Complex Adaptive Enterprises

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INTRODUCTION

In a world where the market, customer profiles and demands change constantly and the events in the global marketplace are unpredictable, it becomes increasingly difficult for an enterprise to sustain its competitive advantage. Under these conditions of uncertainty, complexity and constant change, it becomes very important for an enterprise to be able to learn from its experience and to adapt its behavior in order to constantly outperform its competitors. An enterprise that has these characteristics is a complex adaptive enterprise.

The interrelationships between resources in a complex adaptive enterprise and its global behavior within the marketplace can be numerous and mostly hidden, and can affect many different resources throughout the enterprise. One of the main challenges of the modern enterprise is to understand this complex web of interrelationships and to integrate this understanding into its business processes and strategies in such a way that it can sustain its competitive advantage.

BACKGROUND

The Chain of Sustainability

According to the resource-based theory, there are dynamic relationships between enterprise resources, the capabilities of the enterprise and the competitive advantage of the enterprise. The complex adaptive enterprise maintains a chain of sustainability that constantly evolves from the interactions between the individual resources and the interactions between the resources and the dynamically changing marketplace.

Resources or assets are the basic components in the chain of sustainability. Example resources are products, employee skills, knowledge, and so forth. These resources are combined into complementary resource combinations (CRCs) according to the functionality that these resources collectively achieve. CRCs are the unique inter-relationships between resources and are the source of competitive advantage in an enterprise, as these relationships cannot be duplicated by competitors. The behaviors of the CRCs define the strategic architecture of an enterprise, which is defined as the capabilities of an enterprise, when applied in the marketplace.

Social complexity refers to the complex behavior exhibited by a complex adaptive enterprise, when its CRCs are embedded in a complex web of social interactions. These CRCs are referred to as socially complex resource combinations (SRCs). In social complexity, the source of competitive advantage is known, but the method of replicating the advantage is unclear. Examples include corporate culture, the interpersonal relations among managers or employees in an enterprise and trust between management and employees. SRCs depend upon large numbers of people or teams engaged in coordinated action such that few individuals, if any, have sufficient breadth of knowledge to grasp the overall phenomenon.

Casual ambiguity refers to uncertainty regarding the causes of efficiency and effectiveness of an enterprise, when it is unclear which resource combinations are enabling specific capabilities that are earning the profits.

The Complex Adaptive Enterprise

A complex adaptive enterprise is an enterprise that can function as a complex adaptive system. A complex adaptive system can learn from and adapt to its constantly changing environment. Such a system is characterized by complex behaviors that emerge as a result of interactions among individual system components and among system components and the environment. Through interacting with and learning from its environment, a complex adaptive enterprise modifies its behavior in order to maintain its chain of sustainability.

It is impossible for an enterprise that cannot learn from experience to maintain its chain of sustainability. The learning process involves perception of environmental

inputs, understanding the perceived inputs (making meaning out of these inputs), and turning this understanding into effective action (Senge, Kleiner, Roberts, Ross & Smith, 1994). The Soft Systems Methodology (Checkland, 2004) is a methodology that was developed that involves perception, understanding and acting in an enterprise.

Understanding Emergence

Self-awareness in a complex adaptive enterprise is instrumental in the maintenance of the chain of sustainability. Enterprises need to understand the interrelationships between the individual behaviors of the resources and the emergent behaviors of the CRCs and SRCs. This will enable the enterprise to understand its own social complexity and causal ambiguity.

Emergence, the most important characteristic of a complex adaptive enterprise, is the collective behavior of interacting resources in the CRCs. Emergence is the same as holism (Baas & Emmeche, 1997). Holism in a complex adaptive system means that the collective behaviour of the system components is more than the sum of the behaviours of the individual system components, for example, a flock is more than a collection of birds and a traffic jam is more than a collection of cars (Odell, 1998).

What does it mean to understand something? According to Baas & Emmeche (1997), understanding is related to the notion of explanation. All complex adaptive systems maintain internal models (Holland, 1995). These mechanisms are used for explanation and understanding.

The human mind is self-aware and capable of self-observation and self-interaction. Consciousness may be seen as an internal model maintained by the mind. In Minsky's *Society of Mind*, internal observation mechanisms called A-Brains and B-Brains maintain internal models consisting of hyperstructures called K-Lines. Each K-Line is a wire-like structure that attaches itself to whichever mental agents are active when a problem is solved or a good idea is formed (Minsky, 1988). Minsky describes how a system can watch itself, using its B-Brain.

