A Service Oriented Framework for Construction Supply Chain Integration

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Abstract The benefits of integrating and coordinating supply chain partners have been well recognized in many industries. In the construction industry, supply chain integration is technically challenging due to the high fragmentation of the industry. Information, applications, and services are loosely distributed among participants with a wide range of hardware and software capabilities. In addition, participants are often unwilling to share information because the temporary nature of construction projects often impedes the establishment of trust. A secure, modular, and flexible system that can aggregate scattered information and share that information across applications is, therefore, highly desirable. We have prototyped a service oriented, web-based system that can provide both these capabilities. Called the SC Collaborator, this system facilitates the flexible coordination of construction supply chains by leveraging Web services, web portal, and open source technologies. These technologies enable the SC Collaborator system to provide an economical and customizable tool for integrating supply chain partners with a wide range of computing capabilities. This paper describes the overall architecture and the features of the system. Two example scenarios are included to demonstrate the potential of SC Collaborator in integrating and managing information from project partners. The first scenario is an e-Procurement example whereas the second is a rescheduling scenario based on the data from a completed project in Sweden.

Keywords Construction Supply Chain Integration, Service Oriented Architecture, Web-based Collaborative System, Web Services, Open Source

1. Introduction

A supply chain consists of a network of key business processes and facilities, involving end users and suppliers that provide products, services, and information [33]. 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 [43, 53]. 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 [17, 42]. Information delays and distortions lead to an increase in demand signal variation along the supply chain upstream, a phenomenon called the bullwhip effect [35]. Therefore, integration is one of the keys to effective supply chain management.

Construction is one of the largest industries in any country of the world [28]. In the United States, the value of construction put in place was $1,072 billion in 2008 [59], or 7.5% of the U.S. gross domestic product (GDP) that year [11]. 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 [25]. New [45] and Cox [20] have suggested that supply chain research in construction should focus on the development of interactive, inter-organizational relationships, which requires integration. However, the high fragmentation and project-based nature of the industry pose a significant challenge to cross-enterprise integration of construction supply chains. Briscoe [10] has summarized eight key attributes to successful construction supply chain integration, and this research focuses on two of them – managing communication and managing information flow. The characteristics of construction supply chains lead to various requirements for information and collaborative systems such as low cost and system adaptability. In the manufacturing industry, there are many attempts to develop methodologies, technologies, and tools to integrate various applications for communication and collaboration among supply chain members. However, these technologies and tools such as Electronic Data Interchange (EDI) and enterprise resource planning (ERP) systems often do not meet the needs and requirements for managing construction supply chains, due to their high cost, inflexibility to change, and lack of system extensibility.

With rapid development of communication technology, the Internet has become ubiquitous and instantaneously accessible. The proliferation of the Internet makes it the most cost effective means of driving supply chain integration and information sharing [36]. 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. 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. Web services technology enables a service oriented approach for the integration of distributed information and applications on a network which supply chain members can connect to. The service units act as the components for various business functions and can be reused and aggregated into a complex business process or workflow.

Web portals have been used for information repository and sharing within a company as well as across organizations. Because of its customizability of layouts and access control, a web portal provides a secure, tailored way to deliver the right information to the right user at the right time. Although current web portals can be developed to discover and to deploy services, their functions are usually fixed and cannot be changed or extended to external systems flexibly. Portal systems can become more flexible if the service oriented architecture (SOA) is adopted. In a service oriented portal-based framework, information and system operations are deployed as discrete web service units, which can be combined to perform different business tasks. Exposing the web service units also allows internal information and system operations to be integrated with other systems and applications, increasing the usability of the system and allowing automation of business processes. In this paper, we will describe the service oriented portal-based framework and present the SC Collaborator system, a prototype system that we have developed for managing construction supply chains.

This paper is organized as follows: Section 2 provides the general background of construction supply chain, suggests the requirements for collaborative systems for the construction industry, and discusses the existing tools for supply chain integration and their shortcomings. Section 3 presents how some of these shortcomings can be avoided using a service oriented approach. Section 4 presents the service oriented portal-based framework, describes the architecture and functionalities of SC Collaborator for supply chain management, and discusses its suitability for the construction industry. Section 5 presents two example scenarios to demonstrate the features of SC Collaborator for integrating various information and business functionalities. The second example scenario is drawn from a completed construction project in Sweden. Section 6 concludes the paper with a brief summary and discussion on future works.

2. Information Systems for Construction Supply Chain Integration

2.1 Construction Supply Chains

Construction supply chains are characterized by the involvement of many companies from a wide variety of trades [48]. A construction project involves a diverse group of participants including contractors, architects, engineers, laborers, and developers [29]. A project of medium to large scale typically involve hundreds of different companies supplying materials, components, and a wide range of construction services [21]. 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 [40], 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 [61]. 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.

2.2 System Requirements for Construction Supply Chain Integration

2.2.1 Ease of Installation and Configuration

As discussed in [58], 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 [18]. 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.

2.2.2 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 [21]. 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. Corporations routinely spend up to 50 percent of their information technology budgets on application integration [9]. 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.

2.2.3 Ease of Connection and Integration

As noted earlier, ability to accommodate users with varying degrees of IT sophistication is one of the three requirements for supply chain information infrastructure [58]. 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) [23], 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.

2.2.4 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 [31, 32, 44]. 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 [64]. 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.

2.2.5 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.

2.3 Current Practices for Supply Chain Integration in the Construction Industry

Good communications and information sharing among various parties in construction projects are critical and can be achieved through information technology integration [10, 21]. Some companies in the manufacturing industry establish communication networks using standards such as Electronic Data Interchange (EDI) to connect and exchange data with partners [24, 27, 30]. 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.

Recently, major construction companies have adopted enterprise resource planning (ERP) systems to integrate loosely distributed information and applications within and across companies [18]. 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 [22]. 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 [64]. There are many research studies and efforts on selection and implementation of 'generic' ERP systems in the construction industry [2, 18, 19, 52, 64]. 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 [49] whereas another study reported that 70% of ERP implementations did not achieve their estimated benefits [4]. ERP systems have many limitations such as implementation complexity, integration problems, and customization problems [57]. Akkermans et al. [3] concludes four major limitations of ERP systems as: (1) inflexibility to accommodate changes of supply chain structures, (2) lack of modular and open system architecture, (3) lack of functionality beyond managing transactions, and (4) inability to share internal data efficiently with supply chain partners.

The Internet has emerged as a cost effective means of driving supply chain integration [36]. 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 [14, 47, 54], for document and knowledge management [38, 65], and for project monitoring and management [13, 16, 46]. Figure 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 [8, 46]. 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 [39]. We believe that an Internet-enabled system based on the service oriented architecture (SOA) can address many of the limitations of ERP systems and CPEs.

