An Agent Federation for Supply Chain Integration

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Abstract

Supply chain management represents a critical competency in today's global business environment, but neither commerce through EDI technology nor current Web applications satisfy combined requirements of process integration and flexibility. The present research builds on prior agent work to argue multi-agent systems offer tremendous potential and capability to overcome such limitations. The paper discusses enterprise supply chain integration and outlines the knowledge engineering techniques employed to implement a corresponding agent federation for high-technology product procurement. It highlights the use and utility of this supply chain agent federation and presents results of early verification and validation testing.

Supply Chain Integration

Supply chain management (see Porter and Millar 1985) represents a critical competency in today's global business environment, and a number of effective practices (e.g., just-in-time deliveries, electronic data interchange (EDI), supplier inventory management) are employed to improve the competitiveness and efficiency of enterprises around the world. Our two decades of experience with EDI suggest commercial processes employed by buyers and sellers must be mutually-compatible in order for business exchanges and transactions to occur effectively, and for rapid purchase and responsive order fulfillment, buyer and seller processes must also be closely integrated (Sokol 1996).

The process-integration task is now routinely enabled through EDI technology for many major corporations and government agencies. But not only can it be expensive, this technological approach requires a relatively stable and predictable commercial environment to effect supply chain integration. Such conditions are increasingly unlikely in the fast-paced, hypercompetitive business environment of today (see D'Aveni 1994). And modern enterprises now also require flexibility to quickly change vendors and adapt to dynamic economic conditions and diverse commercial practices (see Davidow and Malone 1992). Commerce through EDI technology does not satisfy the flexibility requirement well.

One approach is to replace EDI with more flexible technology. For instance, with the continuing surge of activities on the World Wide Web (Web) and corresponding research on electronic commerce, many firms are moving to Web-based support for commercial transactions (e.g., electronic catalogs, virtual supply chains and storefronts, intranets/extranets). Indeed, the Internet offers good potential to "revolutionize procurement" and related commercial activities (Gebauer et al. 1998), and Web-based transactions are beginning to supplant the traditional EDI for some business-to-business and business-to-consumer commerce. However, much of the capability for supply chain integration is being lost during the transition from EDI to Web technology. Whereas EDI effectively compels buyers and sellers to integrate their supply chain processes, Web-based supply chain technologies are noticeably one-sided; that is, the latter sites and applications are predominately developed for *either* the buyer or seller, but not both. Commerce though current Web technologies does not satisfy the integration requirement well.

The present research builds on work by Barbuceanu and Fox (1993) and others (e.g., Collins et al. 1998, Gini and Boddy 1998, Rodriguez-Aguilar et al. 1998, Walsh et al. 1998, Wurman et al. 1998) to argue intelligent agents offer tremendous potential and capability for *both* buyer-seller process integration and supply chain flexibility. And multi-agent systems may be able to *both* disintermediate and integrate the supply chain in a cost-effective manner. With the capability to formalize and embed domain-specific knowledge and market-specific expertise in multi-agent systems, this emerging technology offers potential to substitute federations of intelligent agents for the bureaucratic and expensive intermediaries now employed along most major enterprise supply chains. It may also provide the same kinds of value-added services expected from other intermediaries, but without the attendant cost and time associated with human labor.

Agent Supply Chain Integration

This present work builds upon and extends research by Mehra and Nissen (1998) to implement and demonstrate an agent development environment, and by Nissen and Mehra (1998) that explores process redesign enabled by intelligent-agent technology. Two primary processes are involved with a supply chain—customer purchasing and vendor order fulfillment. Although these customer and vendor processes can be viewed as separate, intra-organizational activities within each of the respective buying and selling enterprises, a strong case can be made for viewing such activities *together*, as an integrated, inter-organizational supply chain process.