Gell-Mann (1994) refers to the information about the environment of a complex adaptive system and the system's interaction with the environment as the "input stream" of the system. A complex adaptive system creates and maintains its internal model by separating "regularities from randomness" in its input stream (Gell-Mann, 1994). These regularities are represented using hyperstructures, which in turn constitute the internal model of the complex adaptive system. The observation mechanism of a complex adaptive system is responsible for the identification of regularities in its input stream, as well as for the progressive adaptation of the hyperstructures to include these regularities.

In the complex adaptive enterprise, the hyperstructures encode the knowledge of the enterprise, and are distributed throughout the enterprise. This knowledge belongs to one of the following component knowledge types:

- knowledge related to internal relationships within the company;
- knowledge related to products and services;
- knowledge related to business processes and business units;
- knowledge related to specific projects and project implementations;
- knowledge related to customers;
- knowledge related to the marketplace.

Component knowledge consists of both tacit and explicit knowledge. Tacit knowledge is usually defined as that which cannot be written down or specified. This knowledge is embedded within the interrelationships between the local behaviors of resources within the CRCs and the emergent behaviors of the CRCs. Knowledge, particularly tacit knowledge, is the most important strategic resource in an enterprise (April, 2002).

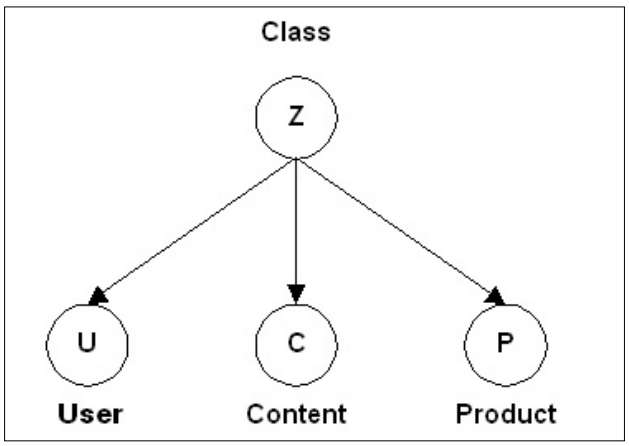
Bayesian Hyperstructures

Bayesian networks provide the ideal formalism to be used as hyperstructures in the complex adaptive enterprise. These networks can be used to encode beliefs and causal relationships between beliefs and provide a formalism for reasoning about partial beliefs under conditions of uncertainty (Pearl, 1988). These networks can be used to learn a probabilistic model of what the emergent effects are of certain interactions and behaviors in response to certain environmental states (the causes). Such a causal model can then be queried by an arbitration process to decide which action(s) are most relevant given a certain state of the environment.

A Bayesian network is a directed acyclic graph (DAG) that consists of a set of nodes that are linked together by directional links. Each node represents a random variable or uncertain quantity. Each variable has a finite set of mutually exclusive propositions, called states. The links represent informational or causal dependencies among the variables, where a parent node is the cause and a child node, the effect. The dependencies are given in terms of conditional probabilities of states that a node can have given the values of the parent nodes (Pearl, 1988). Each node has a conditional probability matrix to store these conditional probabilities, accumulated over time.

Figure 1 illustrates a simple Bayesian network, which we adapted from the user-words aspect model proposed by Popescul, Ungar, Pennock & Lawrence (2001). Our

Figure 1: A Simple Bayesian Network



network models the relationship between three observable variables, namely users (U), the contents of browsed web pages characterized in terms of concepts (C), products bought from these pages (P) and one hidden variable, namely the class variable (Z).

In Figure 1 above, the states of the hidden class variable Z are mined from historical data (observations of U, P and C). The class variable Z is the single cause influencing multiple effects (U, P and C). This probability distribution is called a naïve Bayes model or sometimes called a Bayesian classifier (Russell & Norvig, 2003).

Bayesian learning can be described as the "mining" of the structure of a Bayesian network and the calculation of the conditional probability matrices from history data. The data may be incomplete and the structure of the Bayesian network can be unknown.