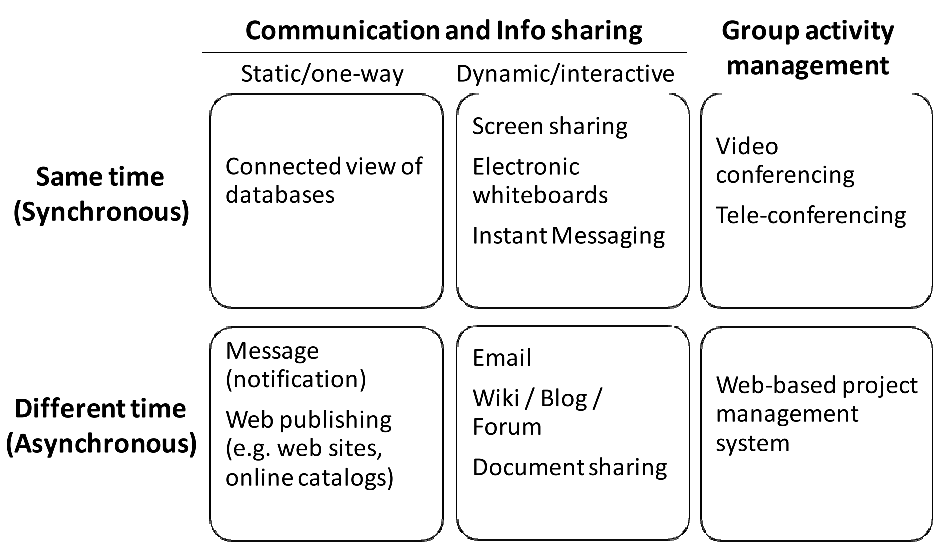


Figure 1: Commonly used web-based collaborative tools

3. Service Oriented Approach for Integration

Service oriented architecture (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, we believe that 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. 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.

Service composition is needed to aggregate multiple web services to perform a complex business task. Consider, for example, a business process "add purchase order" that may require four tasks: add a purchase order to the production plan, send confirmation to the customer, allocate materials to fulfill the order, and change the status of the order and inventory. Each of these tasks could be deployed as an individual web service. A mechanism to integrate them is necessary to complete the business process. There are many research efforts on web-based service integration [12, 15, 26], which deal with the mechanisms to invoke, terminate and orchestrate web services.

4. SC Collaborator Framework

SC Collaborator (Supply Chain Collaborator) is a prototype system developed for supporting information sharing and system integration along construction supply chains. Based on a service oriented portal-based framework, which will be discussed in Section 4.1, SC Collaborator implements the SOA approach to allow flexible reconfiguration and extensible functionality. The system also leverages web portal technology to provide role-based and customizable user interface. Open source technologies are leveraged to minimize implementation costs which hinder the system usability in construction companies that are SMEs. Figure 2 shows the homepage of the prototype system for users to log in.

A supply chain is a network of facilities that procure raw materials, transform them into intermediate goods and then final products, and deliver the products to customers through a distribution system [34]. Therefore, the SC Collaborator system focuses on the buyer-supplier interactions among suppliers, subcontractors, and general contractors (GCs) in the processes of procurement, manufacturing, and delivery. Users assigned to the normal user role of supplier, those to the role of subcontractor, and those to the role of GC have different system layout and functionalities when they log in. In SC Collaborator, suppliers can manage and respond received purchase orders, and share production and delivery information with customers. Subcontractors and GCs can submit and manage purchase orders, monitor product production and delivery information, and update the information of project tasks. Master monitoring and control on all the project tasks are also allowed for GCs. The accessibility of the system functionalities and the internal information and operations can further be customized for individual users.

Figure 2: Homepage of the SC Collaborator system

4.1 Service Oriented Portal-based Framework

Loosely coupled web services can be aggregated using web portal technology. 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 [41]. 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 [60]. The framework presented in this section is a service oriented approach for portal design and implementation. SC Collaborator, which is developed based on a service oriented portal-based framework, will then be discussed and illustrated in Section 4.2.

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. In a service oriented portal-based framework, as illustrated in Figure 3, information sources, application functionalities and system operations are wrapped and deployed into individual web services, which can be located and invoked by application portlet units via standardized protocol. These web services are connected and integrated into various workflows to perform different business tasks in the application portlet units. These web services 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. Communications among portlet units are allowed, supporting aggregation and interaction of service workflows.

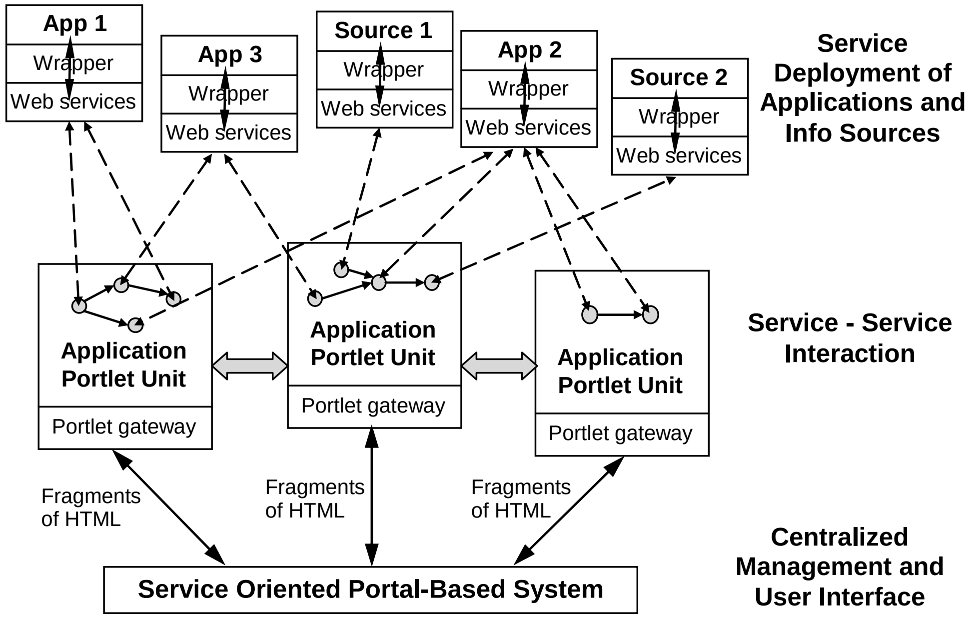


Figure 3: Conceptual framework of service oriented portal-based framework

4.2 System Architecture

Figure 4 shows the system architecture of the SC Collaborator framework. The framework consists of an access control engine, 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 delivery monitoring. The extensible computing layer is potentially comprised of numerous databases, software applications, and web services that the business applications layer can integrate to support high-level or computationally intensive business functions.

