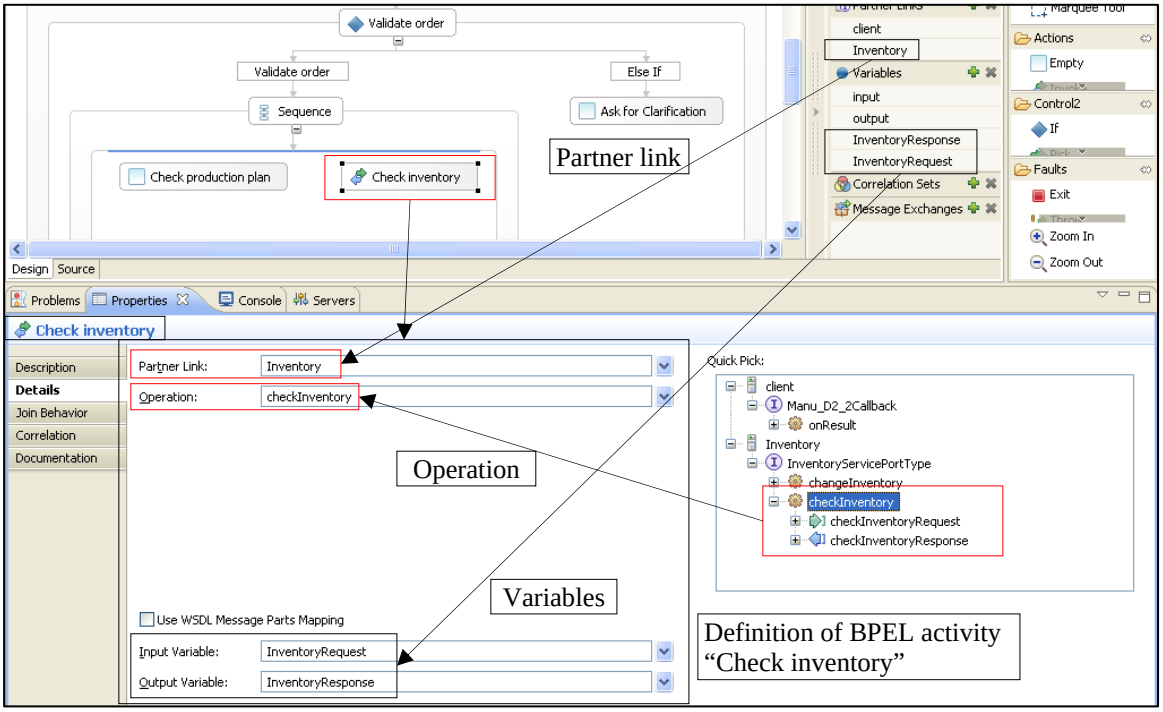


Figure 3.31: Displaying the specification of the BPEL activity "Check inventory"

Based on the BPEL codes from BPEL skeleton files, specification details of the activities, partner links and variables can be added easily using the BPEL editor Eclipse BPEL Visual Designer. As the BPEL process files are changed, the BPEL editor also modifies the WSDL documents associated with them, which are useful for deployment and invocation of the BPEL service units. The complete BPEL process file and the associated WSDL document of the Level 4 model for the process "Manu D2.2 Receive, Configure, Enter & Validate Order" are shown in Figure 3.32 and Figure 3.33, respectively.

For SCOR Level 3 models, similar procedures are taken to build complete, executable BPEL process files from BPEL skeleton files, which are converted from Level 3 BPMN models. The only difference is that SCOR Level 3 BPEL processes integrate multiple Level 4 processes while SCOR Level 4 BPEL processes integrate multiple fundamental service units. Therefore, WSDL documents of various Level 4 BPEL process units are imported when adding specification details to SCOR Level 3 BPEL processes using Eclipse BPEL Visual Designer. The complete BPEL process file and the associate WSDL document of the "Subcontractor" role in the Level 3 model for stocked standard products are illustrated in Figure 3.34 and Figure 3.35, respectively.

```
<bpel:process name="Manu_D2_2" suppressJoinFailure="yes"
 targetNamespace="http://localhost:8080/service/process/Manu_D2_2"
 xmlns:bpel="http://docs.oasis-open.org/wsbpel/2.0/process/executable">
<bpel:import location="Manu_D2_2Artifacts.wsdl"
 namespace="http://localhost:8080/service/process/Manu_D2_2"                    Import
 importType="http://schemas.xmlsoap.org/wsdl/" />
<bpel:partnerLinks>
 <bpel:partnerLink name="client" partnerLinkType="tns:Manu_D2_2"                Partner links
  myRole="Manu_D2_2Provider" partnerRole="Manu_D2_2Requester" />
 <bpel:partnerLink name="Inventory" partnerLinkType="tns:InventoryPLT"
  partnerRole="ServiceProvider"></bpel:partnerLink>
       :
 <bpel:partnerLink name="Message" partnerLinkType="tns:MessagePLT"
  partnerRole="ServiceProvider"></bpel:partnerLink>
</bpel:partnerLinks>
<bpel:variables>
 <bpel:variable name="input" messageType="tns:Manu_D2_2RequestMessage"/>        Variables
 <bpel:variable name="output" messageType="tns:Manu_D2_2ResponseMessage"/>
 <bpel:variable name="InventoryResponse" messageType="ns:checkInventoryResponse" />
 <bpel:variable name="InventoryRequest" messageType="ns:checkInventoryRequest" />
       :
 <bpel:variable name="MessageRequest" messageType="ns:addMessageRequest" />
 <bpel:variable name="CycleTimeRequest1" messageType="ns:calculateCycleTimeRequest" />
</bpel:variables>
<bpel:sequence name="main">                                                     Orchestration
 <bpel:receive name="start" partnerLink="client" portType="tns:Manu_D2_2"       logic
  operation="initiate" variable="input" createInstance="yes"/>
 <bpel:invoke name="Record Time" partnerLink="CycleTime" operation="addCycleTime"
  portType="ns:CycleTimeServicePortType" inputVariable="CycleTimeRequest" />
 <bpel:invoke name="Process PO" partnerLink="MaterialOrder" operation="processOrder"
  portType="ns:MaterialOrderServicePortType" inputVariable="MaterialOrderRequest"
  outputVariable="MaterialOrderResponse" />
 <bpel:if name="Validate order">
  <bpel:condition><![CDATA[$input.payload/tns:orderNumber!="" &&
   $$input.payload/tns:productCode!="" && $$input.payload/tns:quantity>0 &&
   $$input.payload/tns:fromCompany!=""]]></bpel:condition>
  <bpel:sequence>
   <bpel:flow name="Feasibility check">
    <bpel:invoke name="Check inventory" partnerLink="Inventory"
     operation="checkInventory" portType="ns:InventoryServicePortType"
     inputVariable="InventoryRequest" outputVariable="InventoryResponse" />
    <bpel:invoke name="Check production plan" partnerLink="Production"
     operation="checkProductionPlan" portType="ns0:production"
     inputVariable="ProductionRequest" outputVariable="ProductionResponse" />
   </bpel:flow>
   <bpel:if name="Evaluate order">
    <bpel:condition>...</bpel:condition>
   <bpel:invoke name="Notify PO rejection" partnerLink="Message" operation="addMessage"
     portType="ns:MessageServicePortType" inputVariable="MessageRequest" />
    <bpel:elseif>
     <bpel:invoke name="Send confirmation" partnerLink="Message" operation="addMessage"
      portType="ns:MessageServicePortType" inputVariable="MessageRequest" />
    </bpel:elseif>
  </bpel:if> </bpel:sequence>
  <bpel:elseif>
   <bpel:invoke name="Ask for Clarification" partnerLink="Message"
    operation="addMessage" inputVariable="MessageRequest" />
  </bpel:elseif>
 </bpel:if>
 <bpel:invoke name="Calculate cycle time" partnerLink="CycleTime"
operation="calculateCycleTime" portType="ns:CycleTimeServicePortType"
inputVariable="CycleTimeRequest1" />
</bpel:sequence> </bpel:process>
```

Figure 3.32: Excerpt of the complete BPEL process file of the Level 4 model for the process “Manu D2.2 Receive, Configure, Enter & Validate Order”

```
<definitions xmlns="http://schemas.xmlsoap.org/wsdl/"
xmlns:wsdl="http://ws.apache.org/axis2" name="Manu_D2_2"
targetNamespace="http://localhost:8080/service/process/Manu_D2_2">
<plnk:partnerLinkType name="InventoryPLT">
 <plnk:role name="ServiceProvider" portType="wsdl:InventoryServicePortType"/>
</plnk:partnerLinkType>
      :
<plnk:partnerLinkType name="MessagePLT">
 <plnk:role name="ServiceProvider" portType="wsdl:MessageServicePortType"/>
</plnk:partnerLinkType>
<plnk:partnerLinkType name="Manu_D2_2">
 <plnk:role name="Manu_D2_2Provider" portType="tns:Manu_D2_2"/>
 <plnk:role name="Manu_D2_2Requester" portType="tns:Manu_D2_2Callback"/>
</plnk:partnerLinkType>
<import location="InventoryService.wsdl" namespace="http://ws.apache.org/axis2"/>
<import location="CycleTimeService.wsdl" namespace="http://ws.apache.org/axis2"/>
<import location="MaterialOrderService.wsdl" namespace="http://ws.apache.org/axis2"/>
<import location="ProductionService.wsdl" namespace=" http://ws.apache.org/axis2"/>
<import location="MessageService.wsdl" namespace="http://ws.apache.org/axis2"/>
<types>
 <schema xmlns="http://www.w3.org/2001/XMLSchema"
  targetNamespace="http://localhost:8080/service/process/Manu_D2_2">
  <element name="Manu_D2_2Request"> <complexType> <sequence>
   <element name="buyer" type="string" />
   <element name="orderNumber" type="string"></element>
      :
   <element name="delivery" type="dateTime" maxOccurs="unbounded"></element>
  </sequence> </complexType> </element>
  <element name="Manu_D2_2Response"> <complexType> <sequence>
   <element name="result" type="string"/>
  </sequence> </complexType> </element>
</schema> </types>
<message name="Manu_D2_2RequestMessage"> <part element="tns:Manu_D2_2Request"
name="payload"/> </message>
<message name="Manu_D2_2ResponseMessage"> <part element="tns:Manu_D2_2Response"
name="payload"/> </message>
<portType name="Manu_D2_2"> <operation name="initiate">
 <input message="tns:Manu_D2_2RequestMessage"/>
</operation> </portType>
<portType name="Manu_D2_2Callback"> <operation name="onResult">
 <input message="tns:Manu_D2_2ResponseMessage"/>
</operation> </portType>
<binding name="Manu_D2_2" type="tns:Manu_D2_2">
 <soap:binding style="document" transport="http://schemas.xmlsoap.org/soap/http"/>
 <operation name="initiate">
  <soap:operation soapAction="initiate"/>
  <input> <soap:body use="literal"/> </input>
</operation> </binding>
<binding name="Manu_D2_2CallbackBinding" type="tns:Manu_D2_2Callback">
 <soap:binding style="document" transport="http://schemas.xmlsoap.org/soap/http"/>
 <operation name="onResult">
  <soap:operation soapAction="onResult"/>
  <input> <soap:body use="literal"/> </input>
</operation> </binding>
<service name="Manu_D2_2Service"> <port binding="tns:Manu_D2_2" name="Manu_D2_2Port">
 <soap:address location="http://localhost:8080/service/process/Manu_D2_2"/>
</port> </service>
<service name="Manu_D2_2CallbackService">
 <port binding="tns:Manu_D2_2CallbackBinding" name="Manu_D2_2CallbackPort">
  <soap:address location="http://localhost:8080/service/process/Manu_D2_2"/>
 </port>
</service>
</definitions>
```

Partner link type

Import

Types

Message

Port type

Binding

Service

Figure 3.33: WSDL file of the Level 4 model for the process “Manu D2.2 Receive, Configure, Enter & Validate Order”

```
<bpel:process name="Stocked_Subcon"
 targetNamespace="http://localhost:8080/service/process/Stocked_Subcon"
 xmlns:bpel="http://docs.oasis-open.org/wsbpel/2.0/process/executable">
<bpel:import namespace="http://localhost:8080/service/process/Sub_S1_4"
 location="Sub_S1_4.wsdl" importType="http://schemas.xmlsoap.org/wsdl/"></bpel:import>
     :                                                                    Import
<bpel:import namespace="http://localhost:8080/service/process/Sub_P1_4"
location="Sub_P1_4.wsdl" importType="http://schemas.xmlsoap.org/wsdl/"></bpel:import>
<bpel:import location="Stocked_SubconArtifacts.wsdl"
 importType="http://schemas.xmlsoap.org/wsdl/" />
<bpel:partnerLinks>
 <bpel:partnerLink name="client" partnerLinkType="tns:Stocked_Subcon"
  myRole="Stocked_SubconProvider" partnerRole="Stocked_SubconRequester" />
 <bpel:partnerLink name="Sub_P1_4" partnerLinkType="tns:Sub_P1_4PLT"          Partner links
  partnerRole="ServiceRequester"></bpel:partnerLink>
     :
 <bpel:partnerLink name="Sub_D1_12" partnerLinkType="tns:Sub_D1_12PLT"
  partnerRole="ServiceRequester"></bpel:partnerLink>
</bpel:partnerLinks>
<bpel:variables>
 <bpel:variable name="input" messageType="tns:Stocked_SubconRequestMessage"/>  Variables
 <bpel:variable name="output" messageType="tns:Stocked_SubconResponseMessage"/>
 <bpel:variable name="Sub_P1_4Request" messageType="ns1:Sub_P1_4ResponseMessage" />
     :
 <bpel:variable name="Sub_D1_12Request" messageType="ns8:Sub_D1_12ResponseMessage" />
</bpel:variables>
<bpel:sequence name="main">
 <bpel:receive name="receiveInput" partnerLink="client" portType="tns:Stocked_Subcon"
  operation="initiate" variable="input" createInstance="yes"/>
 <bpel:invoke name="Sub P1.4 Est. SC Plans" partnerLink="Sub_P1_4" operation="onResult"
  portType="ns1:Sub_P1_4Callback" inputVariable="Sub_P1_4Request"/>
 <bpel:invoke name="Sub P2.4 Est. Sourcing Plans" partnerLink="Sub_P2_4"
  operation="onResult" portType="ns2:Sub_P2_4Callback" inputVariable="Sub_P2_4Request"/>
 <bpel:invoke name="Sub S1.1 Schedule Prod. Deliveries" partnerLink="Sub_S1_1"
  operation="onResult" portType="ns3:Sub_S1_1Callback" inputVariable="Sub_S1_1Request"/>
 <bpel:if name="Deliver Warehouse"> <bpel:sequence>
  <bpel:invoke name="Sub S1.2 Receive Product" partnerLink="Sub_S1_2"
  operation="onResult" portType="ns4:Sub_S1_2Callback" inputVariable="Sub_S1_2Request"/>
  <bpel:invoke name="Sub S1.3 Verify Product" partnerLink="Sub_S1_3"
  operation="onResult" portType="ns5:Sub_S1_3Callback" inputVariable="Sub_S1_3Request"/>
  <bpel:invoke name="Sub S1.4 Transfer Product" partnerLink="Sub_S1_4"
  operation="onResult" portType="ns6:Sub_S1_4Callback" inputVariable="Sub_S1_4Request"/>
  <bpel:invoke name="Sub P4.4 Est. Delivery Plans" partnerLink="Sub_P4_4"/>
  <bpel:invoke name="Sub D1.8 Receive Prod. from S/M" partnerLink="Sub_D1_8"
  operation="onResult" portType="ns0:Sub_D1_8Callback" inputVariable="Sub_D1_8Request"/>
  <bpel:invoke name="Sub D1.11 Load Product" partnerLink="Sub_D1_11"
  operation="onResult" portType="ns7:Sub_D1_11Callback"
  inputVariable="Sub_D1_11Request"/>                                  Orchestration
  <bpel:invoke name="Sub D1.12 Ship Product" partnerLink="Sub_D1_12"      logic
  operation="onResult" portType="ns8:Sub_D1_12Callback"
  inputVariable="Sub_D1_12Request"/>
 </bpel:sequence> </bpel:if>
  <bpel:invoke name="Sub S1.2 Receive Product" partnerLink="Sub_S1_2"
   operation="onResult" inputVariable="Sub_S1_2Request"/>
  <bpel:invoke name="Sub S1.3 Verify Product" partnerLink="Sub_S1_3"
   operation="onResult" inputVariable="Sub_S1_3Request"/>
  <bpel:invoke name="callbackClient"  partnerLink="client"
   portType="tns:Stocked_SubconCallback" operation="onResult"  inputVariable="output"/>
 </bpel:sequence>
</bpel:process>
```

Figure 3.34: Excerpt of the complete BPEL process file of the “Subcontractor” role in the Level 3 model for stocked standard products

```
<definitions xmlns="http://schemas.xmlsoap.org/wsdl/"
xmlns:soap="http://schemas.xmlsoap.org/wsdl/soap/" name="Stocked_Subcon"
targetNamespace="http://localhost:8080/service/process/Stocked_Subcon">
<plnk:partnerLinkType name="Sub_P1_4PLT">
 <plnk:role name="ServiceProvider" portType="wsdl:Sub_P1_4"/>
 <plnk:role name="ServiceRequester" portType="wsdl:Sub_P1_4Callback"/>
</plnk:partnerLinkType>
    :
<plnk:partnerLinkType name="Sub_D1_12PLT">
 <plnk:role name="ServiceProvider" portType="wsdl8:Sub_D1_12"/>
 <plnk:role name="ServiceRequester" portType="wsdl8:Sub_D1_12Callback"/>
</plnk:partnerLinkType>
<plnk:partnerLinkType name="Stocked_Subcon">
 <plnk:role name="Stocked_SubconProvider" portType="tns:Stocked_Subcon"/>
 <plnk:role name="Stocked_SubconRequester" portType="tns:Stocked_SubconCallback"/>
</plnk:partnerLinkType>
<import location="Sub_P1_4.wsdl"
 namespace="http://localhost:8080/service/process/Sub_P1_4"/>
<import location="Sub_D1_12.wsdl"
 namespace="http://localhost:8080/service/process/Sub_D1_12"/>
<types>
 <schema xmlns="http://www.w3.org/2001/XMLSchema" attributeFormDefault="unqualified"
  targetNamespace="http://localhost:8080/service/process/Stocked_Subcon">
  <element name="Stocked_SubconRequest"> <complexType> <sequence>
   <element name="input" type="string"/>
  </sequence> </complexType> </element>
  <element name="Stocked_SubconResponse"> <complexType> <sequence>
   <element name="result" type="string"/>
  </sequence> </complexType> </element>
</schema> </types>
<message name="Stocked_SubconRequestMessage">
 <part element="tns:Stocked_SubconRequest" name="payload"/> </message>
<message name="Stocked_SubconResponseMessage">
 <part element="tns:Stocked_SubconResponse" name="payload"/> </message>
<portType name="Stocked_Subcon"> <operation name="initiate">
 <input message="tns:Stocked_SubconRequestMessage"/>
</operation> </portType>
<portType name="Stocked_SubconCallback"> <operation name="onResult">
 <input message="tns:Stocked_SubconResponseMessage"/>
</operation> </portType>
<binding name="Stocked_SubconBinding" type="tns:Stocked_Subcon">
 <soap:binding style="document" transport="http://schemas.xmlsoap.org/soap/http"/>
 <operation name="initiate"> <soap:operation soapAction="initiate"/>
  <input> <soap:body use="literal"/> </input>
</operation> </binding>
<binding name="Stocked_SubconCallbackBinding" type="tns:Stocked_SubconCallback">
 <soap:binding style="document" transport="http://schemas.xmlsoap.org/soap/http"/>
 <operation name="onResult">  <soap:operation soapAction=" onResult"/>
  <input> <soap:body use="literal"/> </input>
</operation> </binding>
<service name="Stocked_SubconService">
 <port binding="tns:Stocked_SubconBinding" name="Stocked_SubconPort">
 <soap:address location="http://localhost:8080/service/process/Stocked_Subcon"/>
</port> </service>
<service name="Stocked_SubconCallbackService">
 <port binding="tns:Stocked_SubconCallbackBinding" name="Stocked_SubconCallbackPort">
<soap:address location="http://localhost:8080/service/process/Stocked_SubconCallback"/>
</port> </service>
</definitions>
```

