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Abstract

This paper presents a conceptual design *a*n agent-based *workflow management system capable of adapting to the underlying structure of the business process through the use of organizational self-design. This design approach "bridges the gap" between designs based on centralized or decentralized coordination structures and provides a synthesis of these two structural extremes. Perhaps less tangible, but of no less significance, are contributions to the understanding of the temporal role of hierarchy within intelligent workflow management systems. At the core of this research is an examination of the role of hierarchy within the coordination structure of intelligent workflow management systems and the feasibility of developing a system that is capable of altering the hierarchy in response to the business process.*

Introduction

Workflow management systems are systems used to manage the flow of work items through a business process. Workflow management systems, with origins in office automation and document imaging systems, have evolved from managing repetitive transaction-based business processes to managing ad hoc knowledge-based business processes. The rapidly increasing complexity of workflow management systems has prompted considerable interest in the application of intelligent agents to the various components that compose workflow management systems. As the intelligence of these components increases, each component becomes capable of making decisions that affect the overall performance of the system. The integration and coordination of autonomous decision-making components is a fundamental research issue in the design of intelligent workflow management systems.

This paper presents a conceptual model of a workflow management system capable of adapting to the underlying structure of the business process through the use of organizational self-design.

Literature Review

The nature of this research suggests an interdisciplinary approach. The literature review begins by establishing formal definitions from the field of workflow management systems. Next, an overview of intelligent agent research is presented, with particular emphasis on the concept of organizational self-design. Recent intelligent agent-based workflow management systems are then presented. Finally, the structure of business processes is examined.

Workflow Management Systems

The Workflow Management Coalition (WfMC), an international organization of workflow vendors, users, analysts and university/research groups, provides definitions for terms used in workflow specifications. In order to understand the underlying concepts of workflow management systems, familiarity with common terms such as workflow, workflow management system, business process, activity, and work item is critical.

A workflow management system provides procedural automation of a business process through the management of workflows by software whose execution is ordered by the appropriate activity steps, or workflow logic (Hollingsworth 1995). In order to clarify the above explanation, the terms "business process" and "workflow" must be defined.

A business process is a set of one or more linked procedures or activities that collectively accomplish a business objective or policy goal, normally within the context of an organizational structure defining functional roles and relationships (WfMC 1999). An activity is one of the logical steps that make up the business process, i.e., a business process generally consists of many process activities that are logically related in terms of their contribution to the overall realization of the business process. Each activity may generate one or more work items, which together constitute the task that must be undertaken by a participant within the activity (WfMC 1999).

A workflow is the computerized facilitation of a business process where documents, information, or tasks are passed between participants according to a defined set of rules in order to achieve or contribute to an overall business goal (Hollingsworth 1995). This leads to the formal definition of a workflow management system: A system that defines, creates and manages the execution of workflows through the use of software, running on one or more workflow engines, which is able to interpret the process definition, interact with workflow participants and, where required, invoke the use of IT tools and applications (WfMC 1999).

Intelligent Agents

Intelligent agent-based approaches to software support systems are believed to provide an unparalleled technology for integrating people, materials, and capital equipment. Software agents can be used to automate mechanization strategies for reducing the information content of work. As such, software agents diminish the need for utilizing humans to do repetitive, programmable tasks.

The purpose of studies of communities of intelligent agents is to ascertain their ability to accommodate flexible, agile organizational structures that can respond rapidly to changes in the marketplace, can increase throughput, reduce costs and improve quality. This paper presents a conceptual prototype for agent-based structural self-design and describes experiments conducted regarding such studies together with the results that were obtained.

