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ABSTRACT

This paper provides a background discussion of agent-based modeling (ABM) and simulation and its support for strategic decision support. Causal mapping is introduced as a structured method for situational formulation and analysis of unstructured strategic problems. Causal mapping includes specific processes and analytical approaches offering cognitive modeling support for problem formulation and scenario planning. A prototype system for the development and simulation of causal maps that uses RePast 2.0, a java based ABM simulation library is described. The research opens the door to using human/agent-based conceptual models to guide intelligent searches of internet, intranet and extranet space. Given the wealth of information available from such sources, the development of a human-artificial conceptual map will be an invaluable guide to selecting relevant information for strategic decision making.

Keywords

Cognitive Decision Models, Strategic Decision Making, Artificial Intelligence, Simulation

INTRODUCTION

Strategy and policy situations, real-world problems that exhibit complexity, are composed of many interrelated problems and issues. Uncertainty and turbulence in the environment, competition, firm capabilities and implementation tactics necessitate a comprehensive approach to strategic problem formulation. (Georgantzas & Acar 1995) Problem "framing" is replacing traditional problem solving. (Checkland, 1981) To be effective, strategies must holistically address the complexity of the situation rather than propose solutions to single problems. Formulating and understanding the situation and its complex dynamics, therefore, is key to finding holistic solutions. A systems approach to problem formulation stresses that single problems cannot be isolated from surrounding messy realities. The messiness of reality requires a shift from problem formulation to situation formulation. (Ackoff 1981)

The systems approach to situation formulation generated a variety of strategic knowledge representation techniques. Graphic representations are well known in the management and social science literature as both systems analysis tools and knowledge representation techniques. (Sowa & Dietz 1999) A number of specific approaches have been developed, including adaptations of mathematical graph theory (Harary *et al.* 1965), cognitive psychology and *personal construct theory*, (Kelly 1955) *influence diagramming and causal mapping,* (Maruyama 1963) and *systems dynamics.* (Forrester 1961) Huff (Huff 1990) identifies specific classes of cognitive maps and Eden's work in this domain e.g. (Eden C & Ackermann F 1998) is considerable.

This paper discusses modeling support for strategy and policy using cognitive mapping and causal mapping approaches. Comprehensive Situational Mapping (CSM) is introduced as a causal mapping system that offers a semantically rich modeling support for problem formulation and scenario planning. Object-oriented approaches to CSM automation initially appeared promising, but difficulties in simulating complex causal loops led to significant technical limitations. The recent development of Agent-based modeling and simulation tools provides a distributed solution. A prototype system for the development and simulation of causal maps using RePast 2.0, a java based ABM simulation library, is described. This research uniquely combines cognitive approaches to strategic thinking, knowledge management and agent-based systems in a prototype system for situation formulation in a group decision making environment. It sets the stage for the development of a system that uses human/agent-based conceptual models to guide intelligent searches of internet, intranet and extranet space, thus combining ABM systems with more traditional MAS approaches. Given the wealth of information available from network sources, the development of a human-artificial conceptual map of strategic situations is an invaluable guide to selecting **relevant** information for strategic decisions.

CSM CAUSAL MAPS AND SUPPORTED ANALYSES

Scenario driven planning has also been used to support strategic thinking and planning. Scenarios are key in dealing with "wicked problems" (Mason & Mitroff 1981). The analysis of **change scenarios** (Schoemaker PJH 2002) allows the design of strategies to take place in the messiness of the situation. Scenario-driven planning is a holistic approach to situation formulation and strategy development that blends qualitative planning processes and assumption surfacing with quantitative modeling and simulation in a unified methodology (Georgantzas & Acar 1995). A powerful variety is the *comprehensive situation mapping* (CSM) developed by Acar (Acar 1983) that endows causal mapping with rich computational properties. By including in the method indications, not only of the signs of the presumed causal influences, but also of their intensities and the possible time lags, Acar developed a technique for simulating manually (on the causal map itself) the propagation of change through a causal network. The rich computational semantics of Acar's causal mapping approach support automated modeling and simulation in ways that other varieties of cognitive mapping and causal mapping do not. CSM is a powerful analytical tool that allows the "forward analysis" of a situation in the sense of computing its implications as to the kinds of potential change scenarios that might occur (Acar 1983); (Georgantzas & Acar 1995).