Partner link type

Import

Types

Message

Port type

Binding

Service

Figure 3.35: WSDL file of the “Subcontractor” role in the Level 3 model for stocked standard products

3.4.2.3 Deployment of BPEL Process Files

The SCOR Level 3 and Level 4 BPEL processes are deployed as web service units in SC Collaborator for invocation and integration. Deployment of BPEL processes in SC Collaborator has been discussed in Section 2.4.3.3. To deploy a BPEL process, a deployment package is created and then submitted to Apache Orchestration Director Engine (ODE) engine [9] residing in SC Collaborator. A deployment package contains four components – (1) the BPEL process file to be deployed, (2) a deployment descriptor with file name "deploy.xml," (3) a WSDL document that describes the BPEL process to be deployed, and (4) WSDL documents of the service units invoked in the BPEL process. As an example, the BPEL deployment package of the "Subcontractor" role in the SCOR Level 3 model for stocked standard products contains:

- The SCOR Level 3 BPEL process file, as illustrated in Figure 3.34,
- A deployment descriptor file, as illustrated in Figure 3.36,
- The WSDL document associated with the Level 3 BPEL process file, as illustrated in Figure 3.35, and
- WSDL documents of the SCOR Level 4 process units invoked in the Level 3 BPEL process, such as "Sub P1.4", "Sub P2.4" and "Sub D1.12." The WSDL documents are similar to the WSDL document of the process unit "Manu D2.2," which is illustrated in Figure 3.33.

The BPEL deployment package of the SCOR Level 4 model for the Level 3 process "Manu D2.2 Receive, Configure, Enter & Validate Order" contains:

- The SCOR Level 4 BPEL process file, as illustrated in Figure 3.32,
- A deployment descriptor file, as illustrated in Figure 3.37,

- The WSDL document associated with the Level 4 BPEL process file, as illustrated in Figure 3.33, and
- WSDL documents of the fundamental service units invoked in the Level 4 BPEL process.

```
<deploy xmlns="http://www.apache.org/ode/schemas/dd/2007/03"
xmlns:Stocked_Subcon="http://localhost:8080/service/process/Stocked_Subcon"
xmlns:Sub_D1_11="http://localhost:8080/service/process/Sub_D1_11"
          :
xmlns:Sub_S1_4="http://localhost:8080/service/process/Sub_S1_4">
 <process name="Stocked_Subcon:Stocked_Subcon">
 <active>true</active>
 <process-events generate="all"/>
 <provide partnerLink="client">
   <service name="Stocked_Subcon:Stocked_SubconService" port="Stocked_SubconPort"/>
 </provide>
 <invoke partnerLink="client">
   <service name="Stocked_Subcon:Stocked_SubconCallbackService"
     port="Stocked_SubconCallbackPort"/>
 </invoke>
 <invoke partnerLink="Sub_P1_4">
   <service name="Sub_S1_4:Sub_S1_4Service" port="Sub_S1_4Port"/> </invoke>
 <invoke partnerLink="Sub_P2_4">
   <service name="Sub_P2_4:Sub_P2_4Service" port="Sub_P2_4Port"/> </invoke>
 <invoke partnerLink="Sub_P4_4">
   <service name="Sub_P4_4:Sub_P4_4Service" port="Sub_P4_4Port"/> </invoke>
 <invoke partnerLink="Sub_S1_1">
   <service name="Sub_S1_1:Sub_S1_1Service" port="Sub_S1_1Port"/> </invoke>
 <invoke partnerLink="Sub_S1_2">
   <service name="Sub_S1_2:Sub_S1_2Service" port="Sub_S1_2Port"/> </invoke>
 <invoke partnerLink="Sub_S1_3">
   <service name="Sub_S1_3:Sub_S1_3Service" port="Sub_S1_3Port"/> </invoke>
 <invoke partnerLink="Sub_S1_4">
   <service name="Sub_S1_4:Sub_S1_4Service" port="Sub_S1_4Port"/> </invoke>
 <invoke partnerLink="Sub_D1_8">
   <service name="Sub_D1_8:Sub_D1_8Service" port="Sub_D1_8Port"/> </invoke>
 <invoke partnerLink="Sub_D1_11">
   <service name="Sub_D1_11:Sub_D1_11Service" port="Sub_D1_11Port"/> </invoke>
 <invoke partnerLink="Sub_D1_12">
   <service name="Sub_D1_12:Sub_D1_12Service" port="Sub_D1_12Port"/> </invoke>
 </process>
</deploy>
```

Figure 3.36: Deployment descriptor of the “Subcontractor” role in the Level 3 model for stocked standard products

```
<deploy xmlns="http://www.apache.org/ode/schemas/dd/2007/03"
xmlns:Manu_D2_2="http://localhost:8080/service/process/Manu_D2_2"
xmlns:axis2="http://ws.apache.org/axis2">
 <process name="Manu_D2_2:Manu_D2_2">
 <active>true</active>
 <process-events generate="all"/>
 <provide partnerLink="client">
   <service name="Manu_D2_2:Manu_D2_2Service" port="Manu_D2_2Port"/> </provide>
 <invoke partnerLink="client">
   <service name="Manu_D2_2:Manu_D2_2CallbackService" port="Manu_D2_2CallbackPort"/>
 </invoke>
 <invoke partnerLink="Inventory">
   <service name="axis2:InventoryService" port="InventoryServiceSOAP11port_http"/>
 </invoke>
 <invoke partnerLink="CycleTime">
   <service name="axis2:CycleTimeService" port="CycleTimeServiceSOAP11port_http"/>
 </invoke>
 <invoke partnerLink="MaterialOrder">
   <service name="axis2:MaterialOrderService"
     port="MaterialOrderServiceSOAP11port_http"/> </invoke>
 <invoke partnerLink="Production">
   <service name="production:production" port="productionSOAP"/>
 </invoke>
 <invoke partnerLink="Message">
   <service name="axis2:MessageService" port="MessageServiceSOAP11port_http"/>
 </invoke>
 </process>
</deploy>
```

Figure 3.37: Deployment descriptor of the Level 4 model for the process “Manu D2.2 Receive, Configure, Enter & Validate Order”

3.5 Scenario Demonstration

This section demonstrates the construction supply chain performance measurement system that is developed for the student center construction project using the system development framework presented in Section 3.4. The framework leverages the SCOR models developed in Section 3.3. The scenario is based on the data set obtained from the construction project, but the names of the companies are modified for privacy and proprietary reasons. The first step of the system application is company registration. The submittals from the subcontractors provide the general contractor with information about the suppliers of every product. At the beginning of the system application, the general contractor added the names of the distributors and manufacturers for each subcontractor using an online form in the system (Figure 3.38). Modification and removal of the names

are also allowed through the online form. The subcontractors then initiated the SCOR process for any product when they started procurement according to their schedules.

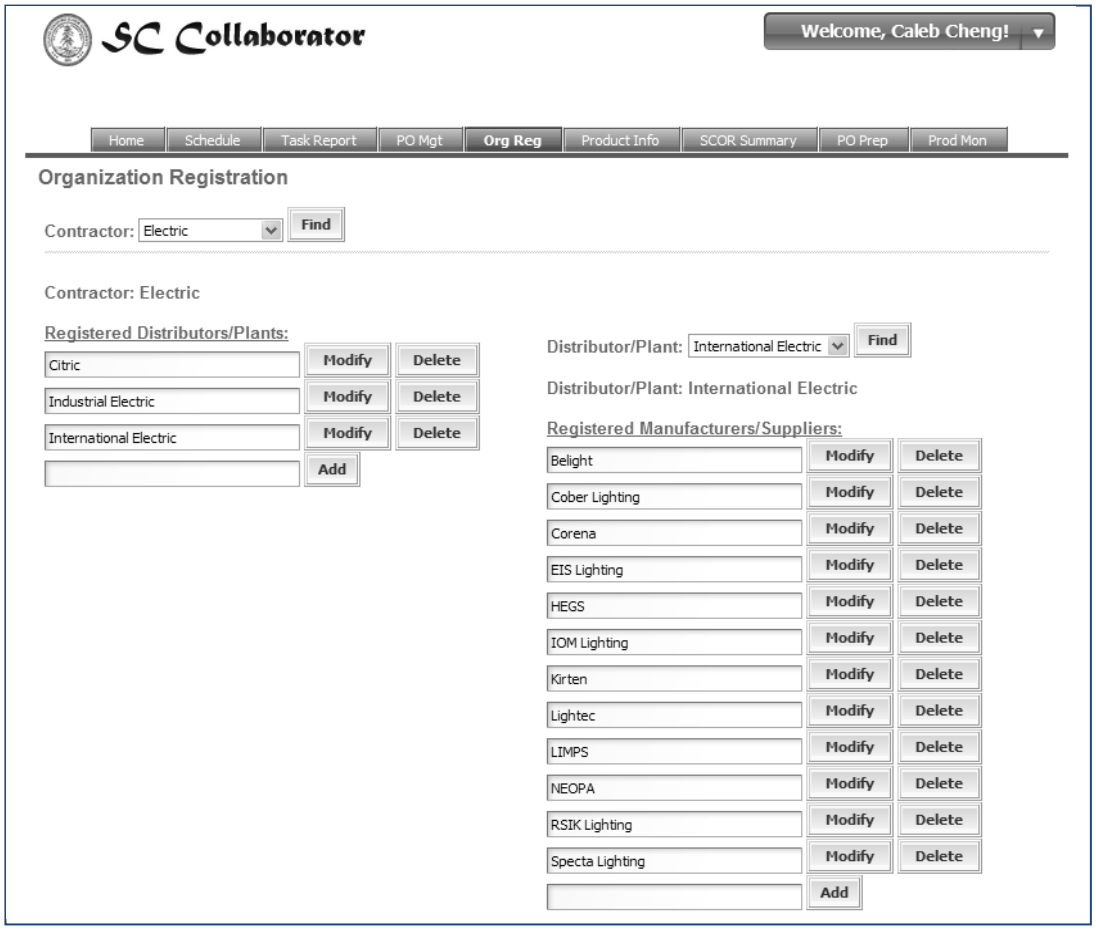


Figure 3.38: General contractor registering the distributors and manufacturers

The system offers a product-based tracking of the supply chain status at the SCOR Level 3. The start time and finish time for each invocation of SCOR Level 3 processes were recorded in the system. The general contractor and subcontractors can log in the system and check the current status of any products they have procured (Figure 3.39). Execution history of the SCOR Level 3 processes is recorded and stored in the back-end database for each product. In addition, contractors can also share the SCOR status records with the members along their supply chains as well as other project participants. For instance, the electrical subcontractor has shared its information of the electrical components to the general contractor for supply chain visibility. The information was also shared with the mechanical subcontractor and the plumbing subcontractor because there were many overlaps of the MEP activities in the project. The sharing settings can be adjusted by the contractors who own the information.

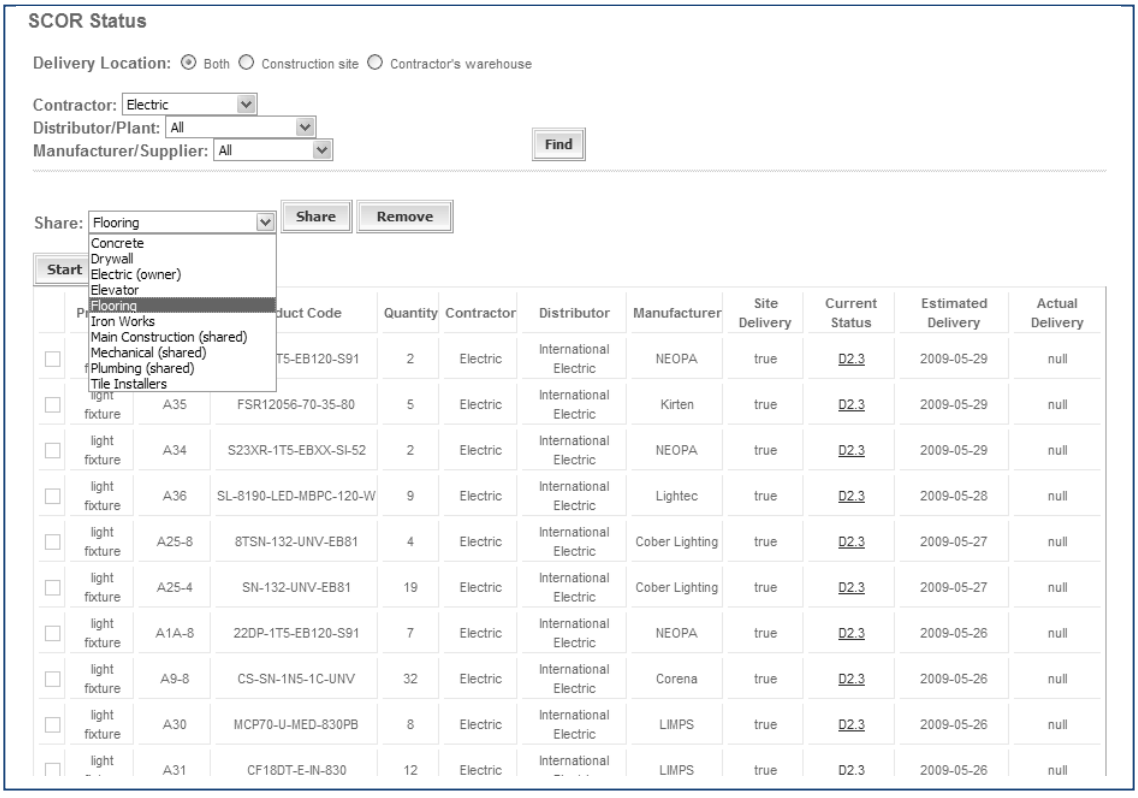
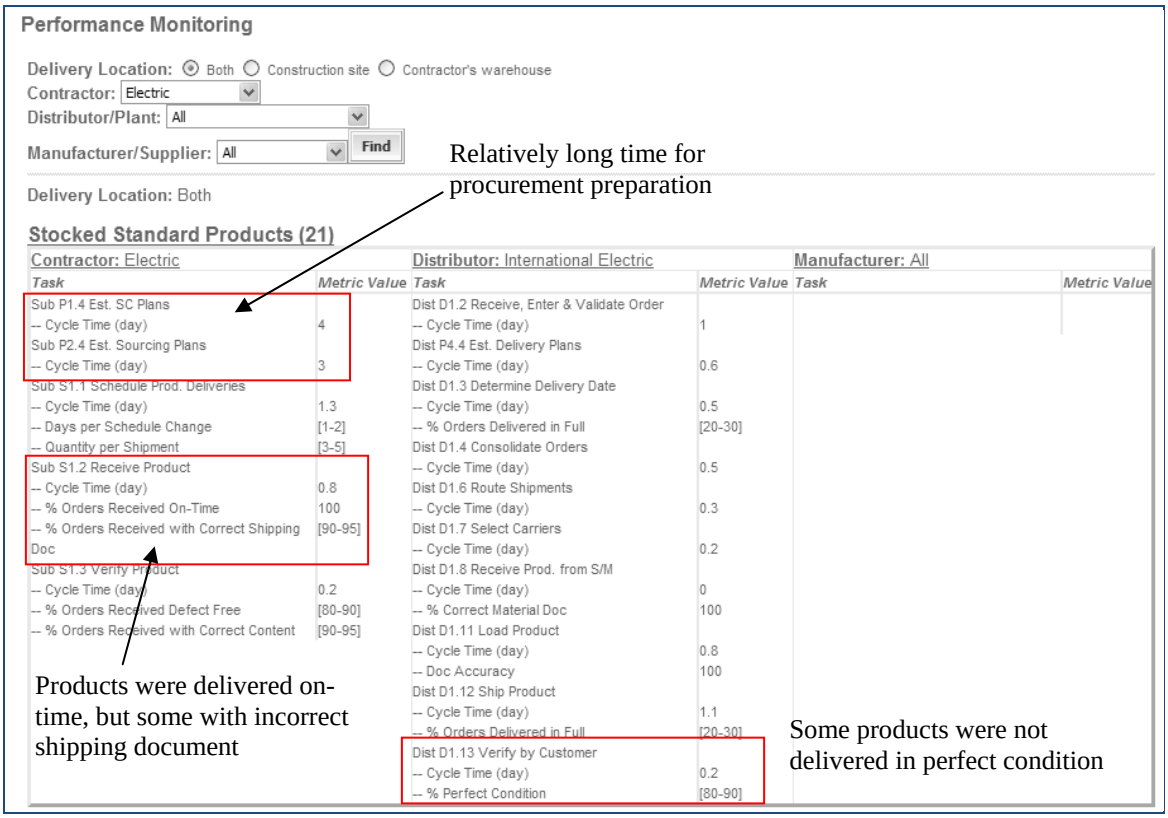


Figure 3.39: SCOR status checking in SC Collaborator



Contractor: Electric		Distributor: International Electric		Manufacturer: All	
Task	*Metric Value*	*Task*	*Metric Value*	*Task*	*Metric Value*
Sub P1.4 Est. SC Plans		Dist D1.2 Receive, Enter & Validate Order			
-- Cycle Time (day)	4	-- Cycle Time (day)	1		
Sub P2.4 Est. Sourcing Plans		Dist P4.4 Est. Delivery Plans			
-- Cycle Time (day)	3	-- Cycle Time (day)	0.6		
Sub S1.1 Schedule Prod. Deliveries		Dist D1.3 Determine Delivery Date			
-- Cycle Time (day)	1.3	-- Cycle Time (day)	0.5		
-- Days per Schedule Change	[1-2]	-- % Orders Delivered in Full	[20-30]		
-- Quantity per Shipment	[3-5]	Dist D1.4 Consolidate Orders			
Sub S1.2 Receive Product		-- Cycle Time (day)	0.5		
-- Cycle Time (day)	0.8	Dist D1.6 Route Shipments			
-- % Orders Received On-Time	100	-- Cycle Time (day)	0.3		
-- % Orders Received with Correct Shipping Doc	[90-95]	Dist D1.7 Select Carriers			
		-- Cycle Time (day)	0.2		
Sub S1.3 Verify Product		Dist D1.8 Receive Prod. from S/M			
-- Cycle Time (day)	0.2	-- Cycle Time (day)	0		
-- % Orders Received Defect Free	[80-90]	-- % Correct Material Doc	100		
-- % Orders Received with Correct Content	[90-95]	Dist D1.11 Load Product			
		-- Cycle Time (day)	0.8		
		-- Doc Accuracy	100		
		Dist D1.12 Ship Product			
		-- Cycle Time (day)	1.1		
		-- % Orders Delivered in Full	[20-30]		
		Dist D1.13 Verify by Customer			
		-- Cycle Time (day)	0.2		
		-- % Perfect Condition	[80-90]		

Figure 3.40: Supply chain performance monitoring in SC Collaborator

The key supply chain performance metrics used in this case scenario are listed in Table 3.5. The developed performance measurement system shows the values of the performance metrics for each manufacturer, distributor, and contractor (Figure 3.40). This information helps the contractors compare their business partners, evaluate their supply chains, and identify bottlenecks and underperformed portions along their supply chains. The information may also indicate performance improvement or deterioration and offer guidelines for future supplier selection and project scheduling. In Figure 3.40, the values of average cycle times were obtained from the schedules provided by the contractors and suppliers. However, it should be pointed out that the companies did not keep track of the numbers of products received on-time, with correct documentation and in perfect condition, days per schedule change, quantity per shipment, and documentation

accuracy in the construction project. The value ranges shown in Figure 3.40 were based on the estimations provided by the companies.

