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Structures for Stepwise Development of Adaptive Supply Chains

Reggie Davidrajuh

ABSTRACT. Falling margins, globalization, and accelerating innova-tion cycles are forcing businesses to switch from traditional (linear and sequential) supply chains to adaptive supply chains that possess the flexibility needed to respond to changing market condition. Developing an adaptive supply chain is no easy task as it is large and complex. In this paper, first, a literature study is given on structures for developing adaptive supply chains; the purpose of this study is to identify the commonly used structures for design and development of some modern supply chain solutions. Second, a new iterative approach to developing an adaptive distribution supply chain is presented.
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KEYWORDS. Adaptive supply chain, distribution chain, transport scheduling, inventory control, service component architecture

INTRODUCTION

Supply chain efficiency is one of the fundamental issues for the survival of enterprises in today's hyper-competitive business environment. In addition, the uncertainties that enterprises are facing these days such as terrorist attacks, labor strikes, sabotage, and weather-related issues make supply chains much more vulnerable. Hence, enterprises need to make use of adaptive supply chains to withstand unpredictable shocks, and to respond to the environment quickly without compromising on operational and financial efficiencies.

Defining Adaptive Supply Chains

A formal definition of an adaptive supply chain is as follows: "An adaptive supply chain is one in which participants are confident in their ability to recognize changing or unanticipated conditions in their supply chain, in a timeframe that allows them to evaluate alternative corrective actions, and react to mitigate the impact to their business. Due to the frequency and volume of supply chain exceptions, the ability to monitor and respond must be highly efficient and at least partly automated. The amount of reserve inventory in a supply chain is usually indirectly pro-portional to the confidence operators have in their ability to recover from supply chain failures without significant impact to schedules, delivery dates, or costs" (World Trade, 2004).

The objective of an adaptive supply chain is to have the highest *visibility*, greatest *velocity*, and best ability to manage *variability* (i2, 2004; SAP, 2002). Visibility is the ability of all the collaborating partners to see vital data; velocity is the speed of information flow across the supply chain; variability is the ability to withstand unpredictable events. Achieving these three objectives is not easy, considering the complexity and diversity of the applications collaborating partners are using. Thus, most supply chain solutions develop supply chains in a stepwise manner, using well-defined structures; some of the commonly used structures are stages, layers, and modules. These will be described in detail in the following.

Scope and Structure of this Paper

The scope of this paper is limited to *structures for developing adap-tive supply chains*. Thus, the usual supply chain issues like production optimization, supplier relationship management, revenues and profit calculations, demand management, customer relationship management, and bullwhip effect are not discussed. The paper concentrates on how an adaptive supply chain can be developed using standardized structures. To this end, a survey on the structures for stepwise development of modern adaptive supply chain solutions is given in the following section. Original work and uniqueness of this paper is given in the section titled "A New Iterative-Based Approach," where a new approach is presented for developing distribution chain structures. This approach uses iterations for variability, a service component architecture based on modules for visibility, and optimal mathematics for velocity.

LITERATURE REVIEW

This section presents a literature review on structures for developing adaptive supply chains. Structures are used to develop supply chains stepwise, but these structures must be a well-defined portion of the system, with carefully defined inputs, outputs, and functions (Silberschatz et al., 2005). In addition, the structures must follow common standards, based on common architecture for seamless integration with the rest of the components. Commonly used structures in supply chain development are:

- Stages (*SAP*, 2002),
- Layers (*Hewlett-Packard*, 2004), and
- Modules (*i2*, 2004).

