The Complex Adaptive Enterprise: Self-Awareness and Sustainable Competitive Advantage using Bayesian Agencies

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Abstract

The complex adaptive enterprise can learn from and react to global events faster than the competition because of its self-awareness and its ability to adapt. An enterprise is self-aware if it understands the interdependencies between its own resources and how these resources and interdependencies contribute to its own competitive advantage. The complex adaptive enterprise then uses this understanding to adapt its business processes and strategies in order to sustain its competitive advantage. In this paper, we describe how simple software agents can be integrated into the enterprise in order to enable the enterprise to function as a complex adaptive enterprise. In our research, we developed Bayesian agencies, which are complex adaptive software systems consisting of simple agents implemented as re-usable components, which can be integrated into the business processes and strategy forming processes. These agencies are able to collectively mine the relationships between resources within the enterprise and the global behaviour of the enterprise in order for an enterprise to be self-aware. Depending on the mined relationships, the agencies can collectively take one or more actions in the enterprise, such as activating or modifying business processes, or participating in the formulation or changing of business or knowledge strategies.

1. 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 behaviour 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 behaviour within the marketplace can be so numerous and mostly hidden, and can affect so many different resources throughout the enterprise that it is impossible for the human mind to comprehend. 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.

2. The Chain of Sustainability in a Complex Adaptive Enterprise

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 (April, 2002). 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 (April, 2002). We summarize April's description of the chain of sustainability very briefly in the rest of this section.

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 behaviours 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 behaviour 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. Socially complex resource combinations (SRCs) depend upon large numbers of people or teams engaged in co-ordinated 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 is enabling specific capabilities that are earning the profits.

3. What is a Complex Adaptive Enterprise?

A complex adaptive enterprise is an enterprise that can function as a *complex adaptive system*. The behaviour of complex adaptive systems is studied under complexity theory research, conducted in centers such as the Santa Fe Institute. A complex adaptive system can learn from and adapt to its constantly changing environment. Such a system is characterized by complex behaviours 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 behaviour in order to maintain its chain of sustainability.

4. Self-Awareness in the Complex Adaptive Enterprise

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 behaviours of the resources and the emergent behaviours 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 behaviour of interacting resources in the CRCs. The collective behaviour of the system components is more that the sum of the behaviours of the individual system components.

All complex adaptive systems maintain internal models (Holland, 1995). Gell-Mann 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. April (2002) defines this knowledge as being 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. According to April, tacit knowledge is usually defined as that which cannot be written down or specified. This knowledge is embedded within the interrelationships between the local behaviours of resources within the CRCs and the emergent behaviours of the CRCs. Knowledge and particularly tacit knowledge is the most important strategic resource in an enterprise.

4. Bayesian Networks as 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 behaviours 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.

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

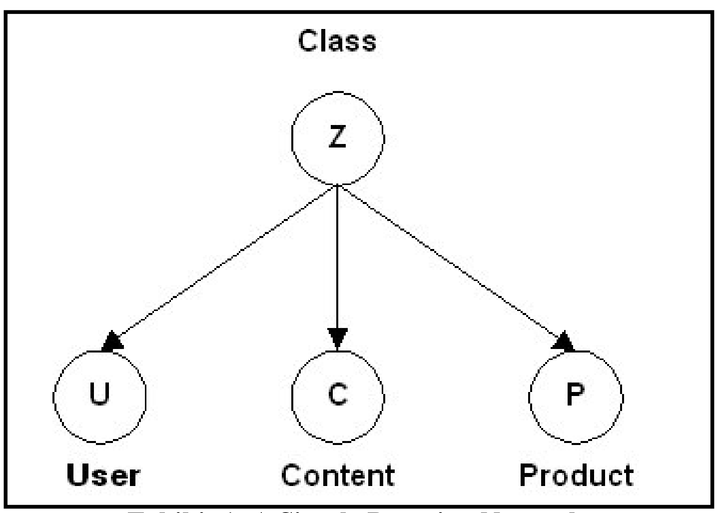

Exhibit 1: A Simple Bayesian Network

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 (assignments of values to a set of evidence variables e),

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

$P(H \mid e)$ 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.

5. Bayesian Agencies

Adaptive agents are the basic building blocks of a complex adaptive system. The collective behaviour 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 behaviour networks.* These networks are Bayesian networks that model the regularities in the input stream of a complex adaptive system. The nodes in a Bayesian behaviour 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 behaviour networks. Each node component implements a

Bayesian behaviour 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 localised 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 must be deployed throughout the enterprise to collect evidence from disparate data sources within the enterprise or from external data sources. The node components 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 agency.

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, 2001). 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 behaviour networks, collectively performing Bayesian learning and Bayesian inference in distributed Bayesian behaviour networks with known structure and no hidden variables. Future research will involve a full implementation of Bayesian learning, were 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.

5. Conclusions

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 behaviours of resources and emergent behaviours 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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