For instance, as illustrated in Figure 3.40, only about 85% of the products that the electrical subcontractor purchased from the distributor *International Electric* were delivered in perfect condition. Perfect condition of an item means that the item meets specification, has correct configuration, is undamaged, is accepted by the customer, is faultlessly installed, and is not returned for repair or replacement. Imperfect condition can be caused by poor transportation conditions, lack of communication between the customer and the supplier, and incorrect documentations, etc. In this case, the subcontractor and the distributor may need to find the causes and prevent further problems.

Figure 3.40 also shows that all of the products the electrical subcontractor purchased from the distributor *International Electric* were delivered on time as scheduled. However, only nearly 95% of the received products came with correct shipping documents, which may lead to confusion of the electrical subcontractor. The problem should have been revealed and improved in the project or even in future collaborations. In addition, the time that the electrical subcontractor generally spent on planning the procurement process was relatively long compared to the duration of the whole sourcing process. It could be difficult and subjective to draw conclusions on the length of the planning time, but the performance measure points out a potential aspect that the subcontractor can pay attention to and improve in the future.

3.6 Summary

This chapter demonstrates the modeling of construction supply chains using the Supply Chain Operations Reference (SCOR) modeling framework. The mechanical, electrical and plumbing (MEP) supply chains of a student center construction project have been

studied retrospectively and used as a case example. In the MEP supply chains we studied, three major types of the construction supply chains were observed – stocked standard products, make-to-order standard / configurable products, and custom products. The three types of supply chains in the student center construction project are modeled through the Level 2, Level 3, and Level 4 modeling of the SCOR framework. SCOR Level 2 models describe the buyer-supplier interactions along supply chains. SCOR Level 3 models specify the material flows and information flows among the Level 3 process elements involved in the supply chains. The implementation details of Level 3 process elements are captured in the SCOR Level 4 models. The SCOR Level 3 and Level 4 models are represented in BPMN standard, which is a reader-friendly open standard for process modeling.

This chapter also presents a model-based service oriented framework to develop a construction supply chain performance monitoring system. The system development framework consists of construction supply chain network, process modeling and definition, performance metrics selection, and process execution. The framework leverages open standards (BPMN, BPEL, WSDL, and SOAP), open source software (SC Collaborator, MySQL, Liferay Portal, Apache Tomcat, Apache ODE, Axis2 framework, Struts framework, and Hibernate framework), and the SCOR modeling framework. The SCOR Level 3 and Level 4 models developed in the first part of this chapter are reused as the baseline in the system design phase. Performance metrics are then determined in a process-based approach for each Level 3 supply chain process element. For system implementation, the Level 3 and Level 4 BPMN models are converted into BPEL files, which are completed with the aid of an open source BPEL editing tool. The BPEL files are finally incorporated in the service oriented SC Collaborator system that is presented in Chapter 2. The modified SCOR-based SC Collaborator system allows product-based supply chain tracking and organization-based performance monitoring, which are demonstrated in Section 3.5.

The system development framework presented in this chapter uses the SCOR models as the backbone. However, the framework is applicable to other supply chain models or process maps. In addition, the system developed in this research is not limited to only MEP supply chains in construction projects of medium scale. In a project of larger scale, the supply chain relationships may be more complex because subcontractors may subcontract some parts of their jobs to other companies. This results in layers of subcontractors each of which is associated with its supply chains with different trading partners. In this case, modifications of the structures and layouts in the SC Collaborator system are needed to meet the actual project needs. However, the system in general can be applied to various types of construction supply chains and to projects of various sizes.

Chapter 4

Distributed SC Collaborator Network

4.1 Introduction

In current collaborative systems, data and documents are commonly stored, managed, and shared in a centralized manner because it facilitates data management and reduces the possibility of data inconsistency. However, information sharing and application integration may be hindered in such centralized systems because some project participants may be reluctant to share information with other participants who do not have direct business relationship. Sharing of information requires mutual trust, which is often difficult to establish among participants in construction projects due to the temporary project-based business relationships. The SC Collaborator system presented in Chapter 2 is a centralized portal system with a single shared database. Despite the security and access control capability of the portal-based system, supply chain members may still be uncomfortable to provide proprietary information for sharing in a system that non-trading partners can physically connect to.

The ownership problem of the shared information is also a common issue for centralized collaborative systems. In a construction project, systems for information and document sharing are commonly installed and hosted in machines that are managed by the general contractor. Contractors and suppliers that do not have direct business relationship with the general contractor may hesitate to provide their information and documents to the general contractor for hosting. Sometimes third party companies are employed to host and manage the collaborative systems throughout a project. When the project is completed, however, how to handle the shared information and documents and who has the rights to own them are often ambiguous and controversial. In addition, companies only have a limited control on the shared data if they are hosted by a third party.

These privacy and ownership problems can be alleviated by separating a centralized system into a distributed network of systems. In such a distributed network, individual project members own and manage their information and applications and, at the same time, share the information and applications with designated project partners at specific time period. Whenever the project finishes or the trading relationship ends, project members can terminate the connections of other project participants to their systems. In this way, people may feel more secure of their proprietary assets and become more willing to share their information, system operations and services.

Establishing a framework for the distributed network is a non-trivial task. Security and information consistency among distributed systems should be maintained. Concurrency and sequencing of the connections across the systems should be facilitated. In this chapter, we will discuss these technical issues and present a distributed network of service oriented portal-based systems.

This chapter is organized as follows. Section 4.2 shows the communication between distributed SC Collaborator systems. Section 4.3 discusses the security protection provided for the service units deployed in a SC Collaborator system. Section 4.4 presents the measures in SC Collaborator to ensure information consistency among service units

in distributed SC Collaborator system. Section 4.5 demonstrates the distributed SC Collaborator network with a procurement scenario and a rescheduling scenario.

4.2 Distributed SC Collaborator Network Architecture

Figure 4.1 shows the schematic representation of a centralized SC Collaborator system and a distributed SC Collaborator network. In the distributed network architecture, each organization has its own database and SC Collaborator system. Each individual SC Collaborator system can act as an intranet and content management system internally, while at the same time allows information exchange and sharing over the web. As illustrated in Figure 4.1, a centralized SC Collaborator system is conventionally used to integrate loosely coupled applications and to share information among project participants from different organizations. The database and the SC Collaborator system are hosted by either one organization or a third party company. With the centralized architecture, individual organizations may hesitate to upload and share their sensitive information depending on their level of trust. On the contrary, for the distributed network architecture as shown in Figure 4.1, the storage and ownership of information are distributed among enterprises and users. They can grant the rights to view or access their own proprietary data and documents to particular collaborating partners for a specific period of time. The distributed systems thus provide better control of the shared information. With the distributed network architecture, enterprises may become more willing to coordinate and share their proprietary information.

The communication between individual SC Collaborator systems is achieved using standardized web service technologies and languages. As illustrated in Figure 4.2, the business implementation core supports the invocation of web services through standardized SOAP. The Apache Axis2 framework allows information, applications, and operations to be exposed and deployed as web services. The deployed functionalities are

described using standardized WSDL language for discovery and invocation. The connectivity between separate SC Collaborator portal systems can be easily created as long as the address of the deployed web services is given.

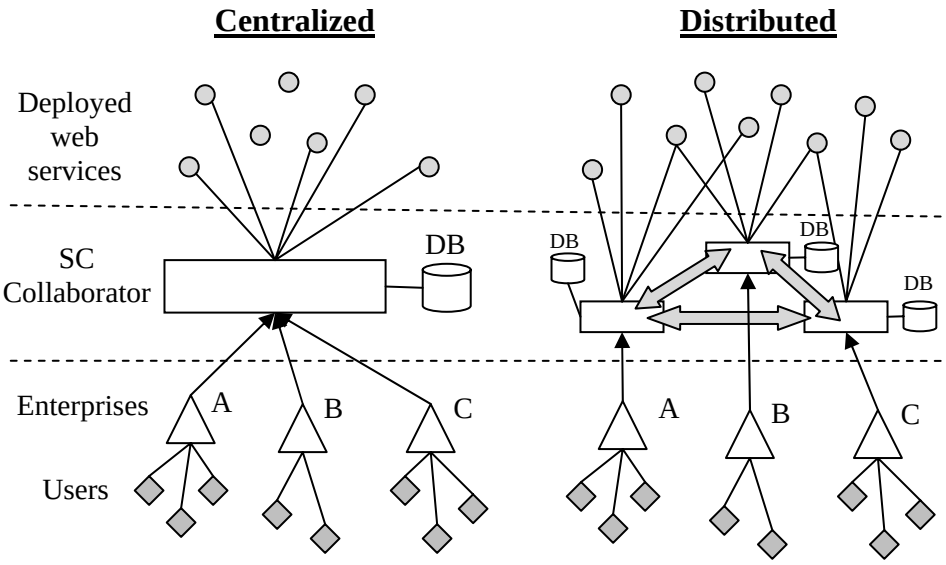


Figure 4.1: Centralized SC Collaborator system versus distributed SC Collaborator network

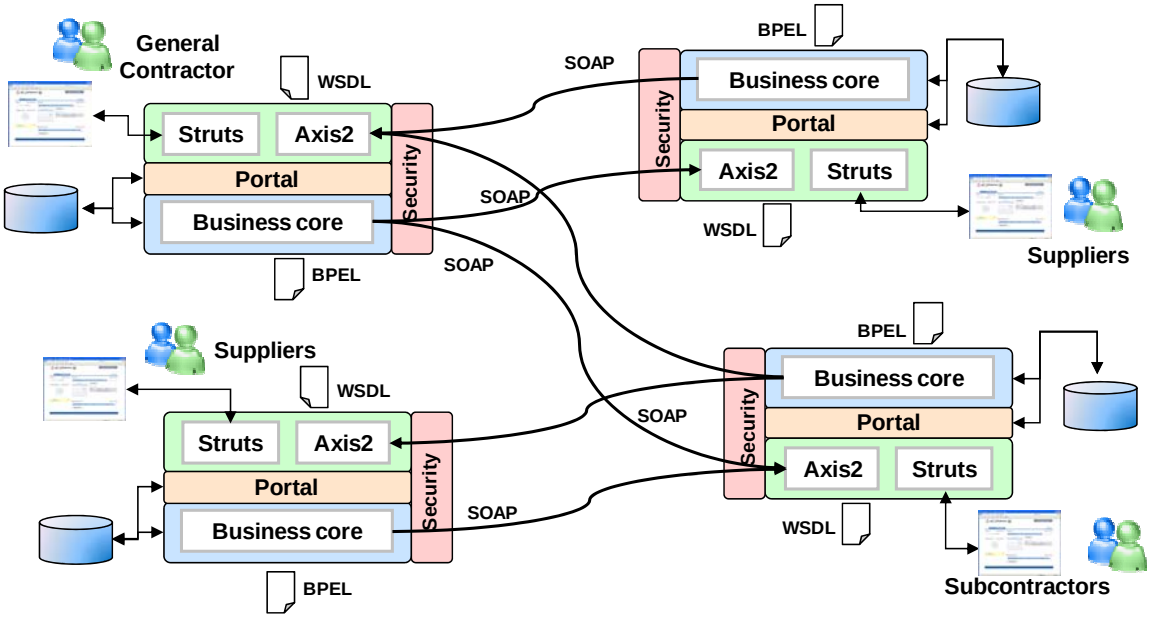


Figure 4.2: System architecture for communications among individual SC Collaborator systems

4.3 Service Security

Security and information consistency are the key issues that a distributed collaborative system network needs to tackle. Security can be performed on the data layer and/or the networking layer. In the former approach, data is manipulated by security functions in the applications before being transmitted from a sender to a receiver. In the latter approach, security is provided by the communication network protocol such as Secure Sockets Layer (SSL). In SC Collaborator, the former approach is adopted and we have developed a layer for access control for the internally deployed web service units.

The web service units can be exposed in a secure way. Each web service unit is treated as a resource with separate permission information, which is stored at the back-end database. Successful authentication with correct user ID and password is required to invoke the service units for data retrieval and application operations. The user ID and password share the same profile with the accounts in SC Collaborator. In other words, the system administrator can manage the access rights to the deployed web services by managing the accounts in SC Collaborator using the administrator portlet. The access rights are established or removed when the corresponding SC Collaborator account is created or deleted. This ensures a consistent access control to the portal system as well as the exposed functionalities.

Since the portal user interface keeps track of the user information after a user logs in the system, the application portlet units can obtain the user identification and check the profiles assigned to the user before invoking web service units in a different SC Collaborator system. The associations between users and external service unit profiles are managed by system administrators and are hidden from the front-end user perspective. The functions to change and to query the associations are deployed as an internal web service unit. Each SC Collaborator system also provides a password protected page for system administrator to check the service operations available for a particular profile, as illustrated in Figure 4.3.

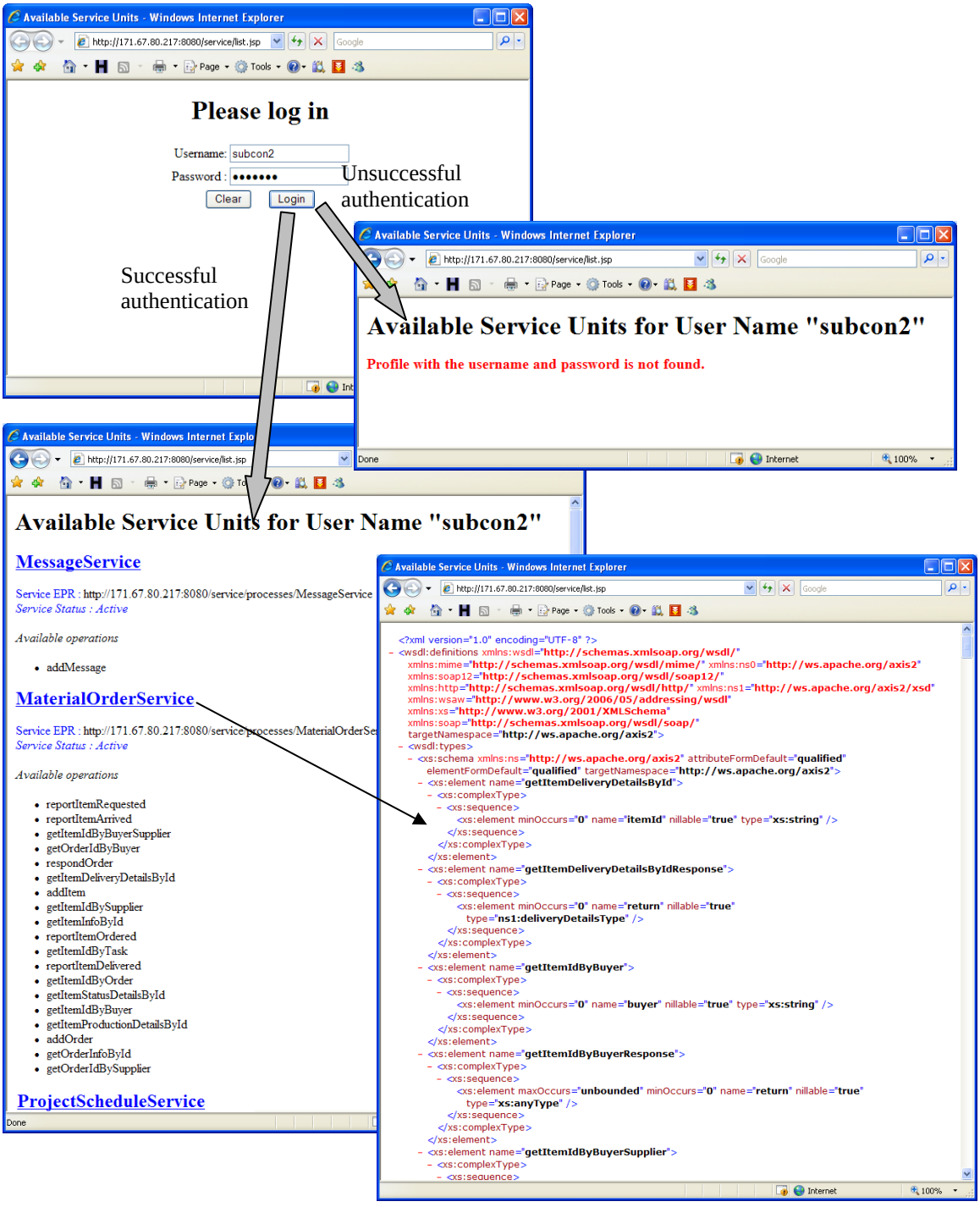


Figure 4.3: Password protected web page allowing users with successful authentication to view available web service units

4.4 Information Consistency

Information consistency is a major issue for collaborations among distributed information sources. In a construction project, for example, project participants may have different copies of the design documents circulating among each other. If the design documents are managed in a centralized system, different participants are guaranteed to obtain the same version of the documents if they connect to the system at the same time. On the contrary, if participants are allowed to obtain a design document from multiple sources, the document that a participant obtains may have a different version from the document obtained by another participant. Therefore, although information and documents are stored and managed in different locations in a distributed SC Collaborator network, they are referenced from a single source in order to maintain consistency. For example, the project schedule is solely provided by the general contractor while the work schedule information is offered by the subcontractors.