Clearly, before agents can be equipped with knowledge required for supply chain integration, their designers must first acquire the requisite knowledge. This is the essence of knowledge engineering, the requirement for which is not much different for multi-agent systems than their expert system counterparts from two decades ago. We present and discuss two, complementary process instances—procurement and order fulfillment—in terms of a single, integrated whole; that is, both purchasing and order fulfillment are modeled as a single process that spans organizational boundaries. Specifically, the university purchasing process examined through this investigation pertains to work done by the procurement department at a graduate educational institution on the West Coast. As an educational institution, this university facility is subject to the full complement of procurement policies and procedures that govern the purchasing activities of most university organizations. The commercial order fulfillment process examined through this investigation pertains to work done by the product and licensing department at a leading high-technology company on the East Coast. This company is a leader in its product market and maintains an active research and development activity that drives frequent introductions and updates. Therefore it maintains the kind of rapid product evolution that has been problematic for procurement in large enterprises such as the university.

The high-level process delineated in Figure 1 depicts the integration of the user, university procurement department and commercial contractor. The author has invested several months' effort acquiring detailed knowledge associated with this process. Knowledge acquisition techniques include document analysis, personnel interviews and direct process observation. One advantage of research in the procurement domain is the process activities tend to be well documented, including, for example, detailed procedures used to guide the day-to-day activities of university procurement specialists. This expedites the knowledge engineering process considerably.

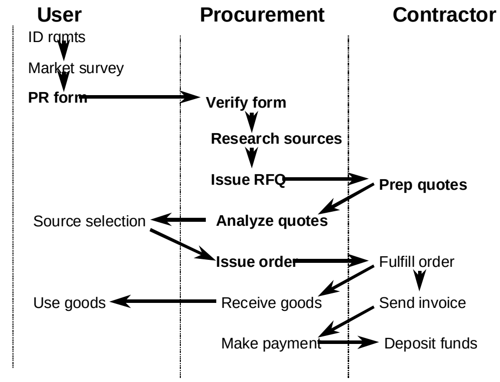

Figure 1 Integrated Supply Chain Model

Not apparent from the figure is the underlying knowledge, expertise and information required for people to perform the purchasing and order fulfillment processes depicted, knowledge which is critical for either disintermediation or integration, human or otherwise. For example, the user must know how to conduct a market survey and have access to information listing alternative sources of supply, as well as an understanding of the basic procedures for university procurement and information pertaining to the specific purchase-request forms used. We note most major corporations, government agencies and other large enterprises have no shortage of like procurement procedures and forms.

Similarly, the buyer must know how to review the purchase request (e.g., what constitutes completeness, when to request additional information) and have current information pertaining to alternative sources of supply—sources which often appear, combine, shift direction and disappear frequently in high-technology markets. This, too, reflects much corporate and government agency procurement, as laws and regulations for inter-state and international commerce can be quite complex and many product markets are now dynamic and unpredictable. The buyer must also have access to one or more suppliers' systems to be able to distribute the RFQs (e.g., by telephone, fax, e-mail, EDI, electronic bulletin board) and requires knowledge of the procedures required for quotation analysis and source selection. Access to and understanding of the receiving and payment systems and procedures is also necessary to complete the transaction. And of course, vendor personnel must understand the policies, procedures and systems associated with price quotation, order fulfillment and billing activities. These kinds of knowledge, expertise and information are used to specify and enable autonomous and flexible behaviors of an intelligent agent federation, essentially by integrating straightforward object and rule-based technologies in conjunction with Grafcets and an agent-development environment.

Supply Chain Agent Federation

Design begins with the process itself, reflecting our emphasis on the organization as well as agent technology. Recall the integrated supply chain process from above. Of the sixteen activities delineated in Figure 1, we assess the knowledge engineering difficulty of each and designate seven of them (highlighted in bold in the figure) for performance by intelligent agents. For reference, these include completing the PR form, procurement department verification, researching alternative supply sources, issuing RFQs, quotation preparation by vendors, quotation analysis by the customer, and issuing the ensuing order by the respective procurement and vendor organizations. Notice these activities span responsibilities of the user (e.g., completing the PR form), procurement department (e.g., issuing RFQs) and vendor (e.g., preparing quotations). This is key to supply chain integration and moves the agent application far beyond just automating activities of the procurement department. Although some commercial exchange activities such as invoicing, payment and funds deposit also clearly lend themselves to electronic intermediation, our greater interest lies in the activities not currently performed through such traditional technologies as EDI. Indeed, EDI support of such activities is now so routine and well understood, we no longer even consider it to represent "research."

