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Decision Support

An options-based approach to coordinating distributed decision systems

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ABSTRACT

Engineering and operations management decisions have become increasingly complex as a result of recent advances in information technology. The increased ability to access and communicate information has resulted in expanded system domains consisting of multiple agents, each exhibiting autonomous decision-making capabilities, with potentially complex logistics. Challenges regarding the management of these systems include heterogenous utility drivers and risk preferences among the agents, and various sources of system uncertainty. This paper presents a distributed options-based model that manages the impact of multiple forms of uncertainty from a multi-agent perspective, while adapting as both the stream of information and the capabilities of the agents are better known. Because the actions of decision makers may have an impact on the evolution of underlying sources of uncertainty, this endogenous relationship is modeled and a solution approach developed that converges to an equilibrium system state and improves the performance of agents and the system. The final result is a distributed options-based decision-making policy that both responds to and controls the evolution of uncertainty in large-scale engineering and operations management domains.

1. Introduction

Technology and operations management decisions have become increasingly complex in recent years. The increased ability to access and communicate information has resulted in expanded system domains consisting of multiple agents (decision-makers), with each exhibiting autonomous decision-making capabilities. Although these systems may possess the ability to perform and achieve benefits that are beyond those capable of smaller networks (Weiss, 1999), the following challenges are presented. First, the agents may possess individual utility drivers, thus creating an environment that must balance the goals of multiple agents and the overall system. Because an agent may exhibit a finite performance capacity, choices must be made regarding how to most effectively utilize each agent. These decisions are further complicated due to both continuous forms of uncertainty that provide a constant source of variability, as well as discrete, and sometimes rare, events that may provide dramatic disruptions to the system processes. Furthermore, the actions of agents may have an endogenous impact on system characteristics, performance capacity, and underlying sources of uncertainty. Because these systems possess dynamic properties, continuous information updating creates a decision timing issue for the agents where the benefits and costs of waiting for additional information must be considered. This paper develops a distributed decision-making approach that incorporates decision flexibility to manage the impact of multiple uncertainties from a multi-agent perspective, and improve both agent and system performances.

Consider the increase in technological innovation and the resulting impact on operations management. As information and communication technologies have increased, the competitive landscape has also increased resulting in a global network of suppliers, producers, and distributors. Many of these supply chain entities are contract manufacturers and compete among other firms for their place in the chain. Because it is imperative to operate in a lean manner, costs must be kept to a minimum and resources allocated to yield a maximum utility. This utility can be viewed in two ways. From a systems point of view, production of the final good or service needs to be performed and delivered to the end customer in the most cost effective manner. However, each entity in the supply chain may be considered an agent (e.g., an individual supplier, producer, distributor) that makes its decisions based on satisfying its own economic utility drivers.

The resulting decisions that each individual agent makes may be further complicated by various sources of uncertainty. For

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example, production facilities typically exhibit a finite resource capacity and challenging decisions must be made when devising operating schedules and determining which customer orders to satisfy. These decisions are complicated by both the uncertain nature of the resource performance and customer order rates. A producer may engage in a contract with an initial customer that utilizes its full capacity, but is then unable to satisfy an additional customer order that may yield even greater profits, thus jeopardizing its competitive position in the supply chain. From the customer's perspective, resource selection and contracting decisions may be based on such factors as a desired delivery date or price. These contracted conditions, however, may ultimately be subject to the performance uncertainty of the production resource. If the resource can produce with lower levels of process variability, then it may be able to quote better delivery dates and lower prices. Therefore, both the customer and producer benefit by more stability in the resource operations.

When devising a decision-making policy for this type of system, it is important to not only consider exogenous factors, but also recognize any endogenous parameter relationships. In this example, a possible endogenous relationship may exist between production stability and the types of customer orders that the resource processes. By recognizing this relationship, the resource may be used to process customer orders that encourage performance stability. These particular orders may be ones that are easier to process or provide smoother scheduling with fewer disruptions and reduced setup costs. The resulting improvements to operational stability may therefore yield reductions in future production uncertainty.