To maintain information consistency among distributed information sources, a business process service should be designed to act as a discrete transaction and to achieve the ACID properties (i.e. atomicity, consistency, isolation, and durability) [69]. The ACID properties provide requirements on concurrency and fault-handling behavior of a service. For atomicity, a service performs as a single logical unit and ensures that either all or none of its components are executed when the service terminates. For consistency, a service either creates a new valid state of data, or rolls back and restores to a state satisfying the consistency rules on the data. For isolation, other operations cannot access or see the data in an intermediate state during the processing of a service. For durability, a service saves the committed data so that changes in the data persist once the user has been notified of success of service completion.

4.4.1 Consistency Issues in Distributed System Networks

A composite process service requires invocation to distributed service components over the network and is vulnerable to network connection failures. Furthermore, a composite process service usually has limited control on the component services which are located and managed in different systems. Therefore, it is challenging for a composite process service in a distributed system network to achieve the ACID properties.

Consider a business process service that changes the project schedule and updates the work schedules of individual contractors. This service is invoked when project managers submit a new proposed project schedule with revised task starting dates. In this example, contractors do not share their full work schedules because they may be involved in other projects. Instead, the contractors distribute the work schedule information as web service units "Work Schedule Service" that allow business partners to inquire their availability in a specific time period. Figure 4.4 shows the Java implementation class of the operations "checkAvailability" and "changeTaskDates" in the service unit Work Schedule Service.

As illustrated in Figure 4.4, the "checkAvailability" operation receives input parameters of a starting date and a finishing date and checks the number of task events in the work schedule in the time period between the two dates. If there is no task event in the time period, the "checkAvailability" operation returns a "true" value; otherwise, a value of false is returned. The "changeTaskDates" operation receives a task number, a starting date, a finishing date, and task information. The operation then removes all the task events labeled with the input task number, and adds new task events in the time period between the input starting date and finishing date.

```
public class WorkScheduleService {
public availabilityType checkAvailability (String start, String finish, String taskId,
String requestedBy) {
  availabilityType output = new availabilityType();
  try { Class.forName("com.mysql.jdbc.Driver").newInstance();
    Connection conn =
      DriverManager.getConnection("jdbc:mysql://localhost:3306/portal","","");
    Statement stmt = conn.createStatement();
    ResultSet rs = stmt.executeQuery("SELECT count(eventId) FROM calevent WHERE
      startDate>='"+start+"' AND startDate<='"+finish+"' AND title NOT LIKE
      '"+taskId+" -'");
    rs.next();
    SimpleDateFormat dbDateFormat = new SimpleDateFormat("yyyy-MM-dd");
    if (dbDateFormat.parse(finish).getTime()>=dbDateFormat.parse(start).getTime() &&
      rs.getInt(1)==0) output.available=true;
    else output.available=false;
  } catch (Exception e) {
  } return output;
}

public void changeTaskDates(String newStart, String newFinish, String taskId, String
title, String description, String requestedBy) {
  try { Class.forName("com.mysql.jdbc.Driver").newInstance();
    Connection conn =
      DriverManager.getConnection("jdbc:mysql://localhost:3306/portal","","");
    Statement stmt = conn.createStatement();
    ArrayList<String> eventIds = new ArrayList<String>();
    ResultSet rs = stmt.executeQuery("SELECT eventId FROM calevent WHERE title like '"+
      taskId+" -'");
    while (rs.next()) eventIds.add(rs.getString("eventId"));
    for (int i = 0; i < eventIds.size(); i++) {
      stmt.execute("DELETE FROM calevent WHERE eventId='"+eventIds.get(i)+"'");
      stmt.execute("DELETE FROM resource_ WHERE codeId='3503' AND
        primKey='"+eventIds.get(i)+"'");
    }
    SimpleDateFormat dbDateFormat = new SimpleDateFormat("yyyy-MM-dd");
    if (dbDateFormat.parse(newFinish).getTime()>=dbDateFormat.parse(newStart).getTime())
    { Calendar calendar1 = Calendar.getInstance();
      calendar1.setTime(dbDateFormat.parse(newStart));
      int eventId = 15000; int resourceId = 44800;
      rs = stmt.executeQuery("SELECT max(eventId) FROM calevent");
      if (rs.next()) eventId = rs.getInt(1)+1;
      rs = stmt.executeQuery("SELECT max(resourceId) FROM resource_");
      if (rs.next()) resourceId = rs.getInt(1)+1;
      while (! newFinish.equals(dbDateFormat.format(calendar1.getTime()))) {
        stmt.execute("INSERT INTO calevent VALUES ('"+ eventId+ "','14901','10095',
          '10112','Jack Cheng',now(),now(),'"+taskId+" - "+title+"','"+description+" -
          "+requestedBy+"','"+ dbDateFormat.format(calendar1.getTime())+
          "','"+dbDateFormat.format(calendar1.getTime())+ " 23:59:59',24,0,1,0,'site-
          work',0,'','none',300000,300000);");
        stmt.execute("INSERT INTO resource_ VALUES ('"+resourceId+"','3503','"+
          eventId+"');");
        calendar1.add(Calendar.DATE, 1); eventId++; resourceId++;
      }
      stmt.execute("INSERT INTO calevent VALUES ('"+eventId+"','14901','10095',
        '10112','Jack Cheng',now(),now(),'"+taskId+" - "+title+"','"+description+" -
        "+requestedBy+"','"+dbDateFormat.format(calendar1.getTime())+"','"+
        dbDateFormat.format(calendar1.getTime())+" 23:59:59',24,0,1,0,'site-
        work',0,'','none',300000,300000);");
      stmt.execute("INSERT INTO resource_ VALUES ('"+resourceId+"','3503','"+
        eventId+"');");
    }
  } catch (Exception e) {
} }
}
```

Find the number of tasks in a specific time period

Available if there is no task in the time period and the time period length is positive

Obtain the task events associated with the specific task

Delete the task events

Add a task event for each day, and register the event in the system

Figure 4.4: Java implementation class of the service unit Work Schedule Service

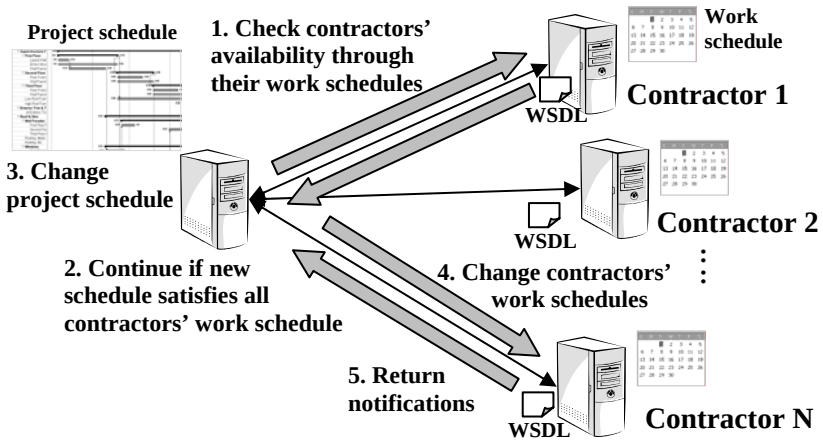


Figure 4.5: Business service that changes project schedule and updates individual distributed work schedules

As illustrated in Figure 4.5, the process service that changes a project schedule first invokes the distributed Work Schedule Service units deployed by individual contractors to check their work availability. If the new project schedule satisfies the work schedules of all the contractors, the process service updates the project schedule residing in the system, and modifies the individual work schedules using the service operation "changeTaskDates" in individual Work Schedule Service units. Otherwise, the project schedule and work schedules are not changed.

Consider a simple case scenario that swaps the schedules of two tasks performed by different contractors. *Task 1* is performed from September 14, 2009 to September 18, 2009 by **Subcontractor 1** while *Task 2* is performed from September 21, 2009 to September 25, 2009 by **Subcontractor 2**. The pseudo code of the processes executed by the schedule changing process is shown in Figure 4.6. Figure 4.7 shows the BPEL process that changes the project schedule as well as the work schedules of **Subcontractor 1** and **Subcontractor 2**. The process invokes the "checkAvailability" operation of **Subcontractor 1** and checks its availability from September 21 to September 25. The process also invokes the "checkAvailability" operation of

Subcontractor 2 and checks its availability from September 14 to September 18. If both service operations return a "true" value, the process changes the project schedule using the operation "changeTaskSchedule" of Project Schedule Service residing on the general contractor's system. The process then modifies the distributed work schedules of both subcontractors using the operation "changeTaskDates" of Work Schedule Service units.

Service invocation sometimes fails due to program bugs in the service unit, failure of the system the service unit is deployed, or connection failure of the network. In this example, if the last activity that changes the work schedule of **Subcontractor 2** fails, as indicated in Figure 4.6, *Task 2* will be scheduled from September 14 to September 18 in the project schedule but scheduled from September 21 to September 25 in the work schedule of **Subcontractor 2**. The mistake may not be discovered until September 14, which is too late for **Subcontractor 2** and the general contractor to accommodate.

Furthermore, ACID properties of the BPEL process that changes the project schedule are violated in this situation. Atomicity is not satisfied because only parts of the process have been executed. Consistency is also violated as the consistency requirement between the project schedule and the work schedules is not met. Durability is not fulfilled since there is no logging and the schedule change is committed from the project manager's view while the service fails to complete.

```
Subcon(Task i) = responsible subcontractor of Task i

Check work schedule service of Subcon(Task 1) for feasibility of
new Task 1
Check work schedule service of Subcon(Task 2) for feasibility of
new Task 2

If feasibility check passes for all tasks
  Change project schedule for new Task 1 and Task 2
  Change work schedule of Subcon(Task 1) for new Task 1
  Change work schedule of Subcon(Task 2) for new Task 2 ⇦ Failure
End
```

Figure 4.6: Pseudo code of the schedule changing business service

```
<bpel:process name="ChangeScheduleService"
 targetNamespace="http://localhost:8080/service/process/ChangeScheduleService"
 xmlns:bpel="http://docs.oasis-open.org/wsbpel/2.0/process/executable"
 xmlns:ns="http://ws.apache.org/axis2">

<bpel:import location="ChangeScheduleServiceArtifacts.wsdl"
 importType="http://schemas.xmlsoap.org/wsdl/" />

<bpel:partnerLinks>
 <bpel:partnerLink name="client" partnerLinkType="tns:ChangeScheduleService"
  myRole="ChangeScheduleServiceProvider" />
 <bpel:partnerLink name="WorkSchedule1" partnerLinkType="tns:WorkSchedulePLT"
  partnerRole="ServiceProvider"></bpel:partnerLink>
 <bpel:partnerLink name="WorkSchedule2" partnerLinkType="tns:WorkSchedule2PLT"
  partnerRole="ServiceProvider"></bpel:partnerLink>
 <bpel:partnerLink name="ProjectSchedule" partnerLinkType="tns:ProjectSchedulePLT"
  partnerRole="ServiceProvider"></bpel:partnerLink>
</bpel:partnerLinks>

<bpel:variables>
 <bpel:variable name="input" messageType="tns:ChangeScheduleServiceRequestMessage"/>
 <bpel:variable name="output" messageType="tns:ChangeScheduleServiceResponseMessage"/>
 <bpel:variable name="WorkSchedule1Response"
messageType="ns:checkAvailabilityResponse"/>
 <bpel:variable name="WorkSchedule1Request" messageType="ns:checkAvailabilityRequest"/>
<bpel:variable name="ProjectScheduleRequest"
messageType="ns:changeTaskScheduleRequest"/>
<bpel:variable name="WorkSchedule1Response1" messageType="ns:changeTaskDatesResponse"/>
<bpel:variable name="WorkSchedule1Request1" messageType="ns:changeTaskDatesRequest"/>
</bpel:variables>

<bpel:sequence name="main">
 <bpel:receive name="receiveInput" partnerLink="client"
  portType="tns:ChangeScheduleService" operation="process" variable="input"
  createInstance="yes"/>
 <bpel:flow name="Check work schedules">
  <bpel:invoke name="Check work schedule 1" partnerLink="WorkSchedule1"
   operation="checkAvailability" portType="ns:WorkScheduleService2PortType"
   inputVariable="WorkSchedule1Request"  outputVariable="WorkSchedule1Response"/>
  <bpel:invoke name="Check work schedule 2" partnerLink="WorkSchedule2"
   operation="checkAvailability" portType="ns:WorkScheduleService2PortType"
   inputVariable="WorkSchedule1Request" outputVariable="WorkSchedule1Response"/>
 </bpel:flow>
 <bpel:if name="If">
 <bpel:sequence name="Modify schedules">
  <bpel:invoke name="Change project schedule" partnerLink="ProjectSchedule"
   operation="changeTaskSchedule" portType="ns:ProjectScheduleServicePortType"
   inputVariable="ProjectScheduleRequest"/>
  <bpel:invoke name="Change work schedule 1" partnerLink="WorkSchedule1"
   operation="changeTaskDates" portType="ns:WorkScheduleService2PortType"
   inputVariable="WorkSchedule1Request1" outputVariable="WorkSchedule1Response1"/>
  <bpel:invoke name="Change work schedule 2" partnerLink="WorkSchedule2"
   operation="changeTaskDates" portType="ns:WorkScheduleService2PortType"
   inputVariable="WorkSchedule1Request1" outputVariable="WorkSchedule1Response1"/>
 </bpel:sequence>
 </bpel:if>
 <bpel:reply name="replyOutput" partnerLink="client"
   portType="tns:ChangeScheduleService" operation="process" variable="output" />
</bpel:sequence>
</bpel:process>
```

Figure 4.7: The BPEL process that changes a project schedule

4.4.2 Implementation in SC Collaborator

To maintain the ACID properties in a distributed SC Collaborator network, three modifications are made to the system framework:

- *Modification of web service units* so that transaction service operations return a response message that contains information about their roll-back operations. Modification of data service operations is not required because they only provide data without making changes to any underlying data.

- *Creation of a Process-in-Progress (PIP) table* in the back-end database to keep records of the on-going processes in the system. There are three service operations on the PIP table – (1) an operation that adds the specifications of the invoked service operations and the information about roll-back operations to the PIP table for temporary storage, (2) an operation that removes all the PIP records of a particular process after process completion, and (3) an operation that reads the PIP records and undoes the changes made by web service units invoked in the process. These operations are wrapped and deployed as service operations "addRecord", "removeRecord" and "restoreState" respectively in a web service unit PIP Service, which BPEL processes can easily invoke and execute. Figure 4.8 shows the Java implementation class of the PIP Service. As illustrated in Figure 4.8, the operation "restoreState" receives a BPEL process identification number and extracts all the PIP records that are related to the process and contain a value of "Return" in the *Notes* column. For every extracted record, the specified roll-back service operation is invoked to undo the modifications previously made in the process. A notification is returned when all the roll-back service operations are successfully called.

- *Modification of the BPEL process unit* so that every invocation of transaction service operation is enclosed in a BPEL *scope* activity that contains elements for logging and fault handling.

```
public class PIPService {

public String addRecord(String processId, String targetNamespace, String serviceName,
String serviceLocation, String operation, String parameters, String notes) {
... }

public String removeRecord(String processId) {
... }

public String restoreState(String processId) {
  String notification = "Error";
  try {
    Class.forName("com.mysql.jdbc.Driver").newInstance();
    Connection conn =
      DriverManager.getConnection("jdbc:mysql://localhost:3306/portal","","");
    Statement stmt = conn.createStatement();

    ResultSet rs = stmt.executeQuery("SELECT recordId, time, targetNamespace,
      serviceName, serviceLocation, operation, parameters, notes FROM PIP WHERE
      processId=\'"+processId+"\' ORDER BY recordId desc");
    ServiceClient serviceClient = new ServiceClient();
    while (rs.next()) {
      String targetNamespace = rs.getString("targetNamespace");
      String serviceName = rs.getString("serviceName");
      String serviceLocation = rs.getString("serviceLocation");
      String operation = rs.getString("operation");
      String parameters = rs.getString("parameters");
      String notes = rs.getString("notes");

      if (notes.equals("Return") && !targetNamespace.equals("") &&
        !serviceName.equals("") && !serviceLocation.equals("") &&
        !operation.equals("")) {
        OMFactory fac = OMAbstractFactory.getOMFactory();
        OMNamespace omNs = fac.createOMNamespace(targetNamespace, "eig");
        OMElement payload = fac.createOMElement(serviceName, omNs);
        String[] elements = parameters.split("!");
        OMElement value;
        for (int i = 0; i < elements.length; i++) {
          value = fac.createOMElement(elements[i].split(":")[0].trim(), omNs);
          value.setText(elements[i].split(":")[1].trim());
          payload.addChild(value);
        }

        serviceClient = new ServiceClient();
        Options options = new Options();
        options.setTo(new EndpointReference(serviceLocation));
        options.setAction(operation);
        serviceClient.setOptions(options);
        serviceClient.sendRobust(payload);
      }
    }

    serviceClient.cleanup();
    conn.close();
    notification = "Success";

  } catch (Exception e) {
  } return notification;
}
}
```

Service operations

Obtain all the PIP records for a particular process

Invoke service units to restore the original state

Returns a notification when all the service units are successfully restored

Figure 4.8: Java implementation class of the service unit PIP Service

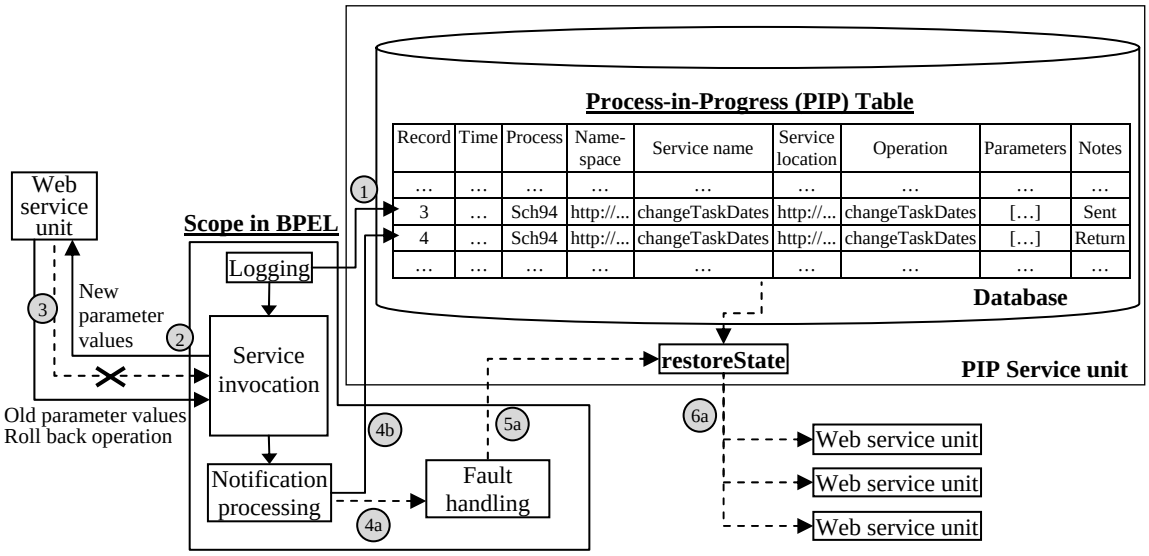


Figure 4.9: Maintaining information consistency in a distributed SC Collaborator network

With these three system modifications, information consistency is maintained among distributed SC Collaborator systems, as illustrated in Figure 4.9. Before a web service unit is invoked in a BPEL process, its service specification information (i.e. target namespace, service name, service location, operations, parameter names, and parameter values) is stored through the operation “addRecord” of PIP Service unit. The BPEL business process then invokes the web service unit and provides the parameter values. The web service unit is modified and returns a notification which contains information about the operation to roll back the modifications made by the service unit.