SC Collaborator implements a service oriented portal-based framework which is described in Section 4.1. The extensible computing layer of SC Collaborator represents a collection of external information sources and applications that are wrapped as web services while the business applications layer contains internal information, applications and system operations that are deployed as individual web services. The business applications layer of SC Collaborator also contains application portlet units which can connect and interact with the internal and external web services. A secure, centralized user interface is provided by the communication layer, the portal interface layer, and the access control engine. The components in SC Collaborator that implement the three functional units of the service oriented portal-based framework are highlighted in Figure 4.

This multi-layer 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. In the following sections, we will discuss the main components of the SC Collaborator framework in detail.

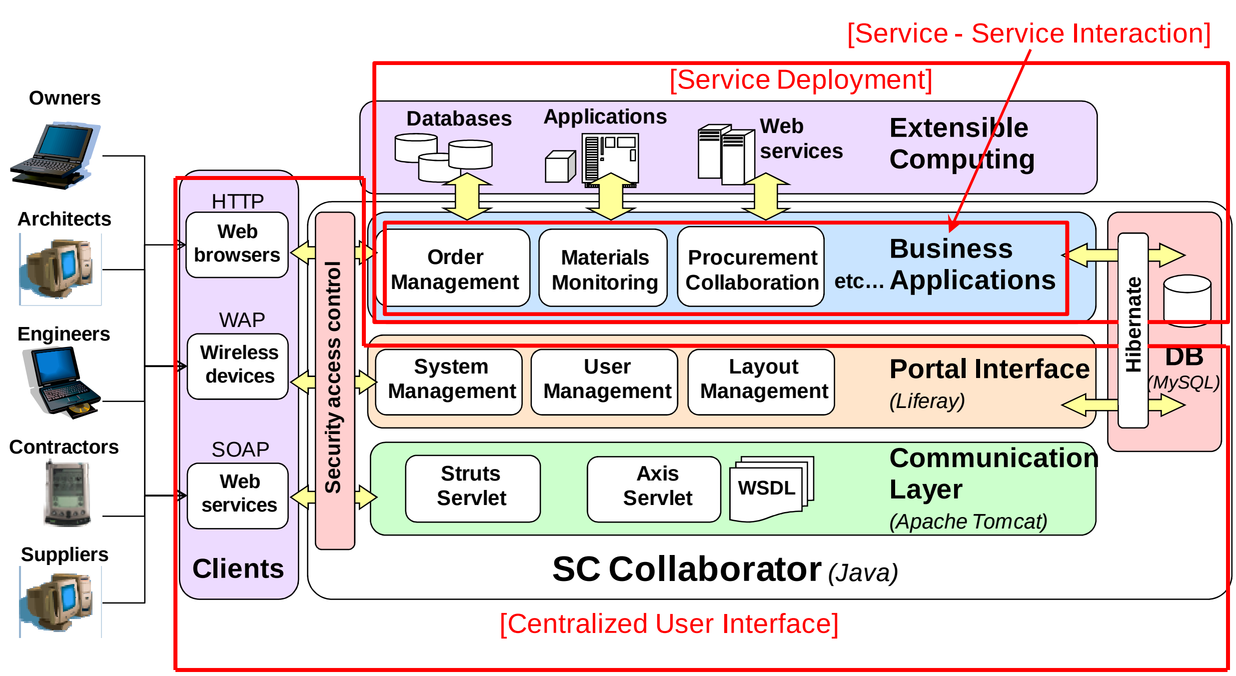


Figure 4: System architecture of the SC Collaborator system

4.2.1 Communication Layer

A user-friendly and readily accessible communication channel is essential to the usability of a system. The SC Collaborator system uses an open source platform – Apache Tomcat [7] – to enable the connectivity and access to the system. Apache Tomcat serves as a web servlet container for the communication servlets, Apache Struts [6] and Apache Axis [5]. While some information systems require the client-side to install particular communication software in order to be connected, the Struts servlet that resides in SC Collaborator allows users to access the system using web browsers, which are commonly available on every computer. The Struts servlet also enables remote users to access the system using wireless devices such as personal digital assistants (PDA) via the Wireless Application Protocol (WAP).

The Axis servlet that resides on the communication layer enables system operations of the SC Collaborator system to be exposed as standard web services. The deployed web services are described in standardized Web Service Definition Language (WSDL) [63] files for service discovery, description, and invocation. Users can request information from the system and execute internal operations via the Simple Object Access Protocol (SOAP) [62].

4.2.2 Portal Interface Layer

An open source web portal system – Liferay Portal [37] – 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. A single module contains a number of submodules, each of which can integrate multiple application portlet units. Configuration, permissions, and layout can be configured for each module, submodule, and portlet. 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.

User management can be performed at the levels of individual users, organizations, user groups, and roles. A user is an individual who performs tasks in the system. An organization represents a corporate hierarchy. A user group is a grouping of users. Unlike organizations, user groups have no context associated with them. They are grouped to facilitate communications and aid system administrators to assign permissions and roles to a group of users. A user can be associated with any number of user groups, but only one organization. Every member inherits the roles and permissions that are assigned to the organization or user group that the member belongs to. SC Collaborator is a role-based system. A role is a collection of permissions. 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, submodules, and portlets.

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 submodules, to set up the permissions of submodules, and to configure the submodule style. On each submodule, the administrative users can add, delete, and allocate application portlet units. The administrative users can also grant individual users the permissions to view, modify, and configure a specific module, submodule, 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.

4.2.3 Business Applications Layer

Each application portlet unit is an independent unit, which performs a specific task or business process. Based on the Java framework, a portlet unit can perform computations, execute other applications, connect to databases, and invoke 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 integrates 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. A portlet unit in SC Collaborator can also interact with other portlets to solve complicated business problems. 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.

4.2.4 Database Support

In the database tier, an open source database – MySQL [56] – is used to store the application data as well as the system information including user information, layout configurations, and user and system settings. The dependencies of the major information managed in the database are depicted in Figure 5. For all the products, a timestamp is generated 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) [55] compliant database without any complicated configuration and modification of codes due to the use of the Hibernate framework [50]. 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.