Increasingly, the productivity of complex, global enterprises is limited not by labor or capital, but by information. Getting a product rapidly to market, for example, depends on hundreds of interdependent decisions by as many individuals. Agent-based approaches to semiconductor manufacturing planning and control have been suggested as a solution to this need (Pan & Tennenbaum 1991). Agents are intelligent objects capable of reasoning about and responding to their environments. They represent and act on behalf of real objects in the "real world." Agent architectures often build upon object-oriented paradigms. Such computerized constructs are believed to provide an unparalleled technology for integrating people, materials, and capital equipment in manufacturing environments. This integration leads to greatly reduced times-to-market, significantly higher productivity, to lower costs and to reduced information content of the work. Agents can invoke other agents to provide services, can decide on the sequencing of a set of activities, can direct the work of resources (humans, machines), can expedite one or more activities when needed and can call upon the services of humans.

Intelligent agent research is concerned with "analyzing and developing intelligent communities [of agents] that comprise collections of interacting, coordinated knowledge-based process' (Gasser 1991, p. 108)." The advantages of modeling a system as a collection of intelligent agents rather than as a single monolithic system are: system modularity, efficiency, fast computer architectures, heterogeneous reasoning, multiple perspectives, distributed problems, and reliability (Rich & Knight 1991).

A principle concern in intelligent agent research is the coordination of intelligent agents for the purpose of achieving system objectives. Organizational self-design (OSD) provides a means by which a system of problem solving agents may dynamically alter their architecture as a function of the problem-solving situation (Corkill 1983). The problem solving system must develop an initial organizational architecture and as problem solving progresses (Corkill 1983, p. 6):

> Monitor for decreased effectiveness caused by [an] inappropriate organizational [architecture];

Determine plausible alternative [architectures];

Evaluate the cost and benefits of continuing with its current [architecture] versus reorganizing itself into one of the alternatives; and

Carry out reorganization if appropriate.

Ishida, Yokoo, and Gasser (1990) use OSD to develop a distributed expert system capable of real-time adaptation, through the introduction and removal parallelism, to a dynamically changing environment. To accomplish reorganization, two reorganization primitives are introduced; composition and decomposition. When the arrival rate of problem solving requests, or the complexity of the problems, reaches a specified threshold, a single agent decomposes into two or more agents to increase parallelism. As the arrival rate or complexity decreases, two or more agents compose, or combine, into a single agent to achieve efficient utilization of computational resources.

Ishida, Gasser, and Yokoo (1992) suggest that the decomposition and composition primitives may be expanded upon. Decomposition may involve, as previously described, the decomposition of one agent into two or more to increase parallelism or by transferring knowledge from one agent to another. Ishida et al. (1992) liken this to the difference between hiring a new employee and transferring an existing employee. Composition may be accomplished by combining two or more agents into a single agent to conserve resources or by simply destroying an entire agent.

Intelligent Agent-Based Workflow Management Systems

Vaishnavi, et al, advocate the use of "smart objects" for the implementation of workflow management systems, noting that a workflow management system is a "distributed knowledge based system because it uses knowledge about procedures and rules that apply in different locations within the organization (1996, p. 2)." They further describe a workflow management system as a reflective system in that the "smart objects" must monitor their own behavior and adapt that behavior to the workflow. Harkar and Ungar (1995) advocate an agent-based workflow management system with workflows and resources participating in a true economic marketplace. Their research uses optimization, control theory, and game theory to examine market behavior and address questions regarding bidding and assignment procedures.

Ottaway and Willis (1996) suggests the use of intelligent agents to represent both workflows and organizations resources. In their research agents representing organizational resources may call upon the services of "manager" agents thus allowing for a global view of resources. They suggest that such an approach facilitates global optimization. In Judge, et al, (1998) agents again represent both workflows and resources and negotiate with one another to govern the distribution of work. In this research, agents may collaborate to perform real-time exception handling thus improving the flexibility of the workflow management system. Sheperdson, et al, (1999) stress the use of industry standard components, such as Java and the Common Object Request Broker Architecture (CORBA), in what they describe as an agent enhanced workflow management system.

Kramler and Retschitzegger (2001) present a flexible workflow management system in which agents are capable of adapting pre-planned workflows to a dynamically changing environment. This is accomplished through the implementation of adaptive agents, a support system to recommend alternative operations, and a knowledge management system which captures these alterations to the workflow so that they may be used when similar situations are encountered.