Bayesian inference is the process of calculating the posterior probability of a hypothesis H (involving a set of query variables) given some observed event e (assignments of values to a set of evidence variables),

$$P(H \mid e) = \frac{P(e \mid H)P(H)}{P(e)}$$, where

$P(H \mid e)$ represents the belief in H given e,

$P(e \mid H)$ represents the belief in e given H, and

$P(H)$ and $P(e)$ represent the beliefs in H and e respectively.

Bayesian inference is NP-hard (Pearl, 1988; Dechter, 1996). In order to simplify inference, Bayesian networks are simplified to trees or singly-connected polytrees. A tree is a DAG in which each node has only one parent (Pearl, 1988). A singly-connected polytree is a DAG in which the nodes can have multiple parents, but with the restriction that there is only one path, along arcs in either direction, between any two nodes in the DAG (Nilsson, 1998; Pearl, 1988).

SELF-AWARENESS AND SUSTAINABLE COMPETITIVE ADVANTAGE USING BAYESIAN AGENCIES

Adaptive agents are the basic building blocks of a complex adaptive system. The collective behavior of the agents, the interactions between the agents and the environment as well as the interactions between the agents themselves comprise a complex set of causal relationships.

We implement complex adaptive systems using Bayesian agencies that collectively implement Bayesian behavior networks. These networks are Bayesian networks that model the regularities in the input stream of a complex adaptive system. The nodes in a Bayesian behavior network are grouped into what we call competence sets, where each competence set has an associated set of actions that must be performed by the Bayesian agencies depending on the states of the nodes in the competence set. These actions are usually part of a business process or workflow in the enterprise.

Complex adaptive systems generate their internal models from re-usable building blocks (Holland, 1995). As an example, the quarks of Gell-Mann (1994) are combined into nucleons, nucleons are combined into atoms, atoms are combined into molecules, and so forth. It is essential that the knowledge in the internal model of the enterprise be represented using re-usable building blocks, in order for the enterprise to be able to function as a complex adaptive system.

Our Bayesian agencies consist of simple re-usable software components, distributed throughout the enterprise. There are two types of Bayesian agencies, namely belief propagation agencies and competence agencies. Belief propagation agencies consist of a collection of components, where each component can be one of three re-usable components, namely node components, link components and belief propagation agents. Collectively these simple components capture the knowledge throughout the enterprise by collectively implementing distributed Bayesian behavior networks. Each node component implements a Bayesian behavior network node. Each network link is implemented by a queue, together with a link component that participates in the synchronization of messages flowing to the child, or to the parent node via the queue. For each queue, a belief propagation agent is

deployed that listens on that queue for messages from the child or parent node of the associated network link.

The belief propagation agents collectively perform Bayesian inference by localized message passing in response to the environmental evidence in order to update the beliefs of network nodes. The competence agencies use the beliefs of selected network nodes to determine if certain business components must be activated or not. Business components are re-usable components containing parts of business processes or workflow processes. Each competence agency monitors a set of constraints on the beliefs of a subset of nodes – the constraint set. If all the constraints in a constraint set are met, the competence agency can activate its associated business component.

Node components are deployed throughout the enterprise to collect evidence from disparate data sources within the enterprise or from external data sources. The Bayesian agencies incrementally learn from this experience.

The Bayesian agencies are observation mechanisms that enable the enterprise to be self-aware. Belief propagation agencies are connected to the real world. As soon as evidence is received from the environment, the belief propagation agents collectively perform Bayesian inference by using local message passing. The competence agencies inspect the beliefs of nodes and act upon these beliefs and possibly change the state of the environment, influencing the collective Bayesian inference of the belief propagation agencies.

The flexibility, adaptability and reusability of automated business processes (enterprise software) determine the ability of an enterprise to evolve and survive in the marketplace (Sutherland & van den Heuvel, 2002). The belief propagation agencies enable the re-usable business components in the competence agencies to be flexible and adaptable.

We have successfully implemented prototype Bayesian agencies using Sun's Enterprise JavaBeans™ component architecture. We developed prototype node and link components and belief propagation agents that are assembled into distributed Bayesian behavior networks, collectively performing Bayesian learning and Bayesian inference in singly-connected Bayesian behavior networks with known structure and no hidden variables.

FUTURE TRENDS

Future research will involve a full implementation of Bayesian learning, where Bayesian agents collectively and incrementally discover structure from data in the presence of known values for variables as well as in the presence of missing data. We will also complete the collective belief propagation capabilities of the Bayesian agencies in order to cope with multiply-connected Bayesian behaviour networks.

