LogDynamics
International Graduate School

Self-organizing Supply Networks: Emergent Agent Coordination in Autonomous Logistics

Industrial production and trade require efficient and reliable supply networks. Growing interrelations between these networks and the inherent dynamics of the logistics domain result in a high complexity of global supply processes. Application of conventional centralized planning and control to these processes suffers from that complexity. Therefore, a need arises for decentralized methods employing autonomous actors representing logistics entities and objects.

From the artificial intelligence point of view, these autonomous entities can be represented by intelligent software agents to model logistics networks as multiagent systems (MAS). These systems may be used to simulate, evaluate, and actually implement new approaches in autonomous logistics.

Coordination and cooperation of autonomous entities is the challenging task that has to be addressed in order to develop such approaches. In the logistics domain, coordination is faced with the contradictory requirements of achieving high operational efficiency while retaining the system's ability to adapt to a changing environment. Supply networks, therefore, need to achieve high performance rates concerning asset utilization, cost reduction, and customer satisfaction on the one hand. On the other hand, they are required to employ flexible and robust structures in order to react to unforeseen changes caused by the domain's inherent dynamics.

In this research, a novel approach to self-organization for multiagent systems is developed, considering particular challenges in supply network structuring and operation. Agent coordination mechanisms are investigated as means for structuring decentralized behavior in logistics networks. Further inspiration is taken from sociological theories describing coordination mechanisms in human society. These considerations form the basis for the development of an adaptive self-structuring paradigm for supply networks modeled by multiagent systems.

Self-organizing Supply Networks

In order to solve repeatedly occurring coordination problems in decentralized systems efficiently, organizational structures have to be established. Yet, it is unclear which kind of structure is applied best, given a particular coordination task. Consider, for instance, a supply network as partly shown in Figure 1: In such a network, the participants must choose which subset of the depicted possible relationships between each two tiers (pictured as arrows in the direction of material flows) actually to establish. This decision has to take into account cost considerations as well as the responsiveness and reliability of possible business partners in order to enable efficient operations within the network. Establishing an organizational structure, thus, refers to the choice of a set of agent relationships to be instantiated. An efficient organizational structure minimizes the actually established relationships while maximizing the achieved operations outcome according to logistics performance measures.

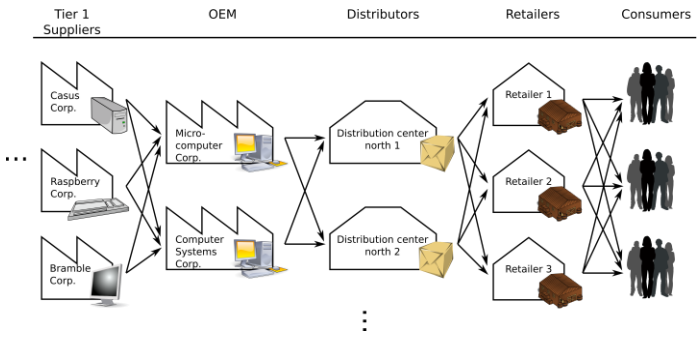

Figure 1: Part of an example supply network in the computer manufacturing domain showing all possible relationships between the participants.

However, due to the dynamics of logistics processes, conventional design time evaluation and optimization of these organizational structures is not sufficient in terms of flexibility and robustness: Not only consumer demand changes as well as unforeseen failures of scheduled

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operations may happen (leading to the need of dynamic replanning and reallocation of resources), but also the logistics market itself may alter. New competitors as well as new customers may enter, causing further changes in demand, prices, and requirements of products and services. These developments evoke the need for each participant to constantly adapt his relationships to customers and suppliers in order to secure market shares and to fulfill his customers' needs.

Thus, modeling and operating supply networks with multiagent systems requires the agents' ability to establish organizational structures that allow efficient operation, while being flexible enough (i.e., alterable) to cope with the dynamics of logistics processes. Hence, the need arises for self-organizing MAS that autonomously adapt to those dynamic changes. In this context, self-organization is therefore considered as the emergent evolvement and modification of organizational structures defining business relationships between supply network partners.

Emergent Agent Interaction Patterns

In order to be able to autonomously coordinate their activities, artificial agents need to interact with each other. For this purpose, agent communication languages that are based on speech acts between agents are commonly used. On the basis of these speech acts, a range of interaction and negotiation protocols haven been developed that may be used to coordinate agent behavior. Patterns of interaction then reflect relationships between the participants and, thus, express the structure of the multiagent system. In the opposite sense, structuring a supply network modeled as a MAS means to define channels and modes of agent communication. The notion of self-organization, thus, refers to an autonomous emergence of those interaction patterns.

Taking further inspiration from the sociological theory of communication systems, these perspectives of structures guiding agent interaction and communicative operations expressing the system's structure can be connected to a control loop. Organizational structures then emerge from agent interaction while guiding the agents' choice of further operations.

Regarding the logistics domain, this means that among the set of all possible operations of goods order and delivery those which follow well-established business relationships are most likely to be instantiated. Hence, the choice of order/delivery operations is restricted by the set of actually established agent interaction possibilities. On the other hand, those structures (business relationships, interaction patterns) which are supported by the most successful operations, i.e., which have proven to provide efficient and reliable operations outcome will consolidate. Unsuccessful ones, in turn, become less likely to be activated. A possible snapshot of such a structured network is shown in Figure 2.

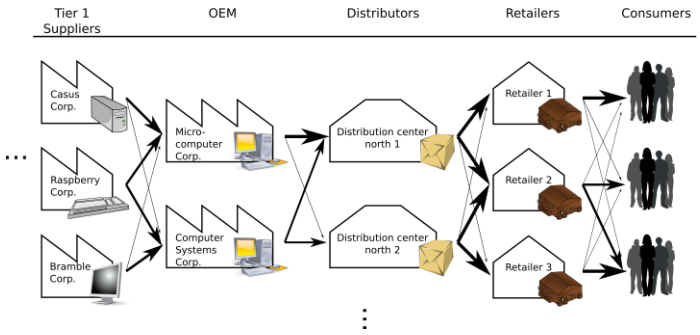

Figure 2: A possible structure for the example network: The arrows' width reflects the likelyhood of each relationship to be activated while resulting from the experienced outcome of past operations.

Thus, self-organization denotes a control loop that guides a system's behavior regarding environmental dynamics: The system reacts to irritations from its environment in terms of operations effects by observing and adjusting its own behavior in the choice of connecting operations.

Research Objectives and Methodology

The aim of this research project is to develop and implement a method for adaptive agent coordination in the domain of logistics networks. Firstly, in this context, agent communication mechanisms are defined that enable the modeling of supply networks by multiagent systems. Secondly, performance measures are explored in order to allow for agents autonomously evaluating the outcome of their operations. This facilitates the identification of those relationships among the agents that permit efficient supply network operations. Thirdly, based on those considerations, an agent decision method is developed, applying the aforementioned control loop of choosing operations according to the system's structure and structuring the system with regard to the chosen operations. Finally, the approach to self-organizing supply networks by emergent agent coordination is implemented and evaluated using multiagent simulation as a testbed for the behavior of decentralized systems facilitating autonomous entities.

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