We employ Grafcets to describe the structure and behavior of intelligent agents. Grafcets are derived from work on Petri Nets (e.g., see Murata 1989) and have been accepted as an international standard (IEC 848 and IEC 1131-3) for specification of programmable logic controllers (David 1995). Grafcets define—explicitly and unambiguously—each step and transition associated with process performance, along with all internal rules and procedures, external events and alternative system states that affect reasoning, decisions and behaviors represented for a process.

Using a research prototype for agent development (see Mehra and Nissen 1998), Grafcets can be represented and developed graphically, and both transitions and steps are implemented through objects, rules, methods and procedures; that is, below the agent level of abstraction, familiar object-oriented analysis, design and programming approaches and techniques apply. The agents are implemented in Java, so their execution is platform independent. And they operate using common Internet protocols (e.g., TCP/IP), so agent mobility has potential to span the global network itself. Current work to implement a Web interface to these supply chain agents enables remote instantiation and control. Thus, not only can such agents travel and execute broadly, but users and developers with Web access have the ability to create and employ agents worldwide.

Our agent-based supply chain implementation involves three Grafcets—two for the vendor and one for the user. Notice this explicitly omits the role of intermediary (e.g., procurement department). Each of the corresponding agent classes inherits architectural, design and communication properties and capabilities from a common superclass (supply chain-agent) and is developed to be explicitly tailorable to reflect specific rules, priorities and preferences within the context of each individual in the organization; that is, we develop agents (classes) that are domain-specific but relatively general and highly tailorable. This allows for commonality of design at the architecture and agent-federation levels but near-absolute flexibility over instantiation and usage of the agents.

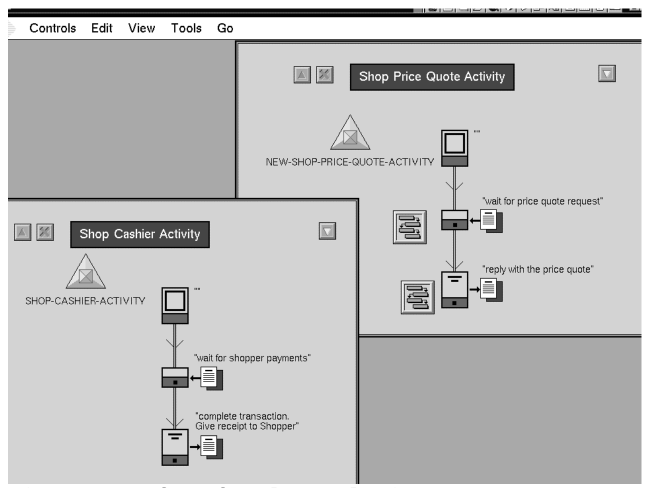

Figure 2 Grafcets for Shop Behavior

The first Grafcets, presented in Figure 2, map roughly to the contractor activities from Figure 1. For instance, the "shop" agent's activity flow begins with the Grafcet at the top right of the figure, which specifies price-quotation behaviors. The agent essentially waits for a quotation request to arrive and then branches to respond with a price quote. The Grafcet at the bottom left of the figure concludes the shop agent's activity flow with cashier or check-out behaviors. The cashiers await customers wishing to exchange money for goods in the shop.

It important to note the agents are multi-threaded by design. For instance, shop agents can do more than just wait for incoming price and availability requests (i.e., RFQs) or check-out needs from a particular shopper. Indeed, each shop agent in this supply chain can simultaneously "listen" for RFQs from any number of potential customer agents (human or machine) while preparing any number of quotations in response to others, helping still other shopper agents fill orders and serving their asynchronous or simultaneous check-out needs. Further, each agent can operate autonomously, in such a multi-threaded manner, and an arbitrary number of instances or clones can execute simultaneously on any number of networked processors. Thus, the agent architecture is extremely scalable, yet each process implementation remains customizable at the level of an individual in the organization. We know of no comparable technology offering such combined scalability and flexibility for supply chain integration.