If the BPEL process receives a notification from the invoked service unit, it means that the service invocation is successful. The BPEL process then extracts the roll-back information from the notification and enters it into the PIP table. Otherwise, the fault handling component in the BPEL process will be triggered. The fault handler invokes the operation “restoreState” in PIP Service unit to undo the modifications previously made by the BPEL process.

Consider the simple scenario that swaps the schedules of two tasks, *Task 1* and *Task 2*. Three system modifications are performed as follows.

- The implementations of the service units Work Schedule Service and Project Schedule Service are modified to return roll-back information in a response message. Figure 4.10 shows the Java implementation class of the modified Work Schedule Service. To roll back a change of task schedule, an operation that changes the task schedule back to its original value is needed. Therefore, the operation "changeTaskDates" of Work Schedule Service is the roll-back operation of itself. As illustrated in Figure 4.10, the modified service operation "changeTaskDates" obtains the old task schedule information before making changes to the data. The old task schedule information and the service specification of the operation "changeTaskDates" are returned in the response message, in a data structure of "notificationType" as described in Figure 4.11.

- PIP table is created in the back-end database and the corresponding PIP Service unit is deployed in the SC Collaborator system of the general contractor.

- The BPEL process that changes a project schedule is modified. The *invoke* activities "Change project schedule", "Change work schedule 1" and "Change work schedule 2" are enclosed in separate *scope* activities because the operation "changeTaskSchedule" of Project Schedule Service and the operation "changeTaskDates" of Work Schedule Service are transaction service operations. The activity "Change work schedule 2" is a simple BPEL *invoke* activity in the original BPEL process, as highlighted in Figure 4.7. As illustrated in Figure 4.12, the activity is enclosed in a scope in the new BPEL process. Before the activity is performed, the operation "addRecord" of the PIP Service is invoked to record the input parameters of the activity "Change work schedule 2." If the activity is successfully performed, the operation "addRecord" is called again to record the roll-back information returned. Otherwise, the operation "restoreState" of PIP Service is called to undo all the changes previously done by the BPEL process.

```
public notificationType changeTaskDates(String newStart, String newFinish, String
taskId, String title, String description, String requestedBy) {
  notificationType output = new notificationType();
  output.notes = "Error";
  try {   Class.forName("com.mysql.jdbc.Driver").newInstance();
    Connection conn =
      DriverManager.getConnection("jdbc:mysql://localhost:3306/portal","","");
    Statement stmt = conn.createStatement();
    SimpleDateFormat dbDateFormat = new SimpleDateFormat("yyyy-MM-dd");
    SimpleDateFormat dbDateFormat2 = new SimpleDateFormat("yyyy-MM-dd HH:mm:ss ");
    ResultSet rs = stmt.executeQuery("SELECT title, description, startDate FROM calevent
      WHERE title like '"+taskId+" -' ORDER BY startDate asc");
    String title2 = ""; String description2 = ""; String start = ""; String finish = "";
    if (rs.next()) {
      title2 = rs.getString("title").replace(taskId+" - ", "");
      description2 = rs.getString("description").replace(" - "+requestedBy, "");
      start = dbDateFormat.format(dbDateFormat2.parse(rs.getString("startDate")));
      finish = start;
    }
    while (rs.next())
      finish = dbDateFormat.format(dbDateFormat2.parse(rs.getString("startDate")));
    ArrayList<String> eventIds = new ArrayList<String>();
    rs = stmt.executeQuery("SELECT eventId FROM calevent WHERE title like '"+taskId+" -
      '");
    while (rs.next()) eventIds.add(rs.getString("eventId"));
    for (int i = 0; i < eventIds.size(); i++) {
      stmt.execute("DELETE FROM calevent WHERE eventId='"+eventIds.get(i)+"'");
      stmt.execute("DELETE FROM resource_ WHERE codeId='3503' AND
        primKey='"+eventIds.get(i)+"'");
    }
    if (dbDateFormat.parse(newFinish).getTime()>=dbDateFormat.parse(newStart).getTime())
    { Calendar calendar1 = Calendar.getInstance();
      calendar1.setTime(dbDateFormat.parse(newStart));
      int eventId = 15000; int resourceId = 44800;
      rs = stmt.executeQuery("SELECT max(eventId) FROM calevent");
      if (rs.next()) eventId = rs.getInt(1)+1;
      rs = stmt.executeQuery("SELECT max(resourceId) FROM resource_");
      if (rs.next()) resourceId = rs.getInt(1)+1;
      while (! newFinish.equals(dbDateFormat.format(calendar1.getTime()))){
        stmt.execute("INSERT INTO calevent VALUES ('"+eventId+"','14901','10095',
          '10112','Jack Cheng',now(),now(),'"+taskId+" - "+title+"','"+description+" -
          "+requestedBy+"','"+dbDateFormat.format(calendar1.getTime())+"','"+
          dbDateFormat.format(calendar1.getTime())+" 23:59:59',24,0,1,0,'site-
          work',0,'','none', 300000,300000);");
        stmt.execute("INSERT INTO resource_ VALUES ('"+resourceId+"','3503','"+
          eventId+"');");
        calendar1.add(Calendar.DATE, 1); eventId++; resourceId++;
      }
        :
    }
    output.notes = "Success";
    output.targetNamespace = "http://ws.apache.org/axis2";
    output.serviceName = "changeTaskDates";
    output.serviceLocation = "WorkScheduleService2";
    output.operation = "changeTaskDates";
    output.params = "start:" + start + "!finish:" + finish + "!taskId:" + tasked +
      "!title:" + title2 + "!description:" + description2 + "!requestedBy:" +
      requestedBy;
  } catch (Exception e) {
  } return output;
}
```

It will be changed to "Success" at the end

Obtain the original state of information

Obtain the associated task events

Add a task event for each day, and register the event in the system

Assign the original state of information to the output response

Figure 4.10: Java implementation class of the modified Work Schedule Service

```
public class notificationType {

  String notes = "";
  String targetNamespace = "";
  String serviceName = "";
  String serviceLocation = "";
  String operation = "";
  String params = "";

  public String getNotes() {
     return notes;  }
  public void setNotes(String notes) {
     this.notes = notes;}
  public String getTargetNamespace() {
     return targetNamespace;            }
        :
]
```

Information for rollback

Figure 4.11: Java class for data type “notificationType”

```
<bpel:scope name="Scope">

<bpel:sequence>
 <bpel:invoke name="addRecord" partnerLink="PIP" operation="addRecord"
  portType="ns:PIPServicePortType" inputVariable="PIPRequest1"
  outputVariable="PIPResponse1" />
 <bpel:invoke name="Change work schedule 2" partnerLink="WorkSchedule2"
  operation="changeTaskDates" portType="ns:WorkScheduleService2PortType"
  inputVariable="WorkSchedule1Request1"
  outputVariable="WorkSchedule1Response1"/>
<bpel:invoke name="addRecord" partnerLink="PIP" operation="addRecord"
  portType="ns:PIPServicePortType" inputVariable="PIPRequest2"
  outputVariable="PIPResponse2" />
</bpel:sequence>

<bpel:variables>
 <bpel:variable name="PIPResponse" messageType="ns:addRecordResponse"/>
 <bpel:variable name="PIPRequest" messageType="ns:addRecordRequest"/>
 <bpel:variable name="PIPResponse1" messageType="ns:addRecordResponse"/>
 <bpel:variable name="PIPRequest1" messageType="ns:addRecordRequest"/>
 <bpel:variable name="PIPResponse2" messageType="ns:removeRecordResponse"/>
 <bpel:variable name="PIPRequest2" messageType="ns:removeRecordRequest"/>
</bpel:variables>

<bpel:faultHandlers> <bpel:catch>
 <bpel:invoke name="restoreState" partnerLink="PIP" operation="restoreState"
  portType="ns:PIPServicePortType" inputVariable="PIPRequest"
  outputVariable="PIPResponse" />
</bpel:catch> </bpel:faultHandlers>

</bpel:scope>
```

Figure 4.12: BPEL codes showing activity “Change work schedule 2” in a scope

With the modifications described above, information consistency can be maintained even though the activity "Change work schedule 2" fails unexpectedly. Figure 4.13 depicts the situation when all the distributed service units are invoked successfully in the BPEL process. The activity "Change project schedule" adds a PIP record, invokes the operation "changeTaskSchedule" of the Project Schedule Service unit in the local system, obtains the roll-back information returned from the service operation "changeTaskSchedule," and enters the information in the PIP table. The activity "Change work schedule 1" then adds a PIP record, invokes the operation "changeTaskDates" of the Work Schedule Service unit in the SC Collaborator system hosted by **Subcontractor 1**, obtains the roll-back information which includes the old work schedule data, and enters the information in the back-end PIP table. The activity "Change work schedule 2" interacts with the Work Schedule Service unit of **Subcontractor 2** and the PIP Service unit in the local system similarly. Finally, the PIP records for the BPEL process are removed by calling the operation "removeRecord" of the PIP Service unit.

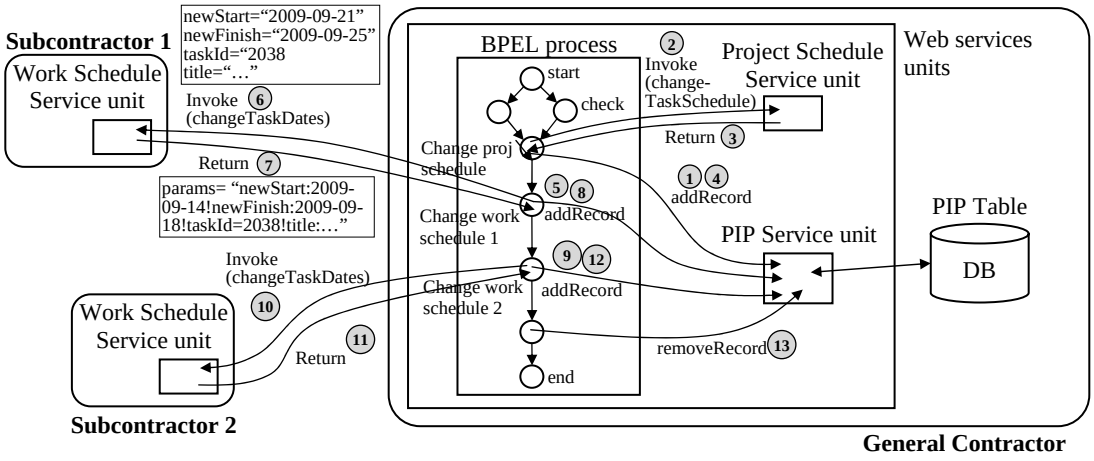


Figure 4.13: Interactions in distributed SC Collaborator network when the BPEL process that changes a project schedule completes successfully

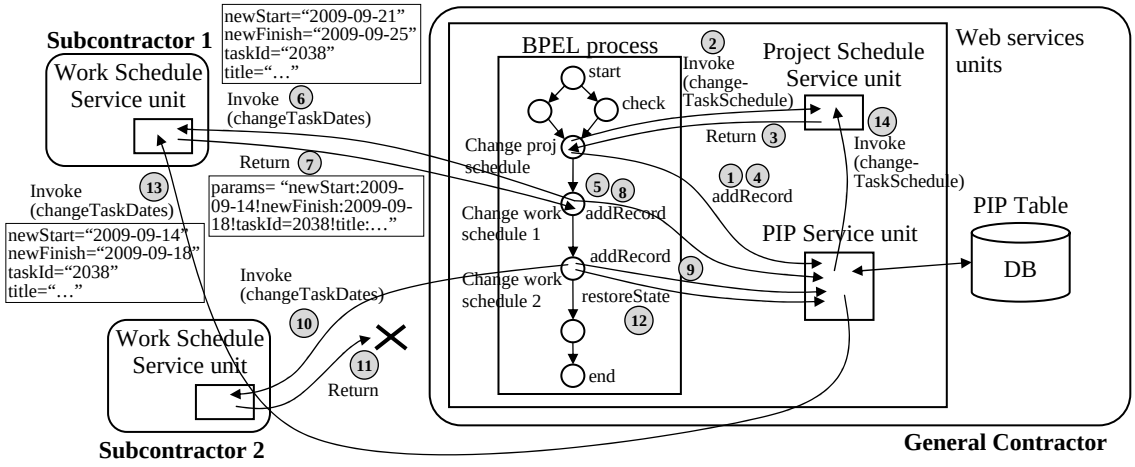


Figure 4.14: Interactions in distributed SC Collaborator network when the activity "Change work schedule 2" fails

Consider the situation that the activity "Change work schedule 2" fails, probably due to system failure of **Subcontractor 2** or deployment problem of the Work Schedule Service unit, as illustrated in Figure 4.14. The BPEL process does not receive a response message from the Work Schedule Service unit of **Subcontractor 2**, resulting in a fault message for the service invocation in the activity "Change work schedule 2." The BPEL process catches the fault message and invokes the operation "restoreState" of the PIP Service unit. The operation "restoreState" then invokes the service operations "changeTaskDates" of **Subcontractor 1** and "changeTaskSchedule" of the local system with the old schedule information to restore the original state of the project schedule and work schedules.

Among the four ACID requirements in a distributed network of systems, service atomicity is achieved because the BPEL process unit performs as a single logical unit and either all or none of its components are executed when the process terminates. Consistency is also achieved because the original valid states of the schedules are restored at the end. Moreover, durability is fulfilled since the PIP records can be played back to recreate the system states right before a failure.

4.5 Scenario Demonstration on the Distributed SC Collaborator Network

In this section, a three-storey residential building as shown in Figure 4.15 is used as a case scenario to demonstrate the implementation of a distributed SC Collaborator network. In the project, the capacity of the building was expanded from 24 to 46 rooms. In this scenario, the general contractor is responsible for windows and doors installation. There are three subcontractors of interest, which are responsible for installation of wall façades, room interiors, and mechanical, electrical and plumbing components (Figure 4.16). The general contractor, subcontractors, and suppliers have their own SC Collaborator systems running and collaborating with each other. The first demonstration is a procurement example between contractors and suppliers while the second demonstration shows a project-wide collaboration for a material delivery delay.

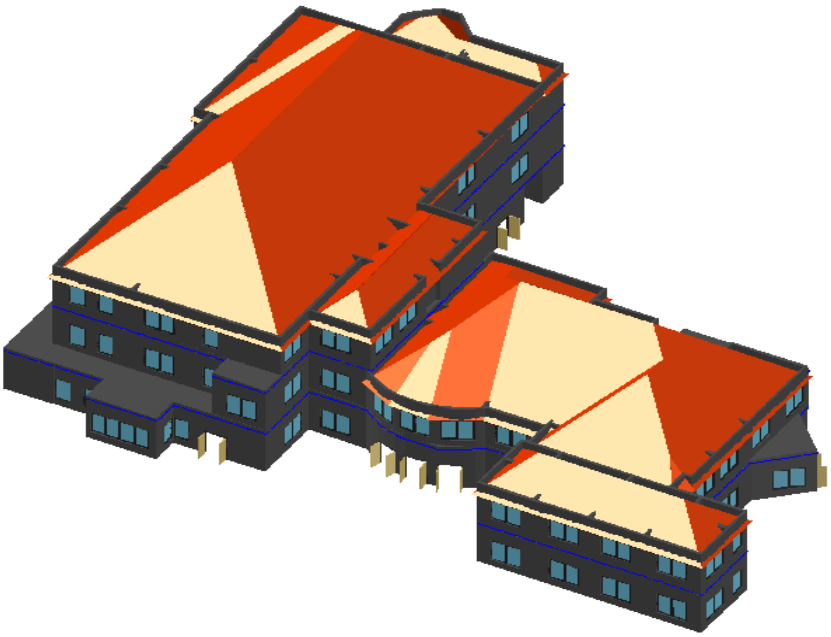


Figure 4.15: 3D model of the three-storey residential building

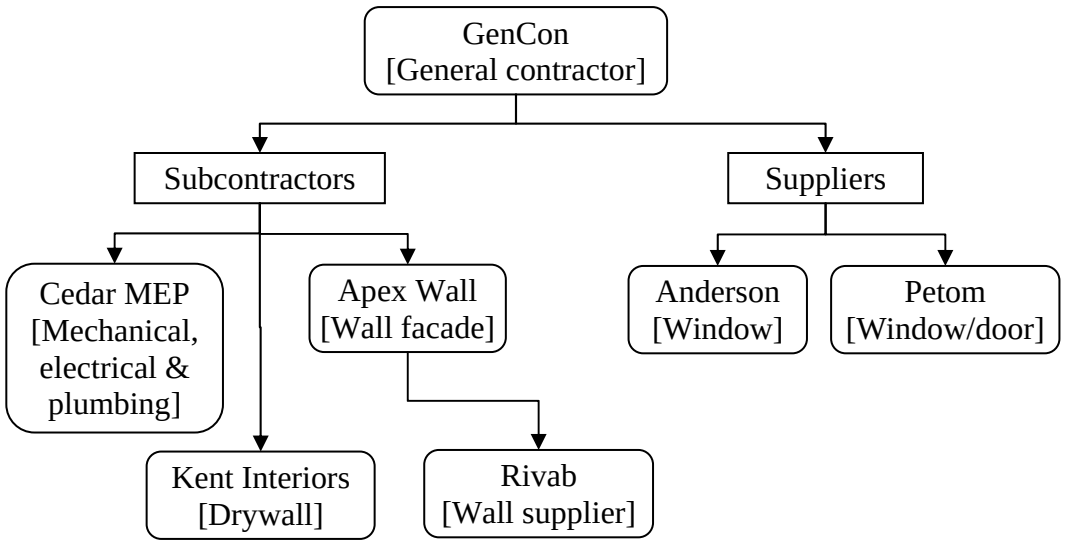


Figure 4.16: Organizations involved in the example scenario

4.5.1 E-Procurement

The benefits of electronic procurement have been discussed in Section 2.6.1. In the demonstration in Section 2.6.1, e-Procurement is performed in a centralized manner in SC Collaborator. Documents such as purchase orders of different suppliers are stored and shared together in a single database. This is not practical in a real supply chain application because many suppliers are willing to share their purchase orders and detailed product information with their direct trading partners only. Purchase orders contain suppliers' price information and delivery decisions. Suppliers may be able to deduce the pricing strategy and inventory management techniques of competitors from their purchase orders. A construction project may involve multiple suppliers that provide similar products and/or services. As opposed to a centralized system, a distributed system network can promote collaboration and information sharing among supply chain members.