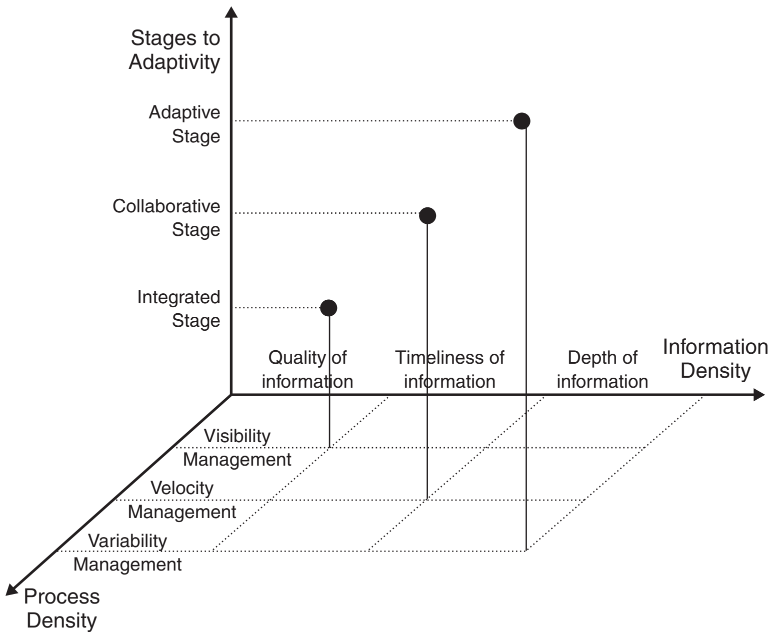
The following section presents some vendor supply chain solutions and the structures they use.

SAP: Development in Stages

The basic design methodology behind SAP's adaptive supply chain is to map the three key process enablers (such as management of visibility, management of velocity, and management of variability) to the three key information enablers (such as quality of information, timeliness of information, and depth of information). The mapping is strength ened in three stages: integrative, collaborative, and adaptive (SAP, 2002) (see Figure 1).

There are three mappings of process enablers to information enablers: First, visibility of quality information is the fundamental building block for adaptive supply chains. This is because visibility of both intra- and inter-organizational information is critical for rapid response to changing market conditions. For example, information visibility of orders, plans, supplies, inventory, and shipments is key to both successfully co-ordinating events across the supply chain and for monitoring and taking proactive actions across the chain. Thus, the first mapping for adaptive supply chain development is the mapping of visibility on information quality.

FIGURE 1. SAP's Supply Chain Development in Stages



The second mapping is to increase the velocity of response by accessing and distributing information rapidly across the supply chain, as velocity of response is the key differentiator in business performance.

Third, depth of information allows enterprises to better manage unpredictability (variability) introduced in the supply chain. This is the final aspect of developing an adaptive supply chain for a dynamic business.

To create an adaptive supply chain, SAP suggests that the enterprise should advance from a traditional supply chain to an adaptive supply chain through three specific stages: integrated, collaborative, and adaptive (SAP, 2002).

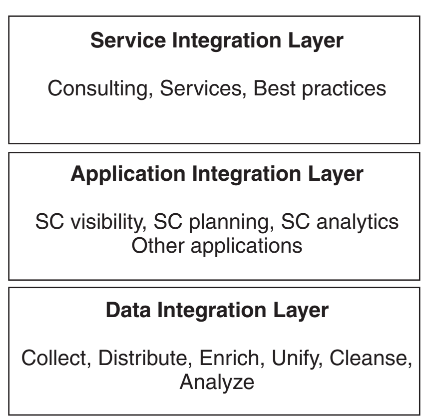
The integrated stage is the first step towards formation of adaptive supply chain, where improvement of the operational visibility and efficiency is accomplished, by integrating diverse applications run by the collaborating partners. The fundamental concept behind the integrated stage is that the extent of integration directly determines the degree of visibility, and that visibility is the basic building block for an adaptive supply chain. In the second (collaborative) stage, the ability of the supply chain to exchange real time information is improved; in other words, the velocity of information is improved. The final stage is the adaptive stage, which is concerned with managing variability.

Hewlett-Packard: The Layered Approach

Hewlett-Packard (HP) emphasizes real time application integration for developing adaptive supply chains (or in HP terminology–the Real Time Supply Chain (RTSC) (Hewlett-Packard, 2004). The RTSC is organized around three layers (see Figure 2):

1. *The foundation layer*: In this layer, the data management component creates a single, consolidated and cleansed repository of key supply chain data from all supply chain applications across the enterprise. Thus, this layer is for increasing visibility of information
2. *The middle layer*: In this layer, the supply chain business application components integrate existing supply chain applications and provides them with a single, real time view of the entire supply chain; in other words, this layer is for increasing velocity of information flow.
3. The upper layer: In this layer, supply chain consulting and integration components provide the services and best practices from HP and its partners in order to manage variability.