In order to effectively manage these types of systems, a decision-making approach must be employed that retains flexibility as the stream of new information arrives, while hedging the impact of uncertainty for multiple agents and incorporating the endogenous relationship between agent decisions, system responses, and future performance capacity. Without flexibility, each agent must act immediately based on the information currently available. Because there is now an increasing amount of real-time system information available, it may be very beneficial to postpone the timing of any decision and re-evaluate based on updated system states. The approach developed in this paper is based on the concept of dynamic flexibility using options-based decision policies. It should be noted that this model does not utilize the Black Scholes options pricing model (Black & Scholes, 1973) or any other closed form solution method that is commonly used in the literature. In an effort to provide insights into systems that do not meet the strict assumptions of these closed form solution approaches, a depiction of a multi-agent resource allocation system was designed and a numerical solution presented in this paper. This model is tested to evaluate the impact of managing uncertainty from a distributed decision-making perspective with respect to improvements in both agent utilities and system properties while adhering to limited and finite capacity resource constraints.

This paper is organized as follows. Section 2 provides an overview of literature encompassing the three primary areas used as the basis of this paper: real options, options exercise games, and risk management in engineering and operational systems. In Section 3, a specific multi-agent system is defined and a distributed options-based model is developed that includes both agents' perspectives while accounting for the endogenous relationship between agent decisions, system performance, and the impact on the underlying source of system uncertainty. This distributed options-based policy is tested numerically in Section 4 and concluding remarks are presented in Section 5. A table giving descriptions of the variables used in the mathematical formulations is presented in Appendix A (online only). Specific model details pertaining to the multi-agent case study consisting of a task and resource agent are included in Appendix B and C (online only), respectively.

2. Background information

The model developed in this paper encompasses three primary research areas: (1) the extension of options-based decision theory into an engineering and operations management domain; (2) the impact of competitive agents on the ultimate decision-making process in an options framework; and (3) current approaches toward managing the impact of uncertainty in large-scale engineering and operational systems. The first area demonstrates the flexibility of utilizing options pricing concepts in non-financial domains; the second area introduces a relatively new area of research referred to as "options exercise games"; and the final area provides a domain for which the findings of this paper may be applied. This section provides a review of some of the more relevant research in these areas to the scope of this paper.

Since the seminal work of Black and Scholes (1973) and of Merton (1973), options pricing concepts have been used extensively to value financial assets, with the theory then extended to real assets (Myers, 1977) and commonly referred to as "real options". Some of the common types of real options used in operations and project management decisions include the following: the option to defer investment decisions; a time-to-build option for staged investments; the option to alter the scale of operations through expansion, contraction, shutdowns, or restarts; the option to abandon operations or a project; the option to switch outputs, inputs, or operating modes; growth options; and complex multiple interacting options (Trigeorgis, 1996). Because managerial and operational decisions may be considered at least partially irreversible, there is a value to waiting for more information about the system prior to making a decision. Detailed accounts of both the theory and applications of real options are provided in Dixit and Pindyck (1994) and Trigeorgis (1996). Similar to these applications, the focus area of this paper is with decisions pertaining to real assets (e.g., production capacity). However, this paper further extends these existing options-based concepts into a domain consisting of multiple decision makers.

In the supply chain situation described in Section 1, each agent may interact in a competitive manner to maximize its own utility. Consequently, the concept of options exercise games has recently evolved and provides an intersection of traditional real options analysis with game theory. In many situations, the ultimate utility gained from an investment in a real asset is affected by the investment strategies and actions of other agents in the system. This characteristic of real options differs from financial options in many application domains. For example, real assets with respect to real estate development often have a finite elasticity of demand; developers may have finite capacities; there is a limited supply of options available; and there is typically less than perfect competition among developers (Williams, 1993). Financial assets, however, do not exhibit these restrictions and the exercise of a financial option by any agent does not change the characteristics of the security or the option (Grenadier, 2002). In order to account for the impact of other agents' exercise strategies on the underlying value of a real option and the subsequent optimal exercise policy for a given agent, game theoretic principles must be included in the analysis. The model presented in this paper incorporates game theoretic options to account for the changes in system characteristics and agent payoffs that occur due to the presence of other agents. Because resource capacities are finite, a task agent's allocation option exercise policy must account for the expected actions of other task agents competing for the resource's services. This scenario provides an extended domain for the application of options exercise games concepts when allocating resources in large-scale engineering and operational systems.

Traditional work in large-scale engineering and operational systems, such as production systems and supply chain networks, has focused primarily on improving the overall cost-efficiency of the