CONCLUSION

Our Bayesian agencies can be distributed throughout an enterprise, enabling it to function as a complex adaptive enterprise. These agencies will assist the enterprise to be self-aware by collectively modeling the complex interrelatedness of local behaviors of resources and emergent behaviors of CRCs, from which the enterprise's tacit knowledge, social complexity and causal ambiguity emerges – the source of its competitive advantage. The enterprise can then use this self-understanding to adapt its business processes and to formulate new knowledge or business strategies in response to the ever-changing marketplace in order to sustain its competitive advantage.

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KEY TERMS

Bayesian Agencies: Agencies consisting of simple agents that collectively implement distributed Bayesian behavior networks. The agents are organized into agencies, where each agency activates one or more component behaviour depending on the inference in the underlying Bayesian behaviour network.

Bayesian Behavior Networks: Specialized Bayesian networks, used by the Bayesian agents to collectively mine and model relationships between emergent behaviours and the interactions that caused them to emerge, in order to adapt the behaviour of the system.

Bayesian Hyperstructures: Bayesian Behavior Networks are Bayesian hyperstructures that in turn constitute the internal model of the complex adaptive system.

Competence Sets: The nodes in a Bayesian behavior network are grouped into competence sets, where each competence set has an associated set of actions that must be performed by the Bayesian agencies depending on the states of the nodes in the competence set.

Resources: Also known as "assets", come in many forms, from common factor inputs that are widely available and easily purchased in arms-length transactions, to highly differentiated resources, like brand names, that are developed over many years and are very difficult to replicate. Resources come in two main forms: "tangible resources" - which are the easiest to value, and often are the only resources that appear on a company's balance sheet. They include real estate, production facilities and raw materials, among others. Although tangible resources may be essential to a company's strategy, because of their standard nature they rarely constitute a source of competitive advantage; and "intangible resources" - include such things as company reputations, brand names, cultures, technological knowledge, know-how shared among employees, patented process and design, trademarks, accumulated learning and/or knowledge, as well as experience. These resources often play important roles in competitive advantage (or disadvantage) and company value. Intangible resources also have the important property of not being consumed in usage.

Complementary Resource Combinations (CRCs): Are not factor inputs, but are complex combinations of interrelated configurations, or networks of assets, people, and processes that companies use to transform inputs to outputs. Many of these configurations are a blend of "hard" tangible resources and "soft" intangible resources which simply cannot be recreated by another company. Finely honed CRCs can be a source of competitive advantage.

Social Complexity: Is when the source of advantage is known, but the method of replicating the advantage is unclear, e.g., corporate culture, the interpersonal relations among managers in a company, or trust between management and labor.

Social Complex Resource Combinations (SRCs): Depend upon large numbers of people, or teams, engaged in coordinated action such that few individuals, if any (both outside the company, as well as inside the company), have sufficient breadth of knowledge to grasp the overall phenomenon.

Strategic Architecture: Refers to a company's capabilities, when applied in the marketplace.

Chain of Sustainability: An evolving, dynamic and matched mix between company resources (arranged in value-generating combinations) and the changing marketplace that gives the company a competitive edge.

Causal Ambiguity: Refers to uncertainty, by competitors, regarding the causes of efficiency and effectiveness of a company, when it is unclear which resource combinations are enabling specific competitive capabilities that are earning the company profits.

Competitive Advantage: A company is said to have a competitive advantage when, based on its strategic architecture and complementary resource combinations (CRCs), it is able to implement a strategy that generates returns and benefits in excess of those of its current competitors – who simultaneously are implementing strategies, similar or otherwise – because of the perceived value in the marketplace. The definition therefore also depends on what the company, its management and its stakeholders, define as what the required returns and benefits should be (because even though many would list it as financial, clearly this does not apply to all companies, i.e., an advantage could be something other than financial). One could reasonably expect, though, that companies within similar industries would define similar variables as the required returns and benefits. A company is said to have a sustained competitive advantage when it is implementing a value-creating strategy, which generates returns and benefits at a level not enjoyed by current competitors and when these other companies are unable to reach an "equilibrium level" with the company enjoying the advantage. In this sense, the definition of sustained competitive advantage adopted here does not imply that it will "last forever," and does not depend upon the period of time during which a company enjoys a competitive advantage (rather, the equilibrium level is critical in this definition).