FIGURE 2. HP's Layered Approach for Real Time Supply Chain Solutions



In summary, HP develops an adaptive supply chain in three stages: data integration for visibility, application integration for velocity, and finally service integration for variability.

i2: Modular Approach

i2 uses a modular approach for developing adaptive supply chains. The modules can be implemented independently to suit the enterprise's specific needs and pressing business challenges first, enabling gradual implementation. They have six modules for developing adaptive supply chains (i2, 2004):

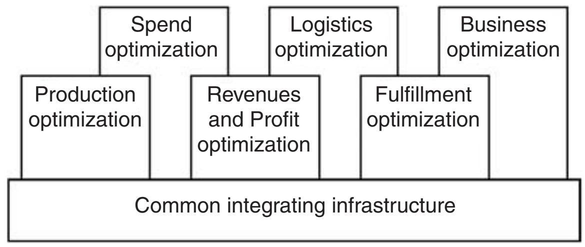
1. Production optimization (meeting the demand in real time),
2. Spend optimization (supplier relationship management),
3. Revenues and profit optimization (demand management, customer relationship management),
4. Fulfillment optimization (real time planning, build-to-order, inventory management),
5. Logistics optimization, and
6. Business optimization (business and process definitions, supply chain analysis).

All these six modules are based on common architecture, common infrastructure, and common parameter-based tools, allowing independent implementation and addition of new functionality. The common integrating infrastructure offers visibility, and the six modules offer velocity (Production optimization module, Fulfillment optimization module) and variability (e.g., Business optimization module, Spend optimization module). The i2 common infrastructure, together with the associated modules, is shown in Figure 3.

Summary of Vendor Approaches

Developing a supply chain in stages allows an enterprise to take the time it needs to do the implementation successfully; the time taken for an enterprise to implement supply chain solutions varies, depending on its degree of technology mastery, the process maturity, and the characteristics of the business. The main advantage of using stages is that each stage provides a functional (even if it is crude, it could still be functional) system. The main disadvantage of the staged approach is that, if a new stage is planned from the current stage, then it is possible that the current stage could not support

FIGURE 3. i2 Six: A Modular Approach



evolution to that stage. This may require a return to previous stages to make the necessary changes (i.e., rewriting code) so that the current stage becomes robust enough to support development of the proposed new stage. Hence, whenever a new stage is planned, this may require modifying several previous stages.

In developing supply chains in layers, the supply chain is broken into a number of layers (levels). The bottom layer (layer 0) is the common integrating infrastructure that connects a supply chain with the commu-nications platform; it is the most primitive layer, offering only basic hardware interface/communication/operating systems services. The highest layer (layer N) is the application layer, interacting with the user and other applications. The main advantage of the layered approach is simplicity of construction and debugging (Silberschatz et al., 2005). The main disadvantage of the layered approach is that a group of layers do not provide a fully functioning system; all the layers (from layer 0 to layer N) are needed to make a functioning system that will offer any services to the user.

Modules give the freedom of selecting and implementing only those modules with specific functions that are needed to take care of pressing business challenges. Though modular implementation resembles the layered approach, modules are more flexible than the layered system in the sense that any module can call any other module (whereas a layer can use only lower-level layers) and that modules can be implemented in any order (whereas lower-level layers must be implemented first).

None of the structures discussed above except the modular structure is adequate for developing an adaptive distribution chain. The reason is that these structures are applicable only for developing internal desktop applications. This does not meet the needs for a truly adaptive supply chain, which is inherently a distributed system.

A NEW ITERATIVE-BASED APPROACH

This section explains the development process for a modern adaptive distribution chain that was designed by the author; this distribution chain is based on *iterations* using *modular components.* It is designed for virtual enterprise environments, and for making strategic and tactical decisions. Definitions for the key terms “virtual enterprise,” “distribution chain,” “strategic decisions,” and “tactical decisions” are given below.

Virtual enterprise. A virtual enterprise is a time-limited (short-term market business-to-business or long-term extended enterprise) collabora-tion between enterprises in which a nucleus enterprise acts as the formulator, promoter, and the principal strategist for the virtual enterprise (Davidrajuh, 2003). The methodology for development of the new distribution chain is addressed to, and biased towards, the nucleus enterprise.