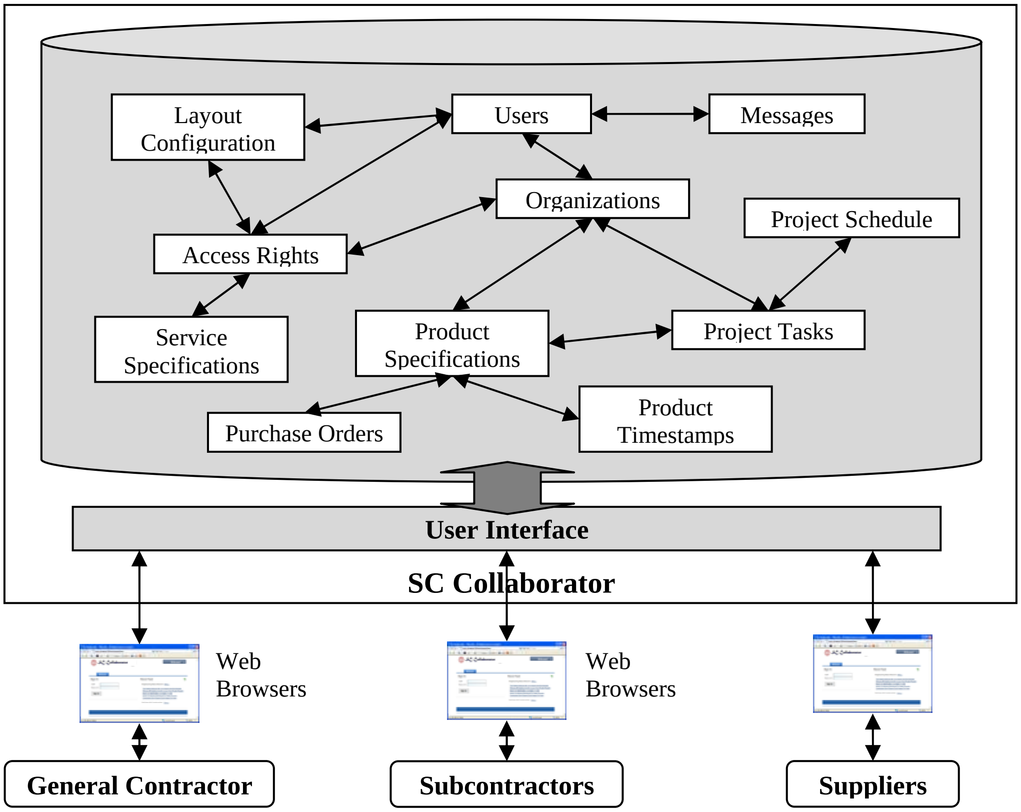


Figure 5: Schematic representation of the major information managed in SC Collaborator

4.3 Discussions of the SC Collaborator System

As suggested in Section 2.2, a collaborative system that is suitable for managing construction supply chains needs to possess the following features: (1) low cost, (2) ability to integrate external systems and information, (3) ease of installation and configuration, (4) ease of connection and integration, and (5) customizable access to information and applications. All of these requirements are satisfied in the SC Collaborator system. The use of widely supported open source technology in SC Collaborator provides an economical solution to system installation and maintenance. In specific, MySQL [56] and Hibernate framework [50] are used for the database support, Liferay Portal [37] for the portal-based user interface, and Apache Tomcat [7], Apache Struts [6] and Apache Axis [5] for the communication layer.

The connection ability 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 entire web can potentially be integrated in SC Collaborator.

Connection to external systems can also be performed in separate web service units that are linked to application portlet units. In this way, the implementation of system operations and the sources of external information and applications can be encapsulated while keeping the layout unchanged. This implementation of SOA and Web services makes the system flexible for installation and configuration, thereby saving a lot of time and effort.

Ease of connection and integration is fulfilled by leveraging Apache Axis, 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 service 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 in the SC Collaborator system is also achieved. The SC Collaborator system not only provides the basic security control of user login with password for the user interface, but also allows access control of individual deployed web services. Successful authentication with correct user login and password is required to discover and invoke the deployed web services. The user login and password share the same profile with the accounts in the portal interface for consistency in security management. As a result, internal information, applications and system operations in SC Collaborator are protected for trading partners.

5. Scenario Example

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.

5.1 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 [29, 51]. 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 6 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 7). As the catalogs are incorporated with Autodesk i-drop 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 7, embedded item information is also dropped to the architectural drawings.

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 7). The procurement is submitted to SC Collaborator via standardized web service 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 8. 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.

The suppliers log into the SC Collaborator system and manage the purchase orders they receive, as illustrated in Figure 9. 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 10). 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 9, 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 11).