Business Process Structure

As previously described, a business process is a set of one or more linked procedures or activities that collectively accomplish a business objective or policy goal. The structure of business processes has been an area of study since Thompson's (1967) seminal work more than thirty years ago. Thompson (1967) describes three structures possible within a business process; pooled, sequential, and reciprocal. A pooled structure is one in which the interdependency of activities within a business process are such that each activity must be completed but no activity is dependent on any other activity within the business process. A sequential structure takes a serial form in which the output of one activity becomes the input to the next. Finally, a reciprocal structure is one in which the output of one activity become the input for the next activity of which the output becomes an input to the first activity and vice versa. Figure 1 depicts these three types of structures:

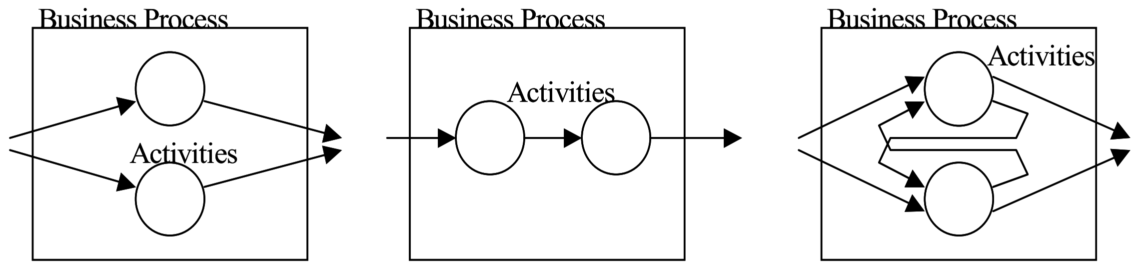

Figure 1. Business Process Structures

Crowston (1997) applies coordination theory to organizational process design in the context of what may be viewed as a workflow management system, the coordination of the software change process. Malone, et al. (1998) provide an authoritative guide to organizational processes. Aalst (2002) maintains a web-site which, when last visited, contained 21 control-flow patterns for realizing workflow processes.

A Conceptual Model of Structural Adaptation in Agent-Based Workflow Management Systems

This section presents the conceptual model of process adaptation in agent-based workflow management systems. First, the desired system behavior of the adaptive system is specified. Once the desired system behavior is specified, knowledge-level concepts necessary to support the desired system behavior are introduced. Having established the knowledge-level concepts, symbol-level concepts are introduced. The symbol-level concepts provide a framework for encoding the knowledge-level.

System Behavior

Academic and practitioner research into the coordination structure of agent-based workflow management systems has focused on the structural extremes; centralized coordination structures and decentralized coordination structures. Yet, as Ishida et al. have shown, it is possible to construct intelligent systems that do not strictly adhere to either of these extremes. This raises the possibility of developing an intelligent agent-based workflow management system that can dynamically alter its coordination structure and thus synthesize the desirable attributes of centralized and decentralized coordination structures. But what are the desirable attributes of centralized and decentralized coordination structures? In a dynamically adaptive system, should one coordination structure be favored over another? Under what conditions should the system make the transition from one coordination structure to another? These questions are addressed in the following paragraphs.

Attributes of Centralized Systems

Centralized coordination structures allow for global control within an agent-based workflow management system. Such control is required within an agent-based workflow management system to facilitate optimization. The need for the hierarchical decomposition of planning and control within information systems has been widely recognized. Three common levels of decomposition are based on dimensions of time horizon, level of management involvement, scope, source of information, level of detail of information, and degree of uncertainty. These three levels are referred to as strategic planning, tactical planning, and operational control. Strategic planning involves such broad activities as investment in new facilities, expansion of existing facilities, and facilities design. Tactical planning is concerned with the effective allocation of resources taking into account costs and revenues associated with the business processes. Operational control addresses day-to-day activities such as the sequencing of work orders and the assignment of tasks or activities to resources. Such a system "although essential, cannot be made without decomposing the elements of the problem in some way, within the content of a hierarchical system that links higher level decisions with lower level ones in an effective manner, and in which decisions that are made at higher levels provide constraints for lower level decision making" (Hax 1974, pp. 235-236).