Distribution chain. A supply chain generally centered with the nucleus enterprise can be divided into three parts: supply, production, and distribution (Davidrajuh, 2003). To satisfy customer demand, to maxi-mize profit, and to win the competition in the increasingly globalized economy, the nucleus enterprise must first analyze the market and un-derstand its customer demand. Then, it may begin to plan its production process and organize its supply chain. As the distribution part plays a crucial role in the management of a supply chain, separation of the distribution chain from the supply chain and dealing with it independently is recommended (Ma and Deng, 2002).

Strategic versus tactical decisions. There are three types of distribution chain decisions that can be distinguished. They depend on the time horizon and on the significance of impact on the management of distribution chain: strategic decisions, tactical decisions, and operational decisions (Ma and Davidrajuh, 2005). The strategic decisions consider time horizons on the order of years; operational decisions involves short-term decisions, on the order of days; and tactical decisions fall between those two extremes with respect to the time horizon, and on their impact. This distribution chain deals with both strategic decisions and tactical decisions.

As the revenue of a supply chain is largely related to the places where the retailers are located, selecting retailers according to location can be considered as a strategic decision. Although logistics cost plays an important role in the total cost of a supply chain, it is basically dependent on the location of the retailers, as is inventory control planning. Thus, when designing a distribution chain, the following strategic and tactical decisions must be made:

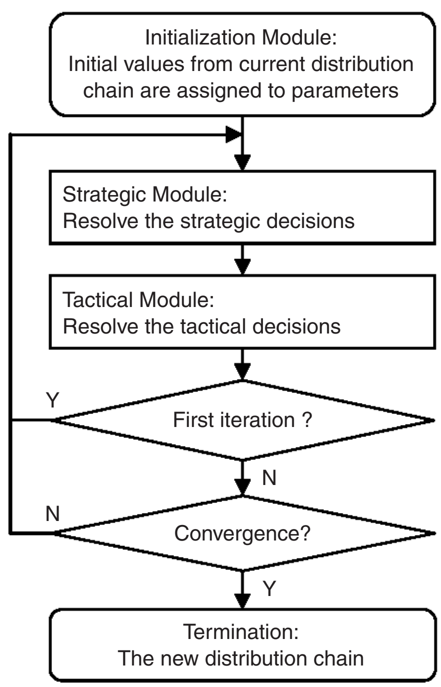
1. *Strategic decision*. Where to locate retailers and wholesalers so as to deliver products to customers efficiently, and maximize profit for the nucleus enterprise?
2. *Tactical decision.* What kind of transportation channels and modes should be used?
3. *Tactical decision*. How many products need to be held at different locations?

The Iterative Approach with Modular Components

Figure 4 shows the proposed iterative approach utilized for developing a new adaptive distribution chain. It also shows the three separate modules that are used for initialization, for making strategic decisions, and for making tactical decisions.

In the initialization module, all parameters (including operations-related parameters) are assigned initial values from the ongoing (and/or from the past) collaboration. Then, in the strategic module, some strategic decisions are made (e.g., optimal number

FIGURE 4. The Iterative Approach



and location of wholesalers and retailers). After this, from the output of the strategic module, tactical decisions can be made (e.g., optimal transportation schedules and routes, inventory control parameters) in the tactical module.

After determining the tactical parameters, the parameter values are input into the strategic module again, starting another re-optimization cycle. Successive design results are compared at the end of each iteration cycle. When there is no remarkable difference between the successive iteration results (iteration results converge), the distribution chain is established.

When market conditions change, there may be changes in the values of some of the parameters such as demand, transportation costs, etc. First, for these new values, the tactical module is invoked (operation related parameters are re-calculated) to adapt to the new market situation. If the resulting operations-related parameter values differ significantly from the older values, then the nucleus enterprise may re-start the iteration cycles until the iteration result converges: at this point, a new distribution chain should be found that is adaptable to the new market.

Optimal Design of the Modules

In an earlier paper, Ma and Davidrajuh (2005) presented complete mathematical details for all these modules (the current paper is concerned with how an adaptive supply chain can be developed by realizing these mathematical details). Rather than repeating these details, a summary is given in the following subsections.