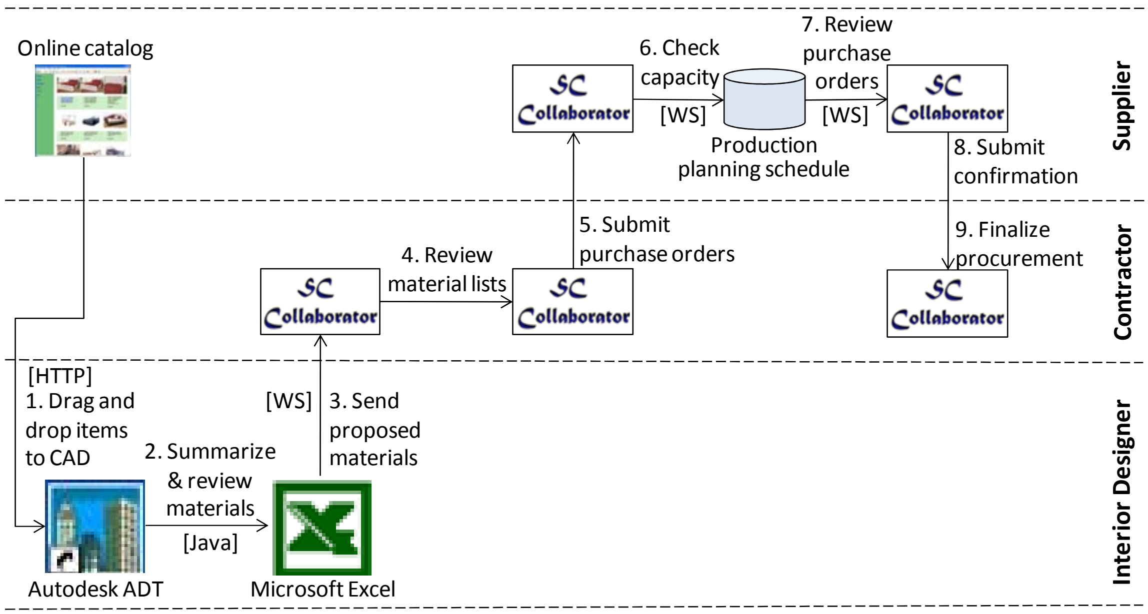


Figure 6: Workflow in the e-Procurement scenario

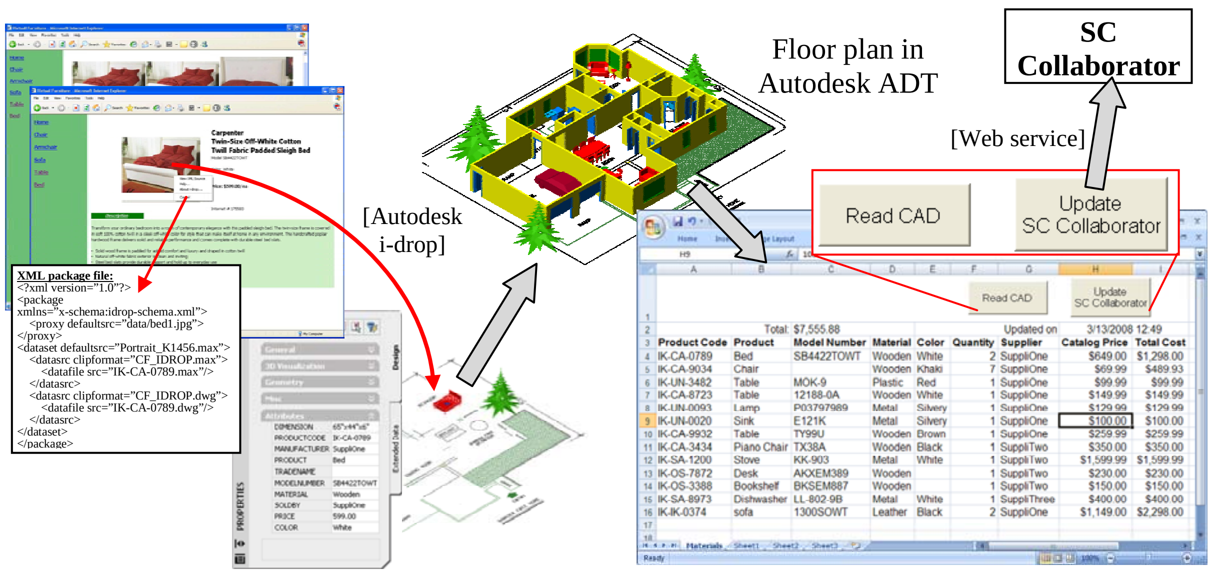


Figure 7: Integrating online purchasing with CAD and procurement services: designers dragging items from supplier's online catalogs to CAD drawings, then extracting the embedded item information to a spreadsheet in Microsoft Excel, finally sending the suggested item list to SC Collaborator for contractor to review

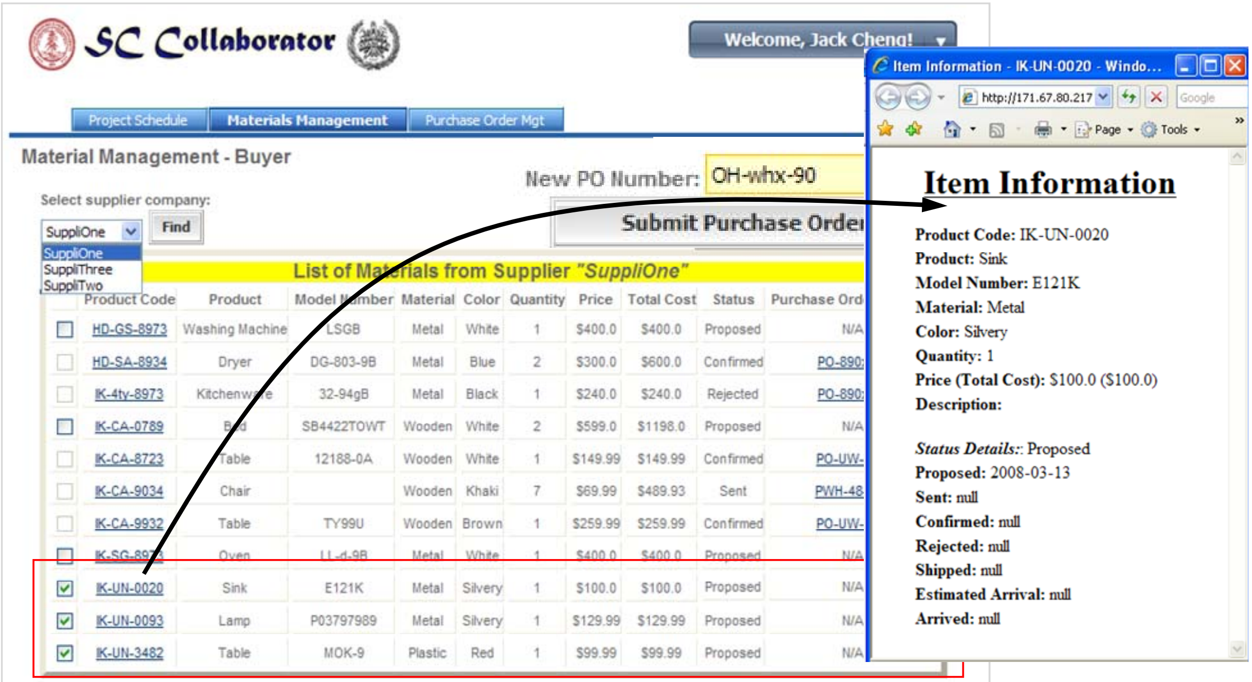


Figure 8: Contractor's layout for review of procurement item list and submission of electronic purchase orders