Attributes of Decentralized Systems

Decentralized systems, encompassing the distribution of processing, data, and knowledge, have been an area of intense research for some time, and the benefits of distribution are well documented. Decentralized systems offer advantages in performance versus cost, modularity, expandability, availability, scalability, and reliability (Mullender 1989). The advantages of distributing knowledge and problem solving enumerated by Smith and Davis (1981, p. 61):

> Distributed problem solving offers advantages of speed, reliability, extensibility, the ability to handle applications with a natural spatial distribution, and the ability to tolerate uncertain data and knowledge. Because such systems are highly modular they also offer conceptual clarity and simplicity of design.

In the context of designing an adaptive agent-based workflow management system, a decentralized approach will reduce the complexity of the system by localizing the information and control. Maintainability and modifiability will be improved because of modularity and self-configurability.

The Preferred Coordination Structure

Organizations are inherently decentralized, comprised of various processes, and people, distributed both spatially and temporally. The processes and people are logically grouped according to business processes. This would suggest that a decentralized coordination structure provides the best fit between the agent-based workflow management system and the business processes being managed.

In attempting to determine the preferred coordination structure of an adaptive agent-based workflow management system some additional insight may be gained by examining current thoughts on organizational theory as applied to traditional corporate organizations. Hammer and Champy (1993) trace the roots of the traditional centralized organizational structure back to Adam Smith's Wealth of Nations. The authors note that the centralized organization, while appropriate during the early years of the industrial revolution, does not allow for the flexibility and responsiveness necessary to compete in today's dynamic marketplace. These problems may be generalized to centralized agent-based workflow management systems.

The decentralized coordination structure has been shown to have distinct advantages in flexibility when compared to centralized coordination structures. The need for centralization of control, through the introduction of hierarchy, is necessary only when the optimization that such centralization would facilitate improves the architecture’s performance. For these reasons, the adaptive agent-based workflow management system has a bias towards a decentralized coordination structure.

The Transition Between Coordination Structures

An adaptive agent-based workflow management system must not only have the ability to make the transition between a decentralized and a centralized coordination structure, it must also be able to detect when such a transition is warranted. Having established a preference for the decentralized coordination structure, some criteria for the transition to a centralized coordination structure must be established. The desired attributes of the centralized coordination structure are primarily related to the need for optimization of the business processes. The transition to a centralized coordination structure should be a function of the level of optimization required by the business processes. The introduction of hierarchy into the agent-based workflow management system need only occur in areas of the system requiring some level of optimization, and need only involve those agents necessary to facilitate the desired optimization activity. Once the required optimization activity has concluded, the need for the hierarchy is eliminated and the agent-based workflow management system should return to a decentralized coordination structure.

The Desired System Behaviors

The desired system behaviors are derived from the need to incorporate into the adaptive agent-based workflow management system the desirable attributes of centralized and decentralized coordination structures. Having established a bias for the decentralized coordination structure, and the motivations for making the transition to a centralized coordination structure, the desired system behaviors may be summarized as follows:

1. The agent-based workflow management system should be capable of making the transition from a decentralized coordination structure to a centralized coordination structure, through the introduction of hierarchy, when such a transition would facilitate optimization of the information system;

2. The system should be capable of limiting the introduction of hierarchy, both in height and scope, to only that portion of the information system that would benefit from the optimization that such hierarchy would facilitate; and

3. The agent-based workflow management system should be capable of allowing those portions of the system in which hierarchy has been introduced to return to a decentralized coordination structure when their respective optimization activities have concluded.

These behaviors enable the adaptive agent-based workflow management system to adapt the coordination structure to the optimization needs of the information system.