The Strategic Module

The strategic module is concerned with finding the optimal number and location of the collaborators, as the performance of a distribution chain is mainly dependent on its structure (Caputo et al., 2004; Childerhouse et al., 2003) and on the relationships that exist between collaborators (Rahman, 2004; Wu et al., 2004).

The strategic module is modeled with mixed integer programming (MIP) composed of two types of formulae: objective function and con-straints. The objective function of the strategic module is to maximize profit, while the constraints include flexibility constraints, material flow balance constraints, etc. In the objective function, *profit* equals total revenue minus total cost; where only four types of costs are considered:

1. Delivery cost from wholesalers to retailers.
2. Delivery cost from distribution centers to wholesalers.

3. Inventory holding cost at wholesalers.

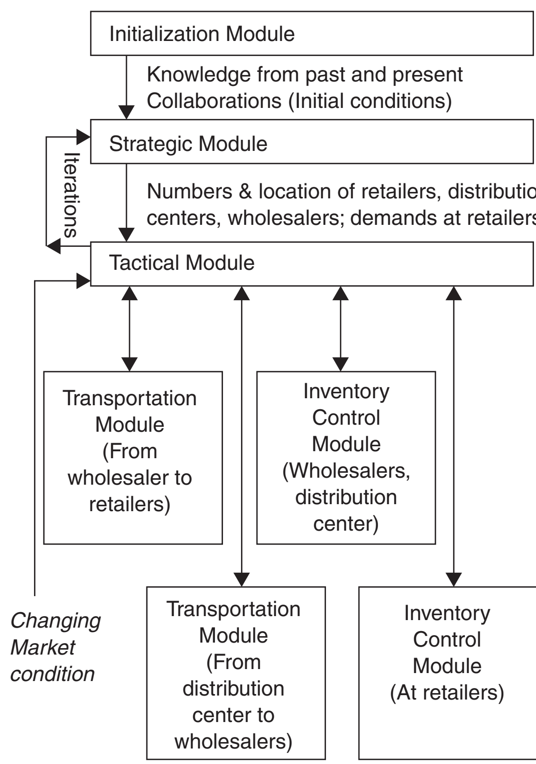
4. Inventory cost at the distribution center.

The Tactical Module

The tactical module is determined on the basis of the output of the strategic module, as shown in Figure 5. The tactical module has the following submodules:

1. Inventory control at retailers.
2. Transportation from wholesalers to retailers.
3. Inventory control at wholesalers and at distribution centers.
4. Transportation from distribution centers to wholesalers.

FIGURE 5. Interactions Between Various Modules



Submodule for inventory control at retailers. According to Tijams (1994), there are mainly two types of inventory control models: periodic review *(R, S)* model and continuous review (*s, Q*) model. For the *(R, S)* model, an order is placed every *R* unit time to raise the inventory level to *S*. For an *(s, Q)* model, an order *Q* is placed when on hand inven-tory is less than or equal to *s*. Ma and Davidrajuh (2005) proposes the use of an *(s, Q)* model for inventory control policy.

Submodule for transportation from wholesaler to retailers. After determining optimal *(s, Q)* for each retailer, transportation between wholesalers and retailers can be planned. In practice, the retailer order quantity is normally small, so it is possible for a vehicle to serve several retailers in one journey. In such situations, the following questions are raised:

1. How to cluster retailers?
2. How to determine routes for vehicles?

Vehicle routing algorithms can answer these questions. At present, there are mainly three types of routing algorithms: heuristics (Tijms, 1994; Christofides, 1985; Viswanathan and Mathur, 1997; Chao, 2002), mathematical programming (Popken, 1994; Wendy et al., 1999), and genetic algorithms (Gabbert et al., 1991; Chen and Gen, 1996; Chen et al., 1998). Ma and Davidrajuh (2005) propose genetic algorithms for routing, for ease of implementation.

Submodule for inventory control at wholesalers and at distribution center. A wholesaler supplies several retailers; adding together random demands at retailers can generate the random demand process at the wholesaler. For the distribution center, the demand parameter determination process is the same one used for wholesalers.