The shopper behavior is specified through the Grafcet presented in Figure 3. As inferred above, each user can create and specialize any number of different shopper-agent instances to reflect various priorities and preferences. For example, one shopper-agent may specialize in office computer hardware and look for inter-application compatibility and price as primary evaluation criteria. Another shopper instance, created to serve this same user, may in turn be specialized to focus on server systems, for which power, functionality and platform support may be specified as more important evaluation criteria for use by the autonomous agent. Clearly, a great many other preferences and priorities (e.g., availability, support, company reputation) can be specified in a similar manner, for this particular user and any variety of different principals. The shopper Grafcet incorporates the necessary knowledge and behaviors of both the user and procurement department from above. This represents the integration step. All the knowledge and expertise required for the shopper to procure goods and services—without intermediation—is embedded into this supply chain federation of agents specialized to shop for specific items or in given markets.

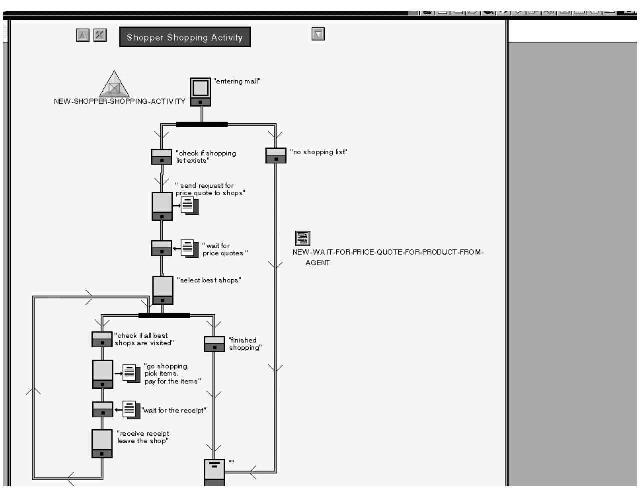

Figure 3 Grafcet for Shopper Behavior

As the name implies, the agent employs a supply chain metaphor for supply chain integration. A supply chain representation is presented in Figure 4 through three (virtual) shops characterized by network locations (i.e., IP addresses) and shop agents. This supply chain is truly virtual, in that the "shops" do not reside in any single physical location. Indeed, the shops do not necessarily exist physically at all. What does exist is a shop agent created to represent some vendor interested in participating in commerce through this medium. We refer to this application as an "intelligent supply chain"—as opposed to the more common "virtual supply chain" name—because it offers more than just virtual shopping; that is, every entity in this environment possesses (artificial) intelligence, and the agent federation is performative, offering the capability of autonomously shopping on behalf of customers as well as selling on behalf of vendors.

Clearly, each shopping agent can be instantiated with a unique shopping list of items to buy, and the user can view a list of all items currently registered and available in the supply chain. Other knowledge and information—such as user preferences and budget restrictions, product requirements and need dates, and consumer heuristics like price comparison—are captured by the agents. The shopping agents also allow each user to specify how price and non-price factors (e.g., product capability, availability) are to be compared, and some architectural features are provided with all agents, such as avoiding inter-network trips if items can be purchased "locally" for the same terms and consolidating all items purchased at one location on a single "trip."

Referring again to Figure 4, it also shows some animation of the shopping activity itself. Each shopper agent sends messages to all shops in the supply chain to see which vendors have for sale the items on their shopping lists. This is equivalent to sending RFQs. Shop agents wishing to sell the requested items will reply to the corresponding "RFQ" messages, providing the specific information requested (e.g., one shopper may only be concerned with price, another may be concerned only with capability, a third with both price and availability). Each shopper agent analyzes the quotes and determines a preferred source for each item, based on the user preferences and vendor information received along with travel costs (e.g., network distance) as appropriate.