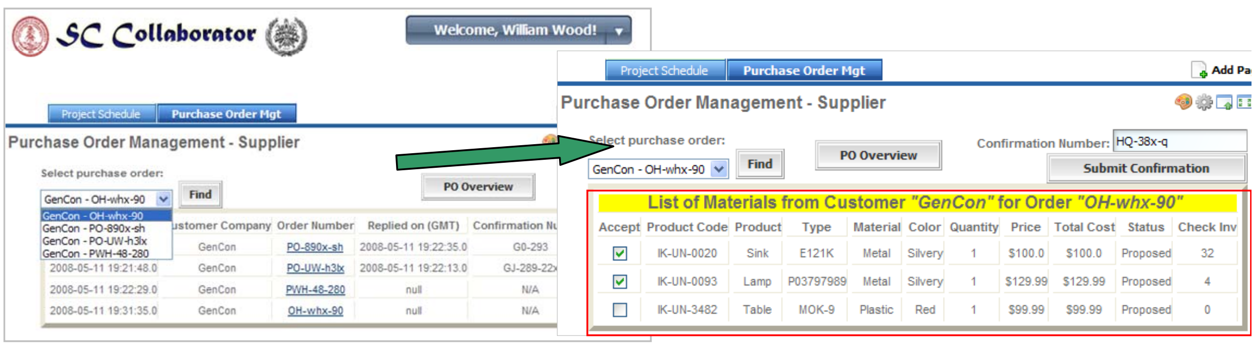


Figure 9: Supplier's layout for managing received purchase orders

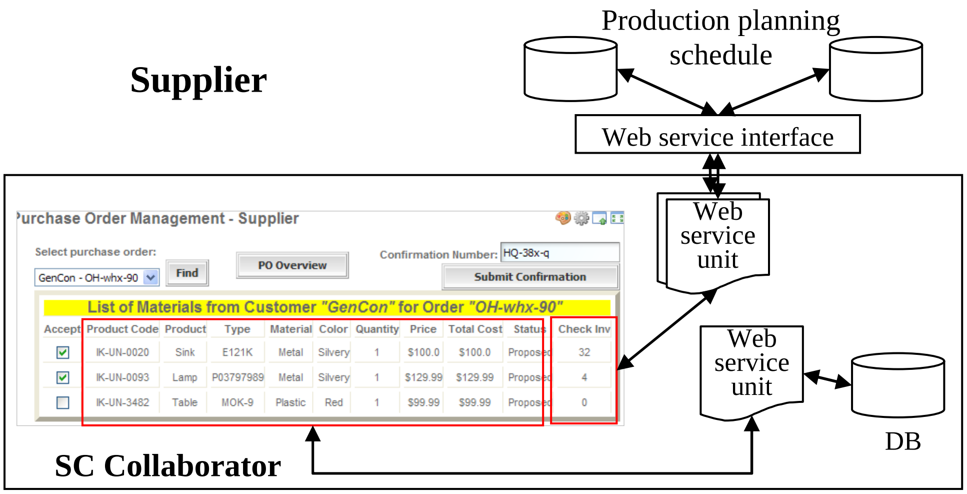


Figure 10: Connection to internal and external information and applications in the portlet unit that suppliers manage and evaluate received purchase orders

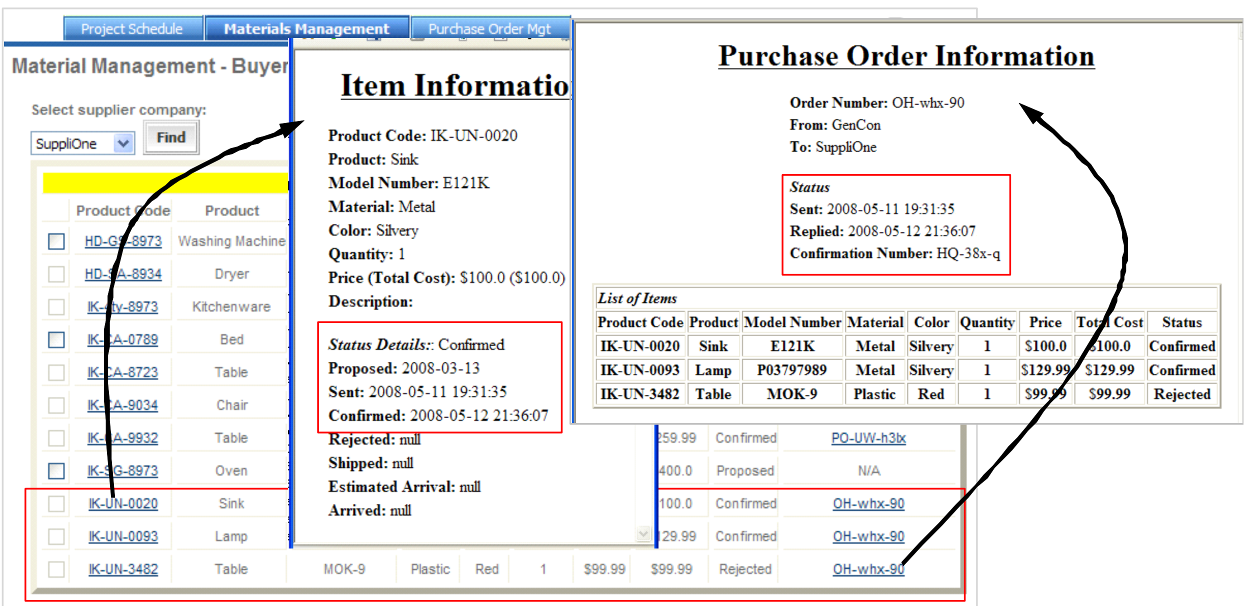


Figure 11: Contractor's layout showing updated item status and purchase order information

5.2 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 12). 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.

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 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 13 shows a portion of the project schedule. Figure 13 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. In this scenario, we extended our focus to the suppliers of a concrete works subcontractor, namely **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 14). In the scenario, production status information and expected delivery time information were reported to corresponding subcontractors by the suppliers (Figure 15). 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 16). 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 17). 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.

Transparency among the suppliers, subcontractors and general contractor is important for construction supply chain management. 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 18 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 the material delivery delay of 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.