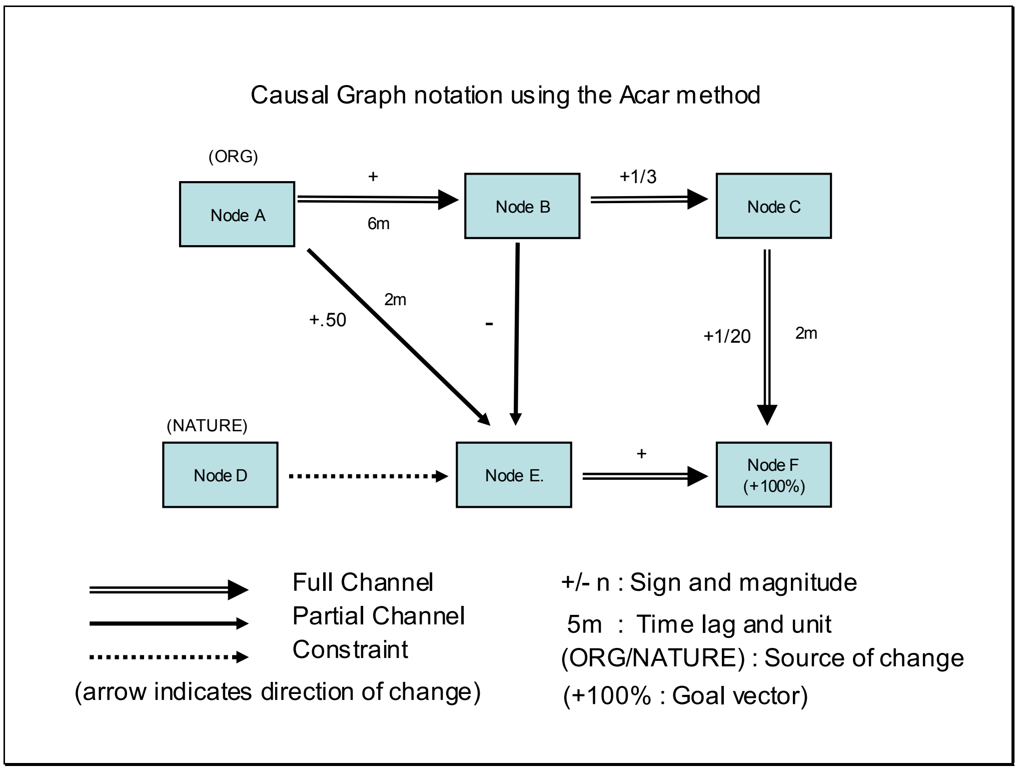

Figure 1: An Example of CSM (Acar, 1983)

The graphically based CSM method uses causal maps developed by individual managers that model the structural systemic elements of their situation and show how change is propagated through the system. Looking at Fig. 1, elements subject to change are modeled with respect to type of channel (single arrow or *half channel*, double arrow or *full channel*, and dashed arrow or *constraint*), sign and magnitude of change (+.50), and minimum thresholds and time elements (6m = six months). Sources of change are noted by the name of the source in parenthesis and goal vectors are noted on the appropriate node by the sign and percentage of change desired. Full channels transmit change as dictated by the signed magnitude, direction and time lag parameters. In order for half-channel linkages to activate, all half-channel inputs to a node must be activated. The flow of change through the system is thereby quantified and may be used for a more in-depth analysis. Causal maps can therefore become the basis of a simulation study of the strategic landscape which allows for evaluation of strategic choices.

CSM is both a collaborative process and an analytical framework. As a process it can be viewed as a collaborative dialectical conversation that through negotiation develops a common conceptual framework (causal map) of the problem situation implemented as an agent-based blackboard structure. As such, it extends the process of "assumptional analysis" described by

Churchman (1968) and Mason & Mitroff (1981). In addition, because of its forward analysis capability, the full CSM process allows for goal mapping and development of scenarios that aid strategic planning and formulation. The process proceeds in stages starting with a divergence phase in which participants create individual causal maps. The resultant maps are personal representations of the system of interest and its environment. This process sets the stage for a convergence phase where a common causal map is collaboratively developed using the insights from the individual maps. The process of convergence creates consensus through dialectical inquiry. Major and minor assumptions about the situation are surfaced and tested resulting in a commonly held perception of the situation. The system is thus classified as a Singerian-Churchman (Churchman 1971) inquiring system because different perceptions of a situation are merged through a "sweeping-in" process providing an inter-subjective view of the situation. The process of negotiation creates a foundational consensus that forms the basis for the development of newer robust strategies.