Knowledge-Level Concepts

For the system to behave as described, each agent within the agent-based workflow management system must possess and maintain at least three general types of knowledge. First, to function in a dynamically changing coordination structure, each agent must have coordination knowledge. Next, each agent must have business process knowledge in order to carry out the basic activities of the information system. Third, each agent must have interface knowledge to enable the agent to interface with the environment and with other agents. These concepts are discussed more fully in the following paragraphs.

Coordination Knowledge

Coordination knowledge consists of knowledge of the relationships between agents (agent-agent) as well as knowledge of the relationships of agents to the coordination structure (agent-coordination structure). Ishida, Yokoo, and Gasser identify three elements of agent-agent coordination knowledge (Ishida, Yokoo, and Gasser 1990, p. 54):

> Dependencies: Each agent knows which rules in the organization have data dependency with its own rules;
>
> Interference: Each agent knows which rules in the organization may interfere with its own rules; and
>
> Locations: Each agent knows the location of rules appearing in its own data dependency and interference knowledge.

Agent-coordination structure knowledge consists of local statistics, coordination structure statistics, and restructuring rules (Gasser and Ishida 1991). Local statistics measure the level of problem solving activity within an agent. Coordination structure statistics provide a measure of overall architectural performance. Restructuring rules are used, in conjunction with local and coordination structure statistics, to facilitate the restructuring of the agent-based workflow management system.

Process Knowledge

Process knowledge refers to knowledge of the capabilities, capacities, and costs associated with the business system under control. Process capabilities describes the nature of the work performed in the business system, the nature of the process the business system can accommodate, and the attributes of the business processes. Knowledge pertaining to resource capacities includes input queue capacity, output queue capacity, in-process capacity, current status of the input and output queues, and number of processes currently in process. Production costs include costs associated with process resources, such as operation costs. Process knowledge is necessary for the agent-based workflow management system to carry out its primary mission, the control of process activities.

Interface Knowledge

Two types of interface knowledge are required: agent interface knowledge and environment interface knowledge. Agent interface knowledge is necessary to facilitate the integration of agents into the overall agent-based workflow management system. In the preferred decentralized coordination structure, agent interface knowledge consists of the knowledge necessary to carry out negotiation using the contract-net metaphor previously described. Agents representing business resources must have knowledge of the pricing mechanism, the bidding protocol, and the bidding activity in which the agent is currently engaged. Agents representing business activities must have knowledge of the funds available with which to bid on resources.

When hierarchy is introduced into the adaptive agent-based workflow management system, agent interface knowledge is required to enforce the hierarchical lines of communication and control. All bidding and negotiating for resources under the control of the hierarchy must occur through the highest level of the hierarchy. Within the portion of the agent-based workflow management system controlled by the hierarchy, resources are not negotiated for. Rather, business tasks are negotiated for by higher-level agents and directly assigned to lower level agents. Given that agents may, at different times, be required to function in centralized or decentralized coordination structures, they require knowledge of how to interface in each structure and when each mode of interfacing is appropriate.

Environment interface knowledge allows the agents to interface with the machines, business processes, and people that comprise the information system. In the context of interfacing to a specific machine, environment interface knowledge consists of knowledge of the machine's communication protocol, knowledge concerning the meaning and severity of fault messages, etc. With respect to business processes, environment interface knowledge consists of knowledge of the sequence and timing of steps in the process, as well as knowledge of communication protocols and knowledge concerning the meaning and severity of fault messages.

Contributions of the Research

This research provides demonstrable support for organization self-design as a viable design alternative for intelligent workflow management systems. This design approach "bridges the gap" between designs based on centralized or decentralized coordination structures and provides a synthesis of these two structural extremes. Perhaps less tangible, but of no less significance, are contributions to the understanding of the temporal role of hierarchy within intelligent workflow management systems. At the core of this research is an examination of the role of hierarchy within the coordination structure of intelligent workflow management systems and the feasibility of developing a system that is capable of altering the hierarchy in response to the business process. Current research streams tend to favor either centralized or decentralized coordination structures without investigating the nature and role of hierarchy within the workflow management system. This research broadens the understanding of hierarchy, pursues a new line of research, and contributes to the understanding of existing lines of research.

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