Figure 12: Floor plan and finished layout of the supermarket in Boras, Sweden

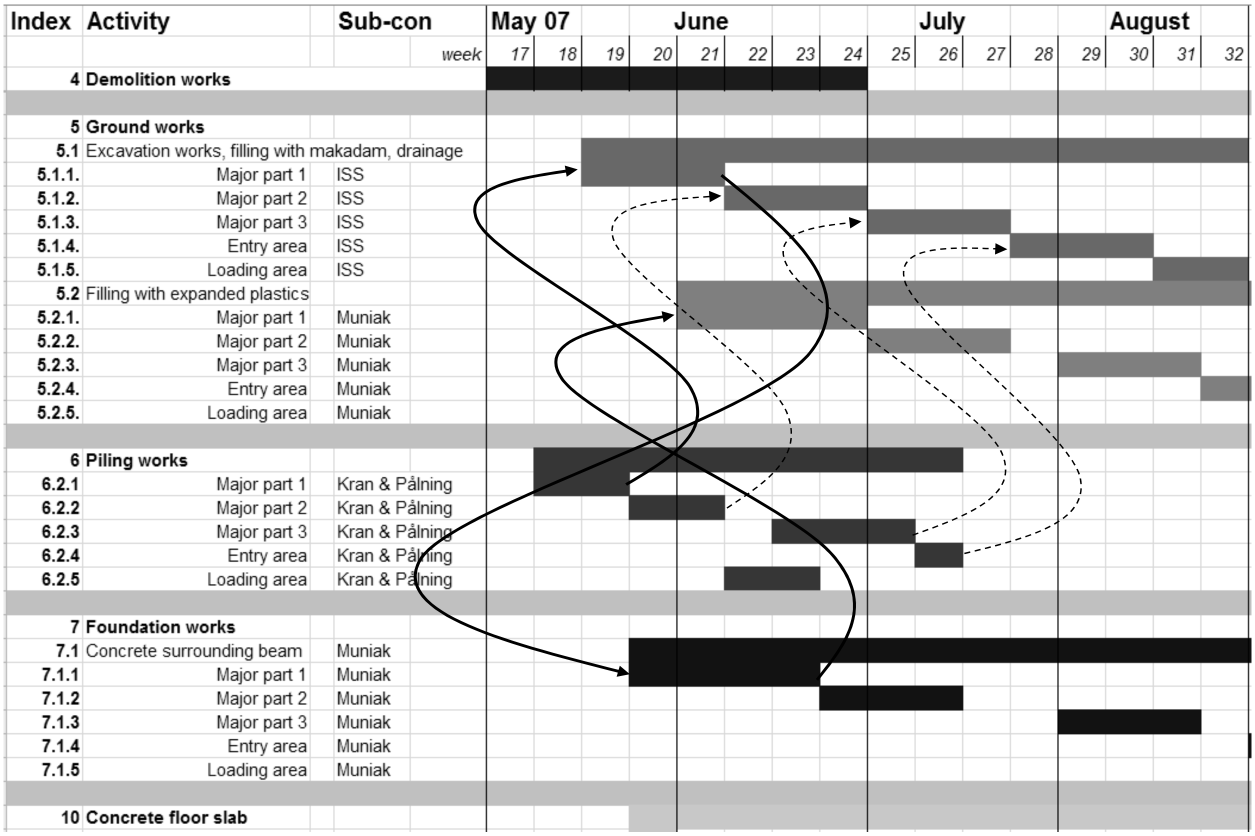


Figure 13: An excerpt of the project schedule between May 2007 and August 2007

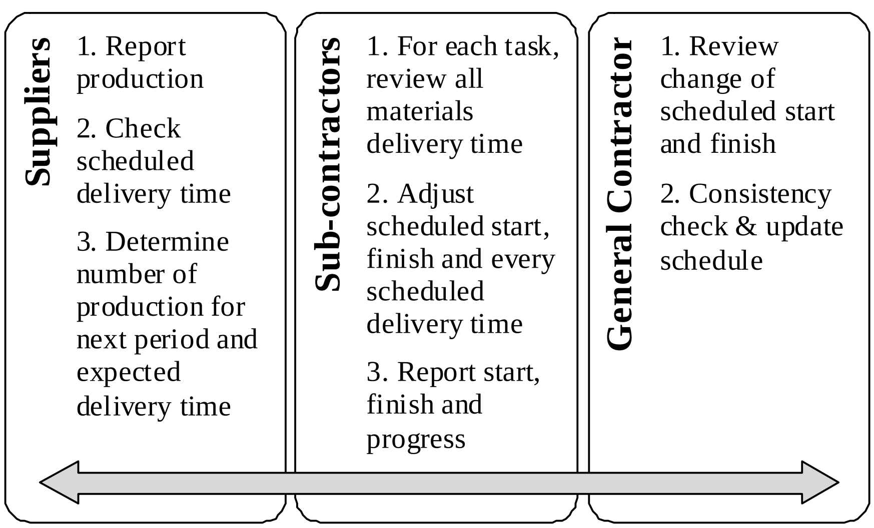


Figure 14: Information flows and interactions in the rescheduling process

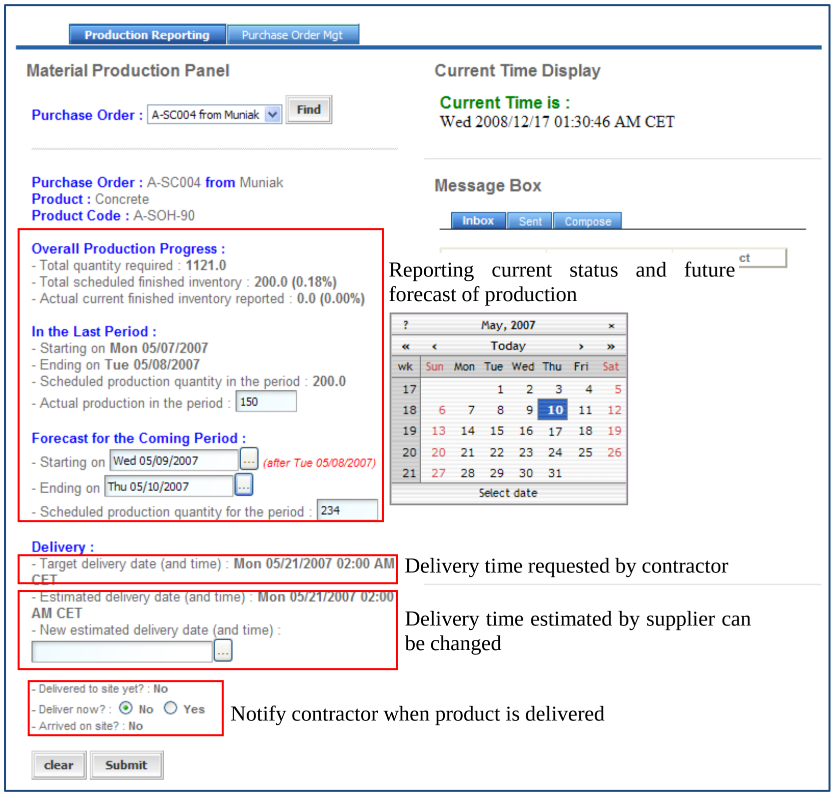
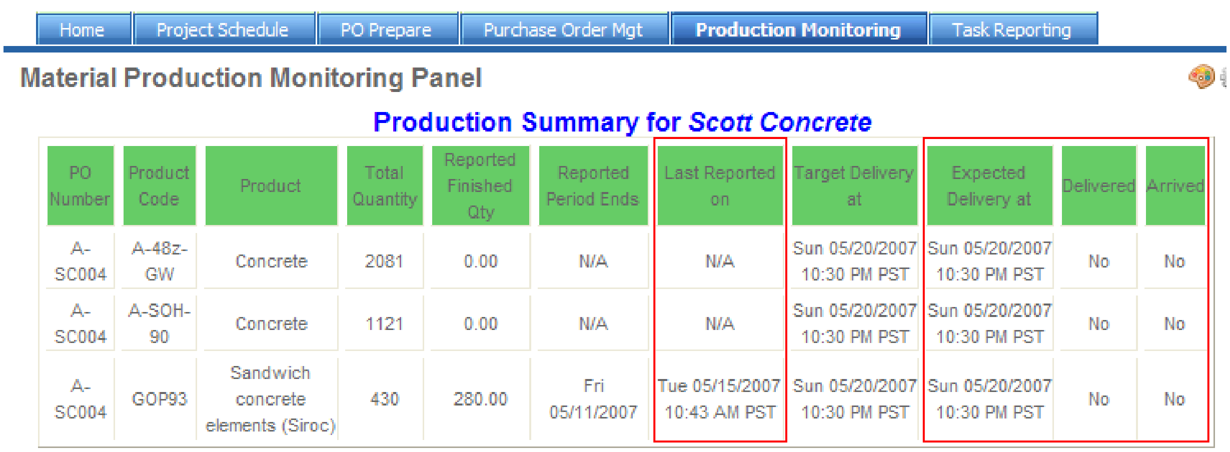