Submodule for transportation from distribution center to wholesalers. Normally, the amount of product demanded by a wholesaler is large. Hence, a vehicle can only serve one wholesaler in its journey. Thus, there is no routing problem in this transportation model (if there is a routing problem, then the mathematical model used for the submodule “Transportation model from a wholesaler to its retailers” can be used). The unit product delivery cost from distribution center to a wholesaler can be calculated by summing together the unit loading cost at the distribution center, the unit transportation cost from distribution center to wholesaler, and the unit unloading cost at the wholesaler.

From Design to Development

This subsection describes how the proposed distribution chain can be developed as a business application, using Service Component Architecture (SCA). SCA is based on Web services (WWW, 2005). Beisiegel et al. (2005) and Beatty et al. (2003) explain its concepts.

Service Component Architecture

A model of a business application (known as the "SCA Assembly Model") consists of a series of artifacts: The basic artifact is the *module*, which is the unit of deployment for SCA and which holds *services* that can be accessed remotely. A module contains one or more *components*, which contain the business logic (function) provided by the module. Components offer their function as services, which can either be used by other components within the same module or which can be made available for use outside the module through *entry points*. Components may also depend on services provided by other components–these dependencies are called *references*. References can either be linked to services provided by other components in the same module, or references can be linked to services provided outside the module, which can be provided by other modules. References to services provided outside the module, including services provided by other modules, are defined by *External Services* in the module. *Wires* represent the linkages between references and services.

Building a business solution can proceed as follows:

1. *Component building*. The implementation of components which provide services and consume other services.

2. *Module building*: Components are assembled together as modules;

   Modules are deployed within an SCA System. An SCA System represents a set of services providing an area of business functionality within a single organization (e.g., inventory control in distributor i).

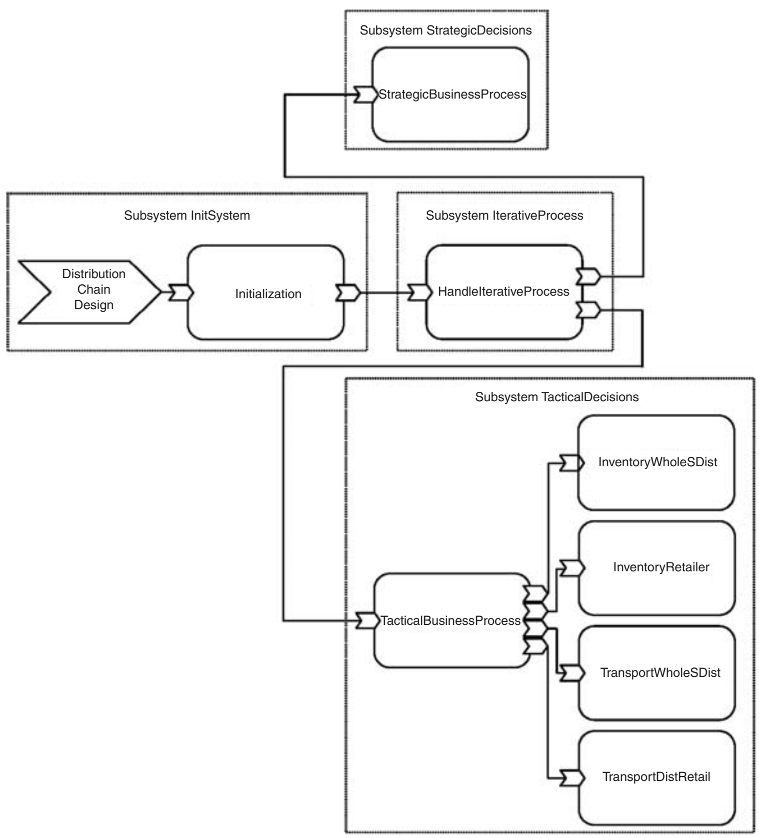
3. *Subsystem building*. To help build and configure an SCA system, subsystems are used to group and configure related modules. Sub-systems contain *Module Components,* which are configured instances of modules. Subsystems, like modules, also have Entry Points and External Services. Subsystems can also contain Wires that connect together the module components, entry points and external services.

4. *System building*. The assembly of subsystems to build the business application through the wiring of service references to services; that is, the subsystems are then linked together to form a cohesive solution.

Model of the Proposed Distribution Chain

Figure 6 shows the assembly model of the proposed distribution chain. The system consists of four subsystems: the first subsystem is the *InitSystem*, which is the Entry Point of the system. *InitSystem* has only one module component called *Initialization*, which loads the necessary

FIGURE 6. The System Assembly



enterprise data and market data through Service Data Objects (Beatty et al., 2003); for brevity, these details are not shown.