In this demonstration example, the general contractor **GenCon** uses Autodesk ADT program as the interface for project management. The CAD program is implemented with a database which stores the building information models of every design. In a model-based CAD framework, each design object (e.g. door, window, and slab) is associated with information related to the product, the supplier, the corresponding task, and so on. An ADT plug-in SpecifiCAD developed by CADalytic Media, Inc. is leveraged to interact with the design objects in an ADT drawing and to retrieve the underlying building information. The plug-in displays web pages written in Java Service Pages (JSP) language which can connect to databases using Java Database Connectivity (JDBC) and to web services using standardized SOAP. As shown in Figure 4.17, when **GenCon** selects a window object in the 3D model of the residential building, the project information including its price and supplier information is displayed in the plug-in.

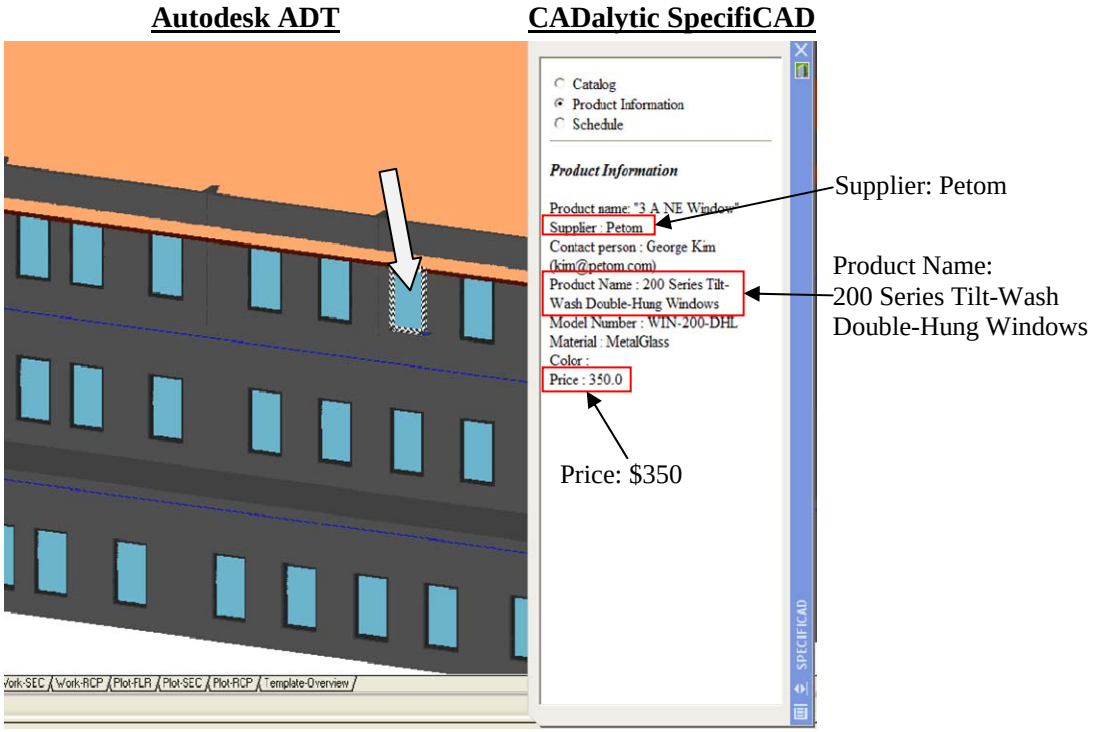


Figure 4.17: Original product information of the selected window

Suppliers may offer different prices and discounts to different customers. In this scenario, suppliers provide customized catalogs to their partners through standardized web services protocol. When **GenCon** selects a window object in Autodesk ADT and clicks the "Catalog" tab in SpecifiCAD interface, the server connects to the extranet of supplier partners and searches their catalogs with keyword "window" and the product name. As illustrated in Figure 4.18, three supplier partners return results with hyperlinks directing to the company websites. **GenCon** can refer to the product websites and replace the existing window object in the drawing with the ones shown in the search results by simply clicking the "Apply" button. As demonstrated in Figure 4.18, the supplier **Anderson** in the example scenario sells the same window product but at a cheaper price than the original one. **GenCon** therefore replaces the window object and the product model information at the back-end is updated instantaneously (Figure 4.19).

GenCon's SC Collaborator shares the same company database with the model-based CAD program. When the architectural design is finalized, the purchasing officers of **GenCon** can log in their SC Collaborator system and submit electronic purchase orders to various suppliers (Figure 4.20). The suppliers use different SC Collaborator systems to manage and respond their received purchase orders (Figure 4.21).

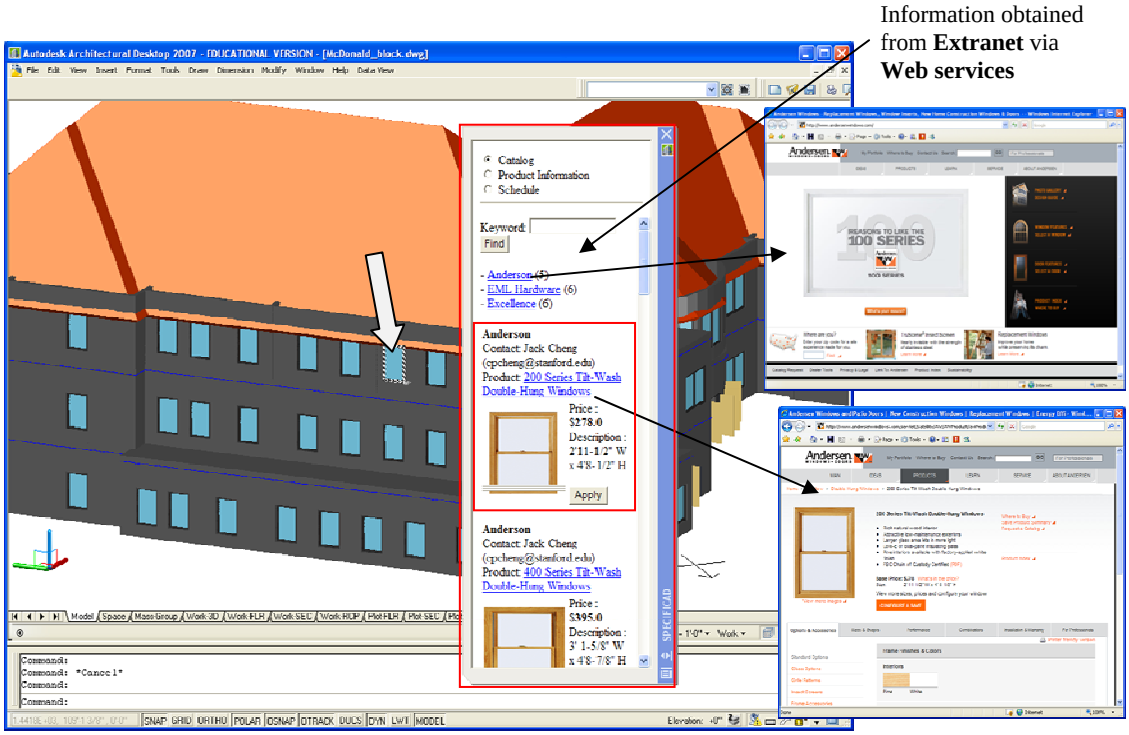


Figure 4.18: Inquiry to window supplier partners

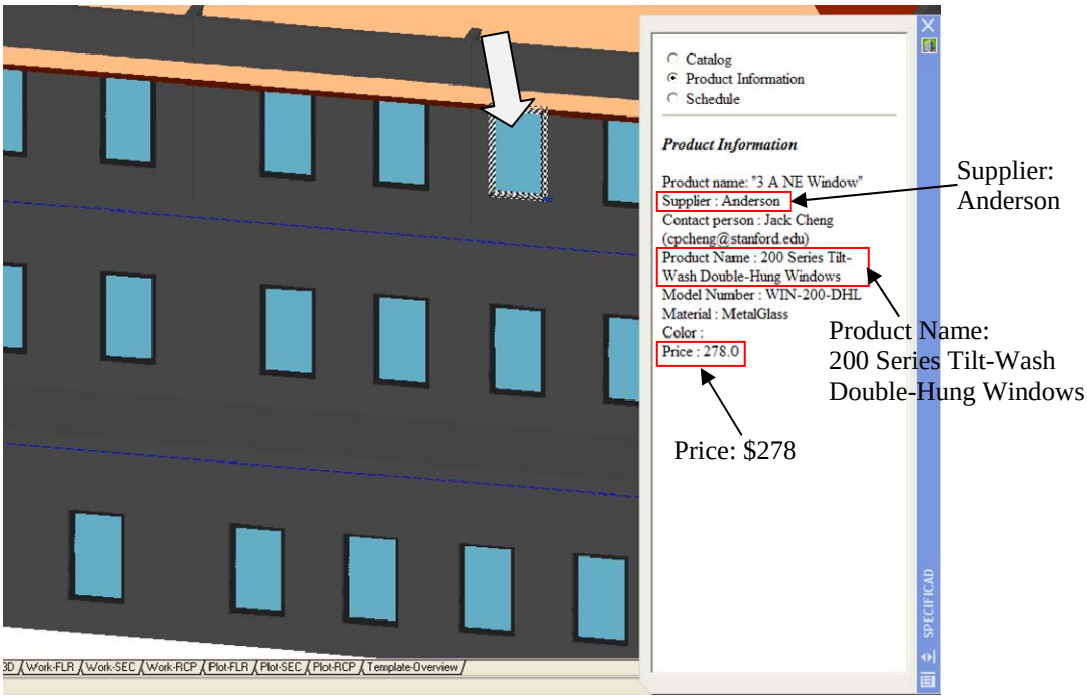


Figure 4.19: Updated product information of the selected window

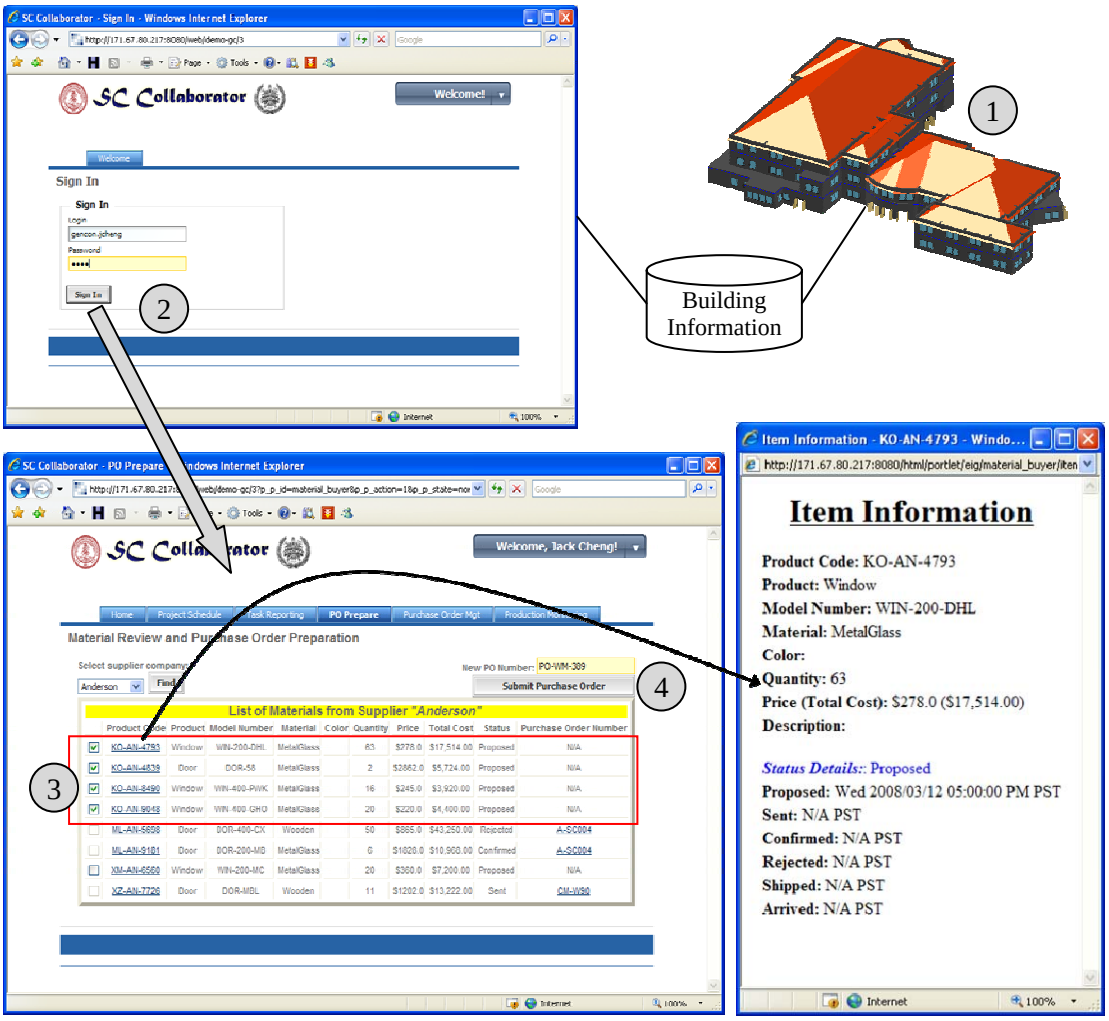


Figure 4.20: E-Procurement by contractor using its SC Collaborator system

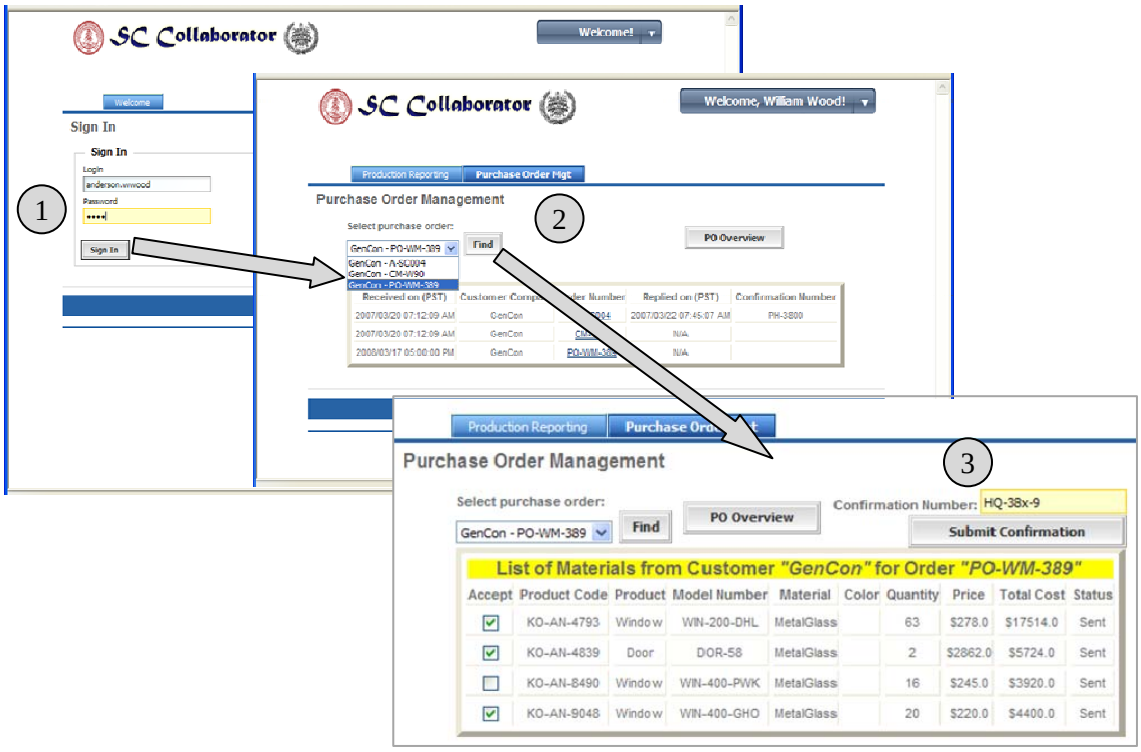


Figure 4.21: Supplier managing and responding received purchase orders using its SC Collabroator system

4.5.2 Responding to Material Delivery Delay

This example demonstrates the collaboration and chain reactions among general contractor, subcontractors, and suppliers to respond to delivery problem of a key material. In this example, as illustrated in Figure 4.22, schedule information is distributed among general contractor, subcontractors, and suppliers in a distributed SC Collaborator network. The general contractor and the subcontractors keep their on-site work schedules internally. The general contractor also provides the project schedule to all the subcontractors. The suppliers manage their production and delivery schedules in their own systems. These schedule information are wrapped and delivered as individual web service units in separate SC Collaborator systems. The general contractor, subcontractors, and suppliers can share schedule information to designated participants

through standardized web services protocol. In this way, organizations have full control on their information and become more willing to share it with other supply chain members in a construction project.