Figure 15: Supplier’s layout for production reporting



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 16: Subcontractor’s layout for monitoring material production and delivery

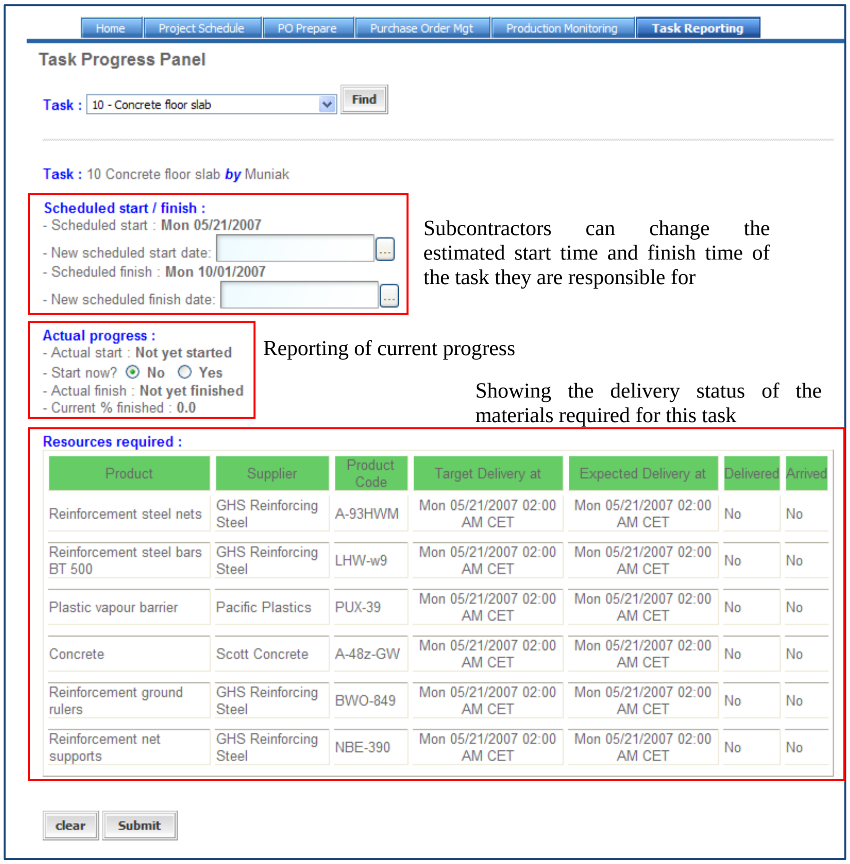


Figure 17: Subcontractor's layout for activity review and adjustment

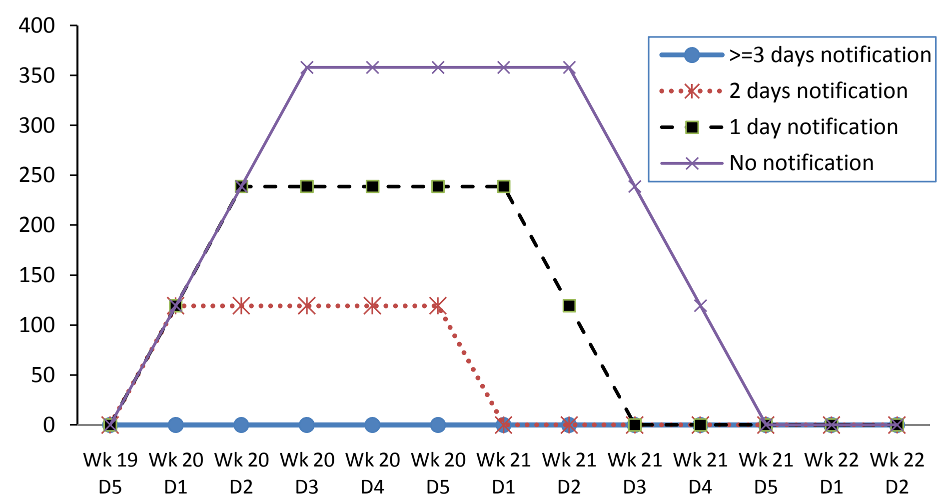


Figure 18: Inventory (in m^2) of form material (wood) under different supply delay conditions

6. Conclusion and Future Work

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. Many supply chain management tools such as ERP systems exist on the market to support integration of organizations. However, these tools are mostly targeted to large companies in the manufacturing industry and not suitable for managing construction supply chains, due to the unstable project-based nature of construction supply chains and the small to medium size of companies in the construction industry. Moreover, ERP systems which are a popular solution to supply chain integration entail a number of drawbacks and limitations. An alternative approach to link individuals across organizational boundaries and to integrate scattered applications is offered by the Internet technology and SOA principles.

This paper describes a prototype service oriented web-based system, SC Collaborator, designed for construction supply chain integration and collaboration. The service oriented approach and the portal technologies have been leveraged. 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 a security access control engine, a communication layer, a portal user interface, a layer of business application units, and a database support component. Based on the characteristics of construction supply chains and the study in literatures, we have summarized five requirements for a collaborative system that supports construction supply chain integration. The SC Collaborator system fulfills all these five requirements, which are (1) ease of installation and configuration, (2) low cost, (3) ease of connection and integration, (4) ability to integrate external systems and information, and (5) customizable access to information and applications.

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 paper.

The SC Collaborator system is a centralized portal system with a single shared database. Information sharing and application integration may be hindered in such a centralized system because some project participants may be hesitant to share information with other participants who do not have direct business relationship. Despite the security and access control capability of the portal-based system, some members are still uncomfortable to share information 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 system.

This problem can be alleviated by separating the platform into a network of distributed 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. Information consistency among distributed systems should be maintained. Security control of web services across different systems should be provided. Alignment, concurrency and sequencing of the connections across the systems should be facilitated. We plan to solve these technical issues and to establish a distributed service oriented portal-based framework in the future.

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