The second subsystem is the *IterativeProcess* subsystem that is responsible for executing the iterative process. The module component *HandleIterativeProcess* of this subsystem realizes the iterative process by starting the iterative process for the first time, getting the services of the necessary subsystems (*StrategicDecisions* and *TacticalDecisions*) during successive iterations, and finally, terminates the iterative process when it converges.

The third subsystem is the *StrategicDecisions* subsystem that will compute the strategic design values. This subsystem has a component module called "StrategicBusinessProcess," which is the realization of the business logic represented by the strategic module in Figure 5.

The fourth subsystem is the *TacticalDecisions* subsystem, which is responsible for computing tactical values. For this purpose, the subsystem gets the services of four other module components: *Inventory WholeSDist* (meaning inventory control at wholesalers and distribution centers), *InventoryRetailers* (inventory control at retailers), *Transport-WholeSDist* (transport scheduling from wholesalers to distribution centers), and *TransportDistRetail* (transport scheduling from distribution centers to retailers).

According to Figure 6, the subsystem *TacticalDecisions* gets the services of the four other modules locally. However, an alternative design may place these four module components as remote service references to *TacticalDecisions*.

Advantages of the New Iterative-Based Modular System

The main benefits of the proposed distribution chain are discussed in the following section. The benefits are grouped under the three basic criteria of adaptive supply chains: visibility, velocity, and variability.

Visibility of key data by all collaborating enterprise is increased because:

- Modular components of the distribution chain integrates data across enterprises. In principle, every component is reusable, independent of its context. This means that a component representing a module should be ready to be used by any other components (modules) running at a remote location. Clients of a component do not need any knowledge of how the component is implemented; they need to know only the interface to the component. As long as the interface remains unchanged, a component can be modified without affecting the clients (Wang and Qian, 2005; Kozaczynski, 1999).

- Service component architecture (SCA) supports data integration and offers many benefits for data integration: infrastructure capability (separation of business logic from infrastructure capabilities by providing infrastructure capabilities like Security, Transactions, Messaging, etc.), programming language independency (separation of service interfaces from service implementation), diverse invocation mechanism (Web services, Messaging, CORBA IIOP, etc.), diverse programming styles (asynchronous message-oriented styles, synchronous RPC style), etc. Beisiegel et al. (2005) and Beatty et al. (2003) give an overview of SCA and its benefits.

Velocity (speed of information flow across collaborating enterprises) is increased by:

- Optimization algorithm: When designing the modular components of the distribution chain, the most suitable algorithm and proper mathematics must be used for each module. These modules will be executed independently by different collaborators in different places. Hence, maintenance and further improvements of these modules can also be done independently. Thus, there is no need to design all these modules with the same mathematical approach, but with the most appropriate approach that will optimize performance of the module.

Variability (withstanding unpredictable events) is increased because:

- An iterative approach offers adaptability. Analyzing the agile na-ture of the global market reveals that the distribution chain should be designed in iterative cycles, so that the distribution chain can be continuously fine tuned to quickly changing market conditions.
- Structured line of business offers agility. With the SCA, the distribution chain is designed as a series of services. By structuring applications as a series of services, IT assets become more agile and enterprises are better able to adapt to the dynamic business environments.

CONCLUSION

In the section titled "Literature Review," a survey was presented on the structures used for developing some of the well-known modern adaptive supply chain solutions. The structures used in these supply chain solutions were stages (e.g., SAP), layers (e.g., HP), and modules (e.g., i2). Although a supply chain solution may use any structure (stage, layer, module, iteration, etc.) as the basic building block to ease supply chain development, it must aim to provide the basic characteristics of adaptive supply chains–namely *visibility*, *velocity*, and *variability*.

To build an adaptive distribution chain, which is inherently distributed, the structures mentioned in "Literature Review" are not adequate enough. Thus, in the section "A New Iterative-Based Approach," a new approach for developing adaptive distribution chain was presented. This distribution chain development approach uses service component architecture based modules for visibility, optimal mathematics for velocity, and an iterative approach for variability.

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