As an example, the window supplier **Anderson** reports a material delivery delay for 10 days to its customer, **GenCon**. The delayed window components are used for the task "13.3.3 Third Floor Windows," which starts on April 10, 2009. The task dependency related to the task "13.3.3 Third Floor Windows" is illustrated in Figure 4.23. A delay of the task affects the task "13.1.3 Third Floor Façade" performed by subcontractor **Apex** and "14.3 Drywall & Taping" performed by subcontractor **Kent**, which in turn affects more succeeding tasks. In this case, tasks performed by subcontractors **Apex**, **Kent** and **Cedar** are influenced.

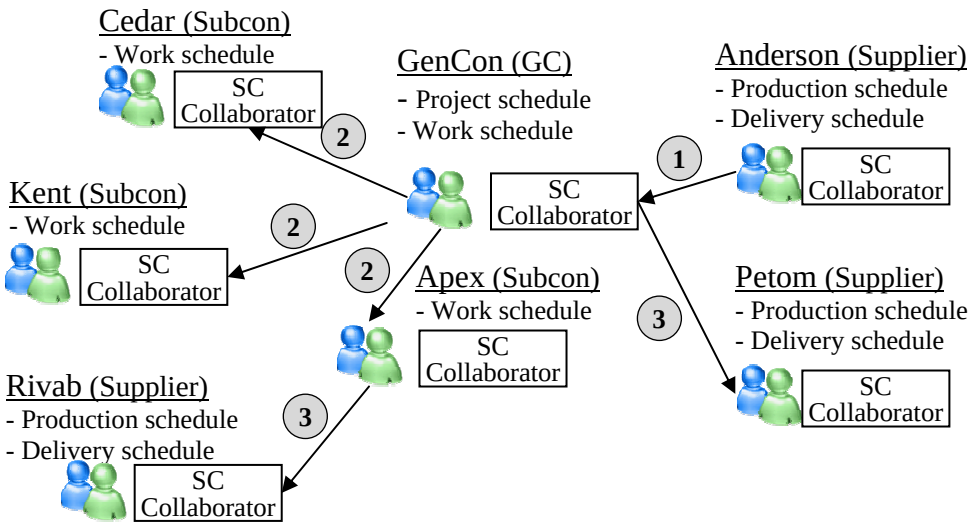
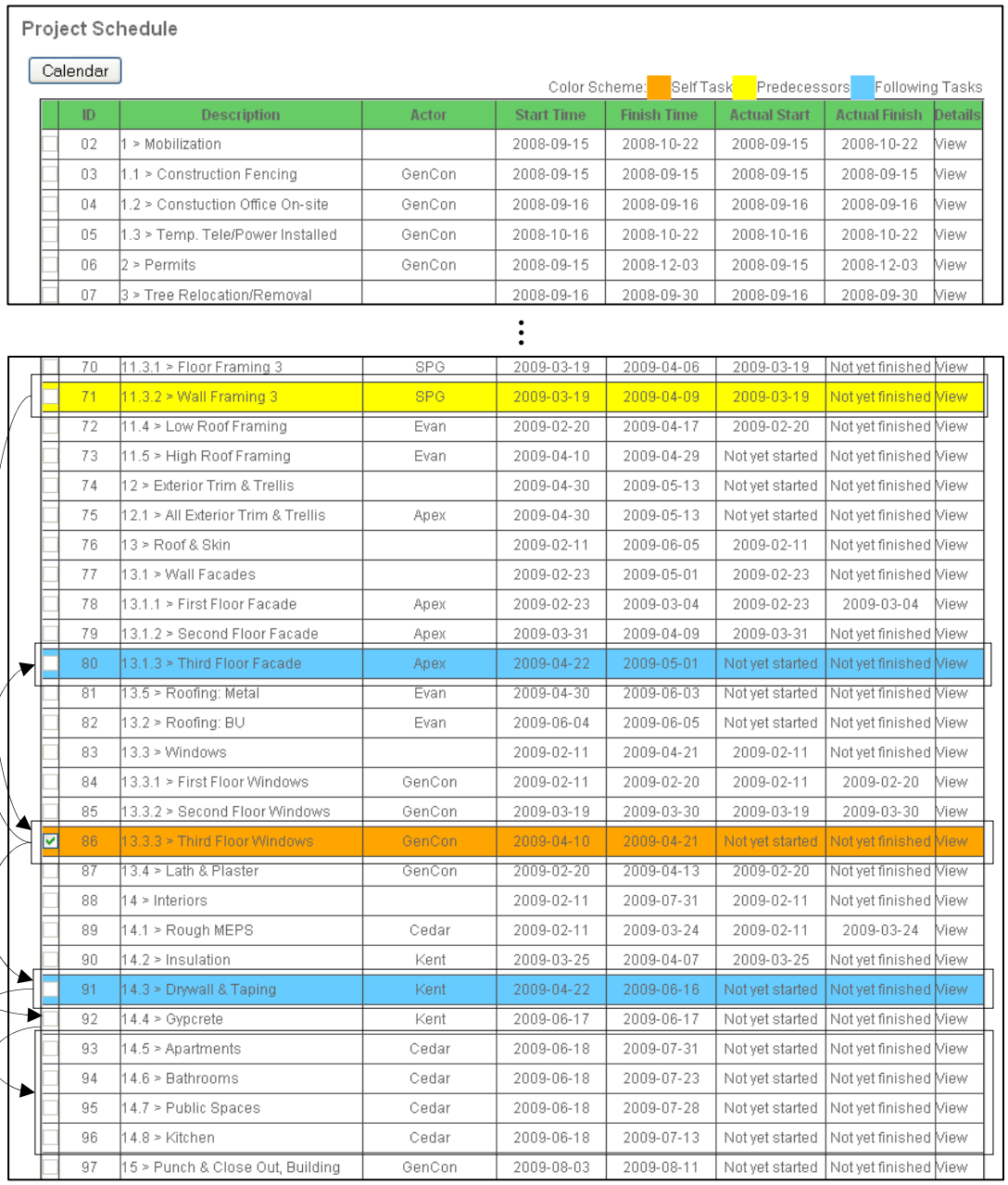


Figure 4.22: Flowchart for coordinating material delivery delay by supplier Anderson



Project Schedule

Calendar

Color Scheme: Self Task Predecessors Following Tasks

ID	Description	Actor	Start Time	Finish Time	Actual Start	Actual Finish	Details
02	1 > Mobilization		2008-09-15	2008-10-22	2008-09-15	2008-10-22	View
03	1.1 > Construction Fencing	GenCon	2008-09-15	2008-09-15	2008-09-15	2008-09-15	View
04	1.2 > Constuction Office On-site	GenCon	2008-09-16	2008-09-16	2008-09-16	2008-09-16	View
05	1.3 > Temp. Tele/Power Installed	GenCon	2008-10-16	2008-10-22	2008-10-16	2008-10-22	View
06	2 > Permits	GenCon	2008-09-15	2008-12-03	2008-09-15	2008-12-03	View
07	3 > Tree Relocation/Removal		2008-09-16	2008-09-30	2008-09-16	2008-09-30	View
70	11.3.1 > Floor Framing 3	SPG	2009-03-19	2009-04-06	2009-03-19	Not yet finished	View
71	11.3.2 > Wall Framing 3	SPG	2009-03-19	2009-04-09	2009-03-19	Not yet finished	View
72	11.4 > Low Roof Framing	Evan	2009-02-20	2009-04-17	2009-02-20	Not yet finished	View
73	11.5 > High Roof Framing	Evan	2009-04-10	2009-04-29	Not yet started	Not yet finished	View
74	12 > Exterior Trim & Trellis		2009-04-30	2009-05-13	Not yet started	Not yet finished	View
75	12.1 > All Exterior Trim & Trellis	Apex	2009-04-30	2009-05-13	Not yet started	Not yet finished	View
76	13 > Roof & Skin		2009-02-11	2009-06-05	2009-02-11	Not yet finished	View
77	13.1 > Wall Facades		2009-02-23	2009-05-01	2009-02-23	Not yet finished	View
78	13.1.1 > First Floor Facade	Apex	2009-02-23	2009-03-04	2009-02-23	2009-03-04	View
79	13.1.2 > Second Floor Facade	Apex	2009-03-31	2009-04-09	2009-03-31	Not yet finished	View
80	13.1.3 > Third Floor Facade	Apex	2009-04-22	2009-05-01	Not yet started	Not yet finished	View
81	13.5 > Roofing: Metal	Evan	2009-04-30	2009-06-03	Not yet started	Not yet finished	View
82	13.2 > Roofing: BU	Evan	2009-06-04	2009-06-05	Not yet started	Not yet finished	View
83	13.3 > Windows		2009-02-11	2009-04-21	2009-02-11	Not yet finished	View
84	13.3.1 > First Floor Windows	GenCon	2009-02-11	2009-02-20	2009-02-11	2009-02-20	View
85	13.3.2 > Second Floor Windows	GenCon	2009-03-19	2009-03-30	2009-03-19	2009-03-30	View
86	13.3.3 > Third Floor Windows	GenCon	2009-04-10	2009-04-21	Not yet started	Not yet finished	View
87	13.4 > Lath & Plaster	GenCon	2009-02-20	2009-04-13	2009-02-20	Not yet finished	View
88	14 > Interiors		2009-02-11	2009-07-31	2009-02-11	Not yet finished	View
89	14.1 > Rough MEPS	Cedar	2009-02-11	2009-03-24	2009-02-11	2009-03-24	View
90	14.2 > Insulation	Kent	2009-03-25	2009-04-07	2009-03-25	Not yet finished	View
91	14.3 > Drywall & Taping	Kent	2009-04-22	2009-06-16	Not yet started	Not yet finished	View
92	14.4 > Gypcrete	Kent	2009-06-17	2009-06-17	Not yet started	Not yet finished	View
93	14.5 > Apartments	Cedar	2009-06-18	2009-07-31	Not yet started	Not yet finished	View
94	14.6 > Bathrooms	Cedar	2009-06-18	2009-07-23	Not yet started	Not yet finished	View
95	14.7 > Public Spaces	Cedar	2009-06-18	2009-07-28	Not yet started	Not yet finished	View
96	14.8 > Kitchen	Cedar	2009-06-18	2009-07-13	Not yet started	Not yet finished	View
97	15 > Punch & Close Out, Building	GenCon	2009-08-03	2009-08-11	Not yet started	Not yet finished	View

Figure 4.23: Originial project schedule

GenCon generates multiple alternative project schedules, which are displayed in the application portlet unit for changing the project schedule as shown in Figure 4.24. The tasks which need to be changed are indicated on the "Status" column in the display. **GenCon** can make the changes described in the alternative project schedule by simply clicking the "Apply" button in the portlet unit. The button triggers a BPEL process unit that changes the project schedule and the distributed work schedules of the affected subcontractors, which is illustrated in Figure 4.25. The process unit connects to the affected subcontractors (**Apex**, **Kent** and **Cedar** in this case), and checks their availability for each modified tasks by invoking the operation "checkAvailability" of the Work Schedule Service unit in their systems. If a "true" value is returned for all the modified tasks, the operation "changeTaskDates" is invoked for each task. When the process completes, the BPEL process invokes the operation "removeRecord" of PIP Service to clear its PIP records.

After the change of project schedule is confirmed, **GenCon** and other subcontractors could change the target delivery date of other materials corresponding to the task postponed. The changes of target delivery date of other materials propagate to **GenCon**'s suppliers who may adjust their production and planned delivery date accordingly.

Maintenance of information consistency is tested in this example. When GenCon invokes the BPEL process unit that changes the project schedule and the work schedules of **Apex**, **Kent** and **Cedar**, the SC Collaborator system of **Kent** is shut down for testing purpose. When invoking the "checkAvailability" operation of the Work Schedule Service unit in **Kent**'s SC Collaborator system, the service operation returns a SOAP response message describing a connection fault, as illustrated in Figure 4.26, which is captured in the BPEL process. Since the BPEL process does not obtain a "true" value for all the modified tasks, it terminates without changing the project schedule and work schedules. Information consistency is achieved.

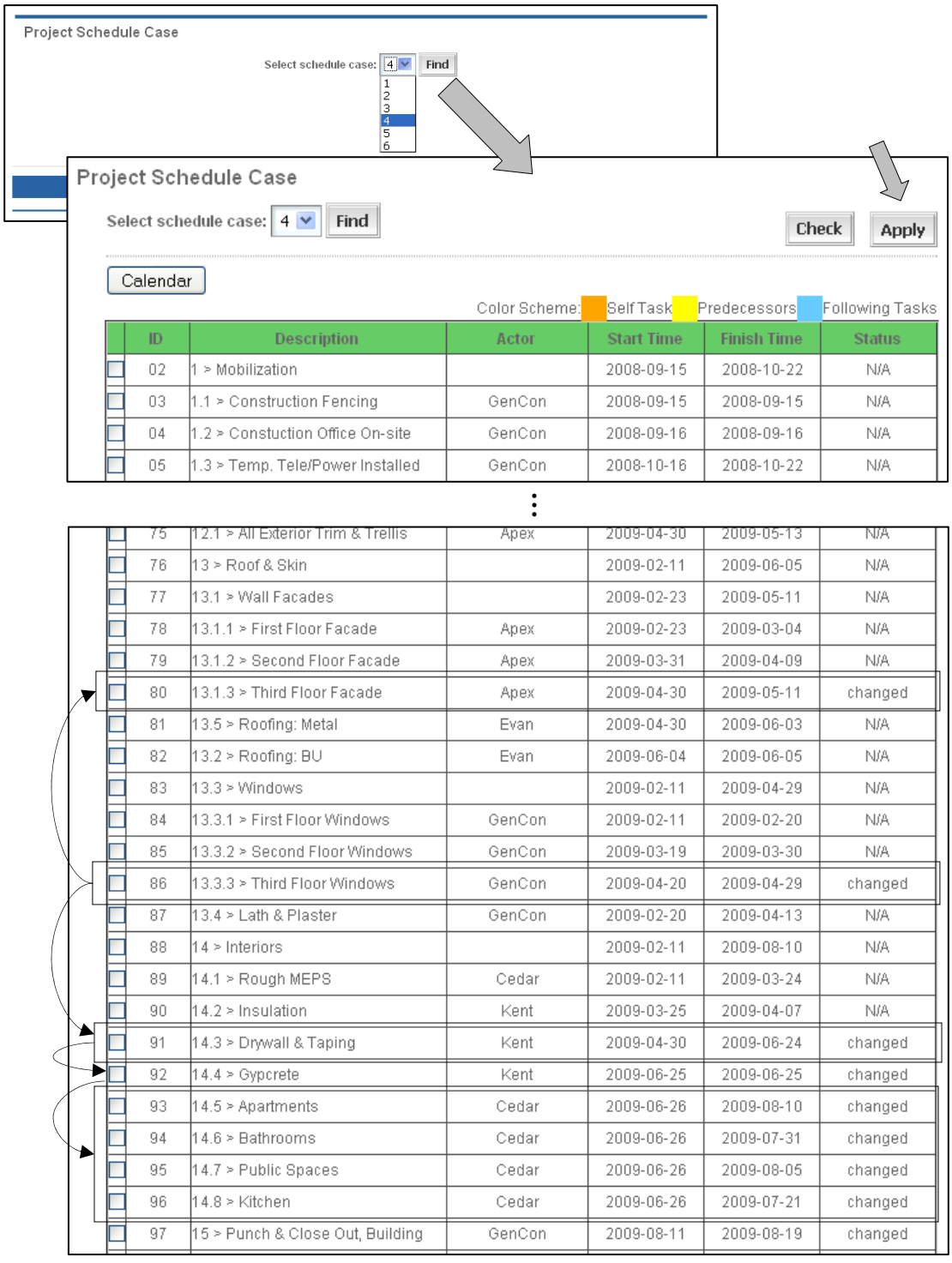


Figure 4.24: Application portlet unit in general contractor's layout that displays alternative project schedules

```
<bpel:process name="ChangeScheduleService2"
 targetNamespace="http://localhost:8080/service/processes/ChangeScheduleService2"
 xmlns:bpel="http://docs.oasis-open.org/wsbpel/2.0/process/executable">
<bpel:import location="ChangeScheduleService2Artifacts.wsdl"
 importType="http://schemas.xmlsoap.org/wsdl/" />
<bpel:partnerLinks>
 <bpel:partnerLink name="WorkScheduleApex" partnerLinkType="tns:WorkSchedulePLT"
  partnerRole="ServiceProvider" />
          :
 <bpel:partnerLink name="PIP" partnerLinkType="tns:PIPPLT"
  partnerRole="ServiceProvider" />
</bpel:partnerLinks>
<bpel:variables> ... </bpel:variables>
<bpel:sequence name="main">
 <bpel:receive name="receiveInput" partnerLink="client"
  portType="tns:ChangeScheduleService2" operation="process" variable="input" />
 <bpel:forEach parallel="no" counterName="Counter" name="ForEach">
  <bpel:scope> <bpel:sequence>
   <bpel:if name="Select contractor">
    <bpel:invoke name="Check availability Apex" partnerLink="WorkScheduleApex"
    operation="checkAvailability" portType="ns:WorkScheduleService2ApexPortType"
    inputVariable="WorkScheduleApexRequest" outputVariable="WorkScheduleApexResponse"/>
   <bpel:elseif>
    <bpel:invoke name="Check availability Kent" partnerLink="WorkScheduleKent"
    operation="checkAvailability" portType="ns:WorkScheduleService2KentPortType"
    inputVariable="WorkScheduleKentRequest" outputVariable="WorkScheduleKentResponse"/>
   </bpel:elseif> <bpel:elseif>
    <bpel:invoke name="Check availability Cedar" partnerLink="WorkScheduleCedar"
    operation="checkAvailability" portType="ns:WorkScheduleService2CedarPortType"
  inputVariable="WorkScheduleCedarRequest" outputVariable="WorkScheduleCedarResponse"/>
   </bpel:elseif> </bpel:if>
  </bpel:sequence>
  <bpel:variables>
   <bpel:variable name="WorkScheduleApexResponse"
    messageType="ns:checkAvailabilityResponse"/>
         :
 </bpel:variables> </bpel:scope> </bpel:forEach>
 <bpel:if name="If">
  <bpel:sequence> <bpel:scope name="Scope"> <bpel:sequence>
   <bpel:invoke name="add Record" partnerLink="PIP" operation="addRecord"
    portType="ns:PIPServicePortType" />
   <bpel:invoke name="Change project schedule" partnerLink="ProjectSchedule"
    operation="changeTaskSchedule" portType="ns:ProjectScheduleServicePortType"
    inputVariable="ProjectScheduleRequest" />
   <bpel:invoke name="addRecord" partnerLink="PIP" operation="addRecord"
    portType="ns:PIPServicePortType" />
  </bpel:sequence>
  <bpel:variables> ... </bpel:variables>
  <bpel:faultHandlers> <bpel:catch> ... </bpel:catch> </bpel:faultHandlers>
 </bpel:scope>
 <bpel:forEach parallel="no" counterName="Counter" name="ForEach1"> <bpel:scope>
 <bpel:if name="Select contractor"> <bpel:sequence> <bpel:scope name="Scope">
        :
  <bpel:invoke name="Change work schedule Apex" partnerLink="WorkScheduleApex"
   operation="changeTaskDates" portType="ns:WorkScheduleService2ApexPortType" />
  </bpel:scope> </bpel:sequence> <bpel:elseif> ...
 </bpel:elseif> </bpel:if> </bpel:scope> </bpel:forEach> </bpel:sequence> </bpel:if>
 <bpel:invoke name="removeRecord" partnerLink="PIP" operation="removeRecord"
  portType="ns:PIPServicePortType" />
 <bpel:reply name="replyOutput" partnerLink="client"
  portType="tns:ChangeScheduleService2" operation="process" variable="output" />
</bpel:sequence>
</bpel:process>
```