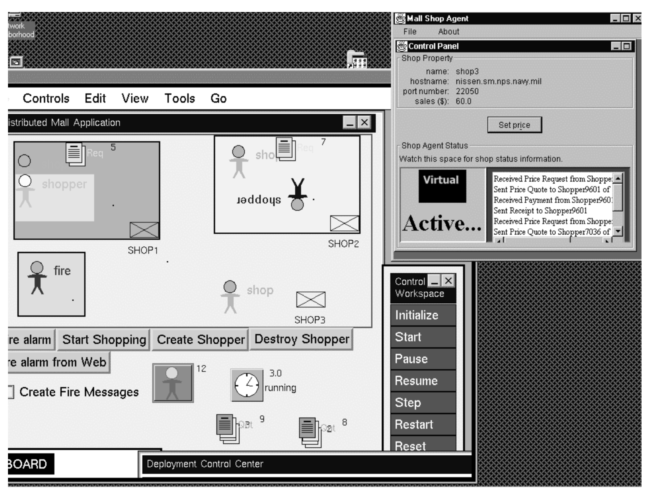

Figure 4 Supply Chain User Interface

Each shopper agent then performs some planning to determine which shops to visit in which order and consolidate multiple items purchased from each shop into a single trip. Notice the one shopper agent is inverted. Such behavior is explicitly required by "regulation" in this supply chain environment when juice is purchased, and although humorous, it serves to demonstrate the intelligent agents can be specified to conform to various procurement regulations. Although difficult to see without animation, the other agent is currently "jumping" up and down, which represents the local custom when shopping at Shop 1. Similar to the regulation-conforming behavior from above, this shop-specific behavior serves to demonstrate the intelligent agents can also be made sensitive to local variations. The number and kinds of such behaviors that can be specified through intelligent agents are limited only by the knowledge engineer's ability to capture and formalize them via objects and rules.

When all items have been purchased from a given shop, the shopper agent proceeds to the "exit," where token messages are exchanged to symbolize making payment and issuing a receipt. Each shopper then moves to the next shop on its shopping route, purchases the corresponding items, and continues in this fashion until all items have been purchased or no vendors are available to sell items still on the list. This latter condition obtains in such a dynamic supply chain, for although an item may be available when the agent *plans* its shopping route, there is no guarantee the item will not subsequently be purchased by another shopping agent, or even that the shop agent will not "close" before the shopper reaches this destination. The dynamic and emergent behaviors associated with this distributed, intelligent application—particularly where intelligent, autonomous agents are free to roam the network and conduct their business as they see fit—are very rich and can be made quite realistic. Clearly, where such an intelligent supply chain is employed for *bona fide* commercial transactions, the behaviors become very real indeed.

Results thus far from our experience with supply chain agents focus principally on feasibility; that is, we find evidence the multi-agent system approach to virtual supply chain integration is technically feasible, and we gain insight into both common and unique requirements associated with development and implementation of intelligent agent federations. First of all, the intelligent supply chain application serves to demonstrate it is feasible to integrate a supply chain through an agent federation. Through several months of verification testing and observation, the supply chain application has been allowed to run continuously for several days without problems of system instability, agent indecisiveness or other maladies that can affect such distributed, intelligent computing applications (see Wooldridge 1998).

Further, we have verified a number of critical multi-agent characteristics: both shop and shopper agents can be created, cloned and specialized through "mouse-clicks" and simple forms; agents send, process and receive the appropriate messages, to and from the correct parties at the right times; agents make correct and justifiable purchasing decisions, conform to diverse context-specific regulations and customs, effectively plan and execute network shopping trips and keep principals apprised of key milestones; and the agents either return or destroy themselves as planned and on schedule. In short, verification testing has demonstrated all technical capabilities expected for this proof-of-concept multi-agent system.

Conclusions

Intelligent agent technology offers good potential to integrate supply chain processes more closely than current Web technologies, but without the rigid inflexibility associated with EDI applications. Viewing the respective procurement and order fulfillment processes of buyer and seller as an integrated whole along the supply chain, we identify opportunities for supply chain integration using agent technology and develop a proof-of-concept agent federation to examine the feasibility and performance implications of this approach. Launching and operating long-lived, autonomous, intelligent agents at several locations across both local and wide area networks, and observing the agents performing their delegated supply chain tasks as prescribed, we conclude first of all that agent-based supply chain integration is feasible.

Although agent-development tools and technologies are only just beginning to emerge and take form, the kind of agent-integrated supply chain investigated through this research appears to be inherently scalable yet customizable to the level of a specific organization or individual. Thus, an intelligent agent approach to supply chain integration also appears to generalize well beyond the specific university procurement process studied here, across to a wide variety of corporations, government agencies and other enterprise forms. Further, because the context of this study (i.e., university procurement of high-technology products) is noted as particularly challenging, the positive results of this investigation should extend to other organizations and processes with even greater feasibility and potential. Indeed, the agent-based supply chain implementation examined in this paper appears to offer good potential for improved process performance, both in terms of cost and cycle time.

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