Checks the availability of Apex, Kent and Cedar for each modified task

Changes the project schedule

Changes the distributed work schedules

Removes PIP records

Figure 4.25: BPEL process that changes the project schedule and the distributed work schedules in the scenario demonstration

```
<?xml version='1.0' encoding='UTF-8'?>
<soapenv:Envelope xmlns:soapenv="http://schemas.xmlsoap.org/soap/envelope/">
 <soapenv:Body>
  <soapenv:Fault>
   <faultcode>soapenv:Client</faultcode>
   <faultstring>
    The service cannot be found for the endpoint reference (EPR)
    http://171.67.80.70:8080/service/processes/WorkScheduleService
   </faultstring>
   <detail> <Exception>
    org.apache.axis2.AxisFault: The service cannot be found for the endpoint
     reference (EPR)
     http://171.67.80.70:8080/service/processes/WorkScheduleService&#xd;
    at org.apache.axis2.engine.DispatchPhase.checkPostConditions
     (DispatchPhase.java:62)&#xd;
              :
    at java.lang.Thread.run(Thread.java:595)&#xd;
   </Exception> </detail>
  </soapenv:Fault>
 </soapenv:Body>
</soapenv:Envelope>
```

Figure 4.26: SOAP response message showing the connection fault when invoking the Work Schedule Service unit located in **Kent**'s system

For further testing, the service operation "changeTaskDates" is removed from the Java implementation class of Work Schedule Service for subcontractor **Kent**. The Work Schedule Service unit is deployed again in **Kent**'s SC Collaborator system. When **GenCon** invokes the BPEL process that changes the project schedule and work schedules, the same SOAP fault response message as shown in Figure 4.26 is captured at the BPEL activity "Change work schedule." Since the activity is enclosed in a scope that contains logging and fault handling functionalities supported by the PIP Service unit, changes made to the project schedule and the work schedules of **Apex** and **Cedar** are rolled back and the old schedule information is restored. As a result, the schedule information described in the project schedule and the work schedules of **Apex**, **Kent** and **Cedar** are consistent even though a service invocation failure occurs in the BPEL process.

4.6 Summary

Current collaborative systems are mostly centralized. Business partners upload information and documents to a single system and share with other companies. However, this kind of collaboration does not satisfy the need in a supply chain setting. Since supply chain management integrates members from suppliers' suppliers to customers' customers, companies who do not have direct business relationships are involved in the same supply chain. Although most collaborative systems for supply chain management provide security control to the information and applications shared in the systems, some companies do not feel comfortable to share proprietary and privacy information and documents in those systems. In addition, there are often debates on who has the rights to host the systems and to keep the shared information. This chapter presents a distributed network of service oriented collaborator systems which aim to tackle these problems.

In a distributed SC Collaborator network, companies can own and manage their information, documents and applications in their own system, and share them with designated partners at a specific time. The communications among distributed SC Collaborator are supported by leveraging standardized web services technologies and protocols. Since the internal information, applications, and system operations of the SC Collaborator system are wrapped and deployed in individual web service units, they can be exposed to other SC Collaborator system for invocation through the SOAP, WSDL, and BPEL standards.

Security and information consistency are key issues for distributed collaborative systems. The security of web service units is managed by the authentication capability provided by the portal system interface in SC Collaborator. This chapter mainly discusses the system architecture to maintain information consistency among distributed systems. It is achieved by the specific design of the back-end database support, the web service units, and the BPEL process services. The database is leveraged for logging of running process services. The web service units return information for roll-back upon successful

invocation. The process services leverage the fault handling functionality of BPEL standard to roll back in case of service failures. This chapter also demonstrates the distributed SC Collaborator network for procurement and task rescheduling among distributed systems of general contractor, subcontractors, and suppliers. Inconsistency consistency among distributed SC Collaborator systems is also successfully tested.

Chapter 5

Conclusions and Future Works

Importance of supply chain integration and collaboration has been shown in many industry sectors. However, the construction industry is one of the least integrated among all major industries. The current technologies and tools for supply chain integration such as enterprise resource planning (ERP) systems are designed for construction supply chains, which are highly fragmented and unstable project-based in nature. This thesis presents a system framework that addresses the requirements for managing and integrating construction supply chains. This chapter provides a summary of the thesis, discusses the main contributions of the thesis, and describes some future research directions.

5.1 Summary of Research

With the proliferation of the Internet and the increasingly maturity of web services standards, the adoption of service oriented architecture (SOA) with open source technologies is a desirable computing model to support construction supply chain

management due to its flexibility and low cost. This thesis presents a prototype service oriented collaborative system framework, namely SC Collaborator (Supply Chain Collaborator), that was designed and developed to facilitate integration, collaboration, and monitoring of construction supply chains in a flexible manner. The implementation of SC Collaborator leverages web services and portal technologies, open standards, and open source packages. The SC Collaborator framework consists of a database support and four layers of integrated functionalities – a communication layer, a portal interface layer, a business applications layer, and an extensible computing layer. The communication layer provides a communication channel for users to access the system. The portal interface layer serves as a secure and customizable user interface. The business applications layer implements SOA and integrates information, applications and services in a flexible and reusable manner. Internal information sources, application functionalities, and system operations are wrapped and deployed into individual web service units on this layer. The extensible computing layer may include databases, software applications, and web services that the business applications layer can integrate externally. The framework is tested and demonstrated in a procurement scenario and a project rescheduling example.

This thesis demonstrates the modeling of construction supply chains and proposes the incorporation of supply chain models in a service oriented system framework. Specifically, the Supply Chain Operations Reference (SCOR) framework developed by Supply Chain Council is used to model the network structure and processes in construction supply chains. The mechanical, electrical and plumbing (MEP) supply chains in a student center construction project has been studied and used as the case example. Information and documents have been collected and interviews with the general contractor, subcontractors, and suppliers have been conducted in the study. The MEP supply chains models developed using the SCOR framework are then utilized to build a supply chain performance monitoring system. This is achieved by wrapping each SCOR Level 3 and Level 4 models into individual web service units, which can be integrated and orchestrated in the service oriented SC Collaborator framework. The

development and implementation details of the SCOR-based performance monitoring system are included in this thesis.

The SC Collaborator framework is further extended to support collaboration among distributed SC Collaborator systems. Currently, supply chain members collaborate and share information and operations in a centralized manner. In this way, members only have a limited control on the information they share and the ownership of the shared information is controversial. Project participants that do not have direct business partnership may be reluctant to expose and share sensitive and proprietary information with each other. This thesis thus introduces a distributed SC Collaborator network. Communication between SC Collaborator systems is achieved through standardized web services protocol. System modifications are made to ensure information consistency among distributed SC Collaborator systems. Web service units are modified to return roll-back operation information whereas BPEL processes are changed to perform logging and fault handling for every invocation of transaction service operations. In addition, service invocations of on-going processes are recorded at the back-end database. In this way, consistency among distributed SC Collaborator systems can be maintained regardless of network failures or service failures. The distributed SC Collaborator network is tested with a case scenario of a completed expansion project of a three-storey residential building.

5.2 Research Contributions

Integration of information and applications is one of the keys to effective supply chain management. This thesis investigates and demonstrates the use of service oriented architecture, web services and portal technologies, and open source tools to develop a prototype service oriented framework that can facilitate integration and collaboration among supply chain members. The framework supports flexible system reconfiguration

and integeration of scattered information and application operations, system alignment based on supply chain configuration, and distributed network of collaborative systems. The thesis also demonstrates the modeling and performance monitoring of construction supply chains. Four major contributions are made in this thesis:

- **Incorporation of supply chain models in a collaborative system framework:** This thesis proposes and demonstrates the integration of supply chain models and web services technology in a service oriented SC Collaborator system framework. The Supply Chain Operations Reference (SCOR) modeling framework is employed to model and monitor construction supply chains in this research. The SCOR framework is widely used to model supply chain network structures and operations for strategic planning purposes. The SCOR framework is seldom leveraged for the design and implementation of information systems for supply chain management and collaboration. The resulting SCOR-based SC Collaborator framework allows flexible alignment with supply chain configuration and modular modification of the system.

- **Distributed network of collaborative systems:** In current collaborative systems, members share information, documents, and operations in a centralized manner. This thesis proposes a distributed network of collaborative systems that allows users to fully control the data and operations they share and promotes information sharing among supply chain members. This thesis presents a distributed SC Collaborator network which is based on standardized web services technologies, and addresses the information consistency issues among the distributed SC Collaborator systems.

- **A collaborative system framework that is designed for construction supply chain management:** A collaborative system that is designed to manage construction supply chains needs (1) ease of installation and configuration, (2) low cost, (3) ease to be connected and integrated, (4) ability to integrate external systems and information, and (5) customizable access to information and

applications. Current solutions do not fulfill all of these requirements. To demonstrate a SCOR-based system and a distributed network of collaborative systems, a prototype service oriented system framework SC Collaborator is developed. Leveraging web services and portal technologies, open source tools, and open standards in system implementation, the SC Collaborator framework is designed according to the five system requirements and is desirable for construction supply chain collaboration and management. The system framework is tested and validated through various case scenarios.

- **Modeling and performance monitoring of construction supply chains:** The planning and management of supply chains require properly specifying the participating members, identifying the relationships among them, and monitoring their performance. However, there is no formal methodology that models and represents the supply chain networks and operations in the construction industry. Study on the performance monitoring of construction supply chains is also lacking. This thesis employs the Supply Chain Operations Reference (SCOR) modeling framework to model and monitor construction supply chains. The mechanical, electrical and plumbing (MEP) supply chains in a student center construction project has been studied and modeled using the SCOR framework as a case example in this thesis. The development of a performance monitoring platform for the MEP supply chains is also illustrated.

5.3 Future Directions

This section describes the limitations of this research and how they can be addressed in future research.

5.3.1 Ontology Based Systems

Supply chain members may use different representations to describe the same piece of information. Web Services Description Language (WSDL) documents specify the data structures and data types of the elements in the request and response messages of each web service operation. Based on WSDL, the prototype SC Collaborator framework enables integration of information, applications, and services with different representations. However, supply chain members may use the same terminology to describe different concepts or use different terminology to describe the same concepts, due to the differences in their domains and perspectives. The specifications in WSDL documents do not provide the semantics of the data being exchanged between partners. Misunderstanding and misinterpretation of the data may be resulted. Ontologies could be used to describe the data semantics and to serve as a terminological basis for information interoperability. In a system framework that is supported by both WSDL documents and ontologies, information, applications and services can be syntactically and semantically integrated and interoperated.

5.3.2 Extending the Research Scope on Modeling

The three configurations of MEP supply chains described in Chapter 3 are based on our study of a student center construction project. The MEP supply chains in other construction projects may have different configurations in terms of organizations and business operations. The configuration of a supply chain may be affected by factors such as the common practice of the supply chain members, the scale and budget of the project, and the type of the construction. Further study of the MEP processes in other construction projects may be needed to validate the generality of the three supply chain configurations described. Moreover, the research can be extended to other kinds of processes in a construction project, for example, steel erection and window installation to study the supply chains involved in these processes, to model them using the SCOR

framework, and to build a performance monitoring system for these supply chains using the framework we presented in this thesis. By extending the scope of our research, we hope to test the developed methodology and framework and to enhance their usability. We may also integrate the SCOR models with the existing construction process maps to better reflect the structure and configuration in construction supply chains.

5.3.3 Application Programming Interface for SC Collaborator

Many system and applications offer an application programming interface (API) that enables software programs to connect to and interact with them. APIs define how other software can make calls to or request services from them. Software programs can interact with the SC Collaborator system through web services protocol. With successful authentication, users can view the names of the web service units and their service operations that are available for invocation. The list of web service units is also hyperlinked to individual WSDL documents, which describe the service specification that users can refer to when calling the service operations. However, SC Collaborator does not provide a description of the behaviors and relationship of the web service units. In the future, the behaviors and dependency of the service units and their operations will be specified and documented. An interface that allows users to view and search the detailed documentation should also be provided.

5.3.4 Evaluation of SC Collaborator Using TAM

Although the SC Collaborator framework has been tested and demonstrated using various example scenarios, the value and deficiency of the framework is not evaluated and analyzed in this thesis. Technology acceptance model (TAM) [30] can be adopted to

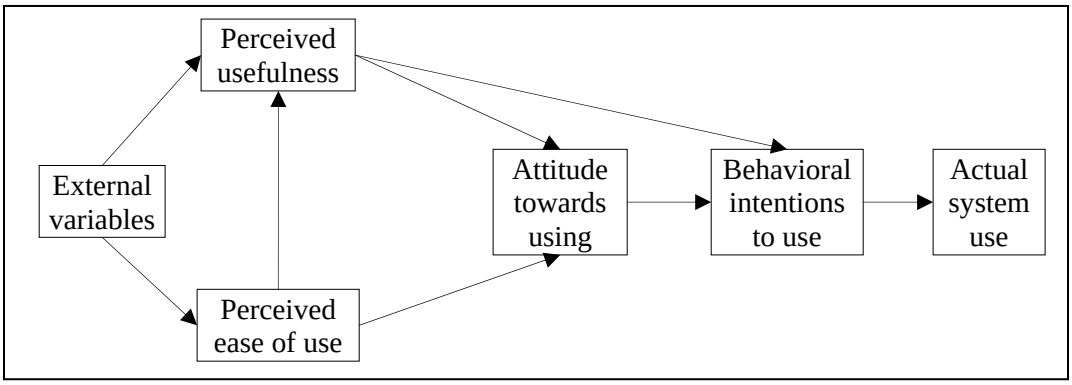


Figure 5.1: Technology acceptance model (TAM) [30]

evaluate SC Collaborator in terms of perceived usefulness and perceived ease of use. TAM is an information systems theory that models how users come to accept and use a technology. As illustrated in Figure 5.1, the perceived usefulness and ease of use of a system affect the attitude towards using the system and the behavioral intentions to use the system, which eventually are reflected in the actual system use. To improve the value and impact of SC Collaborator, we will demonstrate the SC Collaborator framework to industry practitioners and gather their feedbacks on the perceived usefulness, ease of use, and intentions to use the system. By study the feedbacks, we can prioritize the system features and components, and determine the most value-adding improvements we can make.

5.3.5 Applications of the GreenSCOR Framework

There have been increasing concerns on the environmental impacts of the construction industry. In 2008, Supply Chain Council released the GreenSCOR framework [91] which is a generic conceptual framework for measuring the total carbon footprint and total environmental footprint in a supply chain. As illustrated in Figure 5.2, the GreenSCOR framework considers five performance metrics – (1) carbon footprint in tons of carbon dioxide equivalent, (2) air pollutant emissions in tons or kg, (3) liquid waste

generated in tons or kg, (4) solid waste generated in tons or kg, and (5) percentage of solid waste that is recycled. Since the GreenSCOR framework is based on the SCOR framework, it could be incorporated in the SCOR-based SC Collaborator to build a green supply chain performance monitoring framework designed for the construction industry. Further study on the GreenSCOR framework and its integration with the SCOR-based SC Collaborator will be conducted.

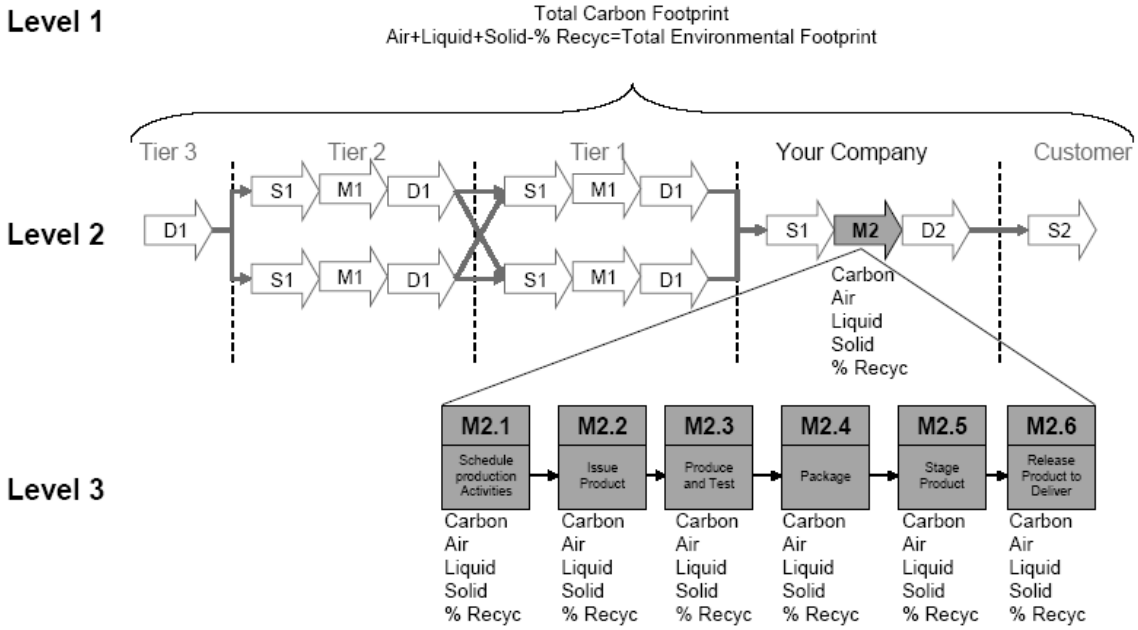


Figure 5.2: The GreenSCOR framework [91]

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