The benefits of automated support for cognitive mapping are well established and researched (Eden C & Ackermann F 1998), (Chaib-draa 2002), (Heintz & Acar 1994). Recent research (Hodgkinson *et al.* 1999) also shows that causal mapping reduces cognitive bias in the strategic decision-making process through collaborative causal mapping. Strategists, however, have long been suspicious of computer modeling and simulation as a support despite the availability of powerful tools used by management science and operations research. These tools are not user friendly to decision makers, are time consuming and expensive to develop and maintain, and frequently result in models that fit the designer's conception of the problem rather than the decision-maker's (Mason & Mitroff 1981).

The Problem of Causal Map Automation

Acar's causal mapping approach was originally designed as a manual system because of this. While these assumptions held true in the early 80's, improvements in information technology and the proliferation of automated decision support systems, group decision support systems and GUI object-oriented techniques of development forced a re-examination of those design constraints. Heintz and Acar (Heintz & Acar 1994) describe an early prototype of the system including a description of Acar's CSM semantics, process and a supporting object model. While the prototype (implemented as a Smalltalk application) demonstrated the ease of development with object oriented techniques, it was limited to the graphic editing of causal maps. This research identified technical problems associated with the initial implementation that represented limitations of the prototype:

1. *Support for a networked, platform independent application*.

The advent of internet technologies, client-server techniques and more powerful cross platform development tools such as Java in the late 90's offered a solution to the problem of networked platform-independence. A Java-based implementation supporting collaborative editing of causal maps across a network was developed, but a resolution to the second problem remained elusive:

2. *Support for Simulation and forward analysis of causal maps.*

The complexity of causal loops in the models and calculations of successive waves of change through the model when simulated, presented a substantial design challenge for developing automated scenario support using object-oriented techniques alone. The initial prototype study suggested an AI solution. However, no specific implementation was suggested. This constituted a serious limitation of the prototype and precluded its use for scenario development.

The MAS solution

Developments in distributed artificial intelligence (DAI) and multi-agent systems (MAS) have renewed interest in the project and offer unique solutions to both problems in a powerful and integrated way. ABM modeling tools share a vulnerability with other computerized approaches to modeling and simulation: they are not user friendly, are time consuming and expensive to develop and maintain, and frequently result in models that fit the designer's conception of the problem rather than the decision-maker's. The current prototype offers a unique opportunity to research human interactions and interfaces within multi-agent environments. Of particular interest in this study is the coordination of autonomous intelligent-agent activities with human agent control through agent based conceptual models of causality. Agent-based development platforms provide powerful support for creating a networked, platform independent application that can be linked with ABM simulation tools for forward analysis of scenarios. Application of these new technologies has resulted in completion of a prototype for real decision situations.

Agent-based modeling and simulation systems (ABM) have only recently been used to research and analyze business systems and environments (Robertson 2003). Originally applied to biological and ecological systems for modeling complex adaptive systems, the technique is being applied to the social sciences as well. Agent-based modeling, embraced by a growing number of scientific researchers in a variety of natural and social science disciplines, creates artificial worlds that model real world environments. Agents are used to populate these worlds and, based on simple rules, simulate the behavior of their real world counterparts. Researchers use these simulated worlds to test theoretical and empirical constructs (Panepento 2000).

ABMs provide unexpected insights into holistic patterns based on the dynamic interactions of simple components. Two basic research questions are pursued through ABM simulation: empirical evaluation of system dynamics and development of new "things that 'ought' to work" (Marcus Daniels 1999). Both of these questions are relevant to scenario planning and strategic decision support. The interaction of autonomous entities in a common environment is typically a mutually recursive process that is analytically intractable. Causal maps are models of such environments. Simulation of complex systems allows evaluation and observation of global behaviors and system dynamics that cannot be analytically predicted *ex ante.* Similarly, simulation assists the design of new complex systems composed of multiple interacting agents. Strategy is ultimately concerned with designing complex systems.

CURRENT DESIGN AND APPLICATION PROTOTYPE

The current prototype provides a graphic user interface for creating causal maps using the Acar semantic system. Once constructed, maps can then be put into motion (simulated) using RePast. Agent-based modeling and simulation is uniquely suited to analyzing the complex loops found in causal maps. The complexity such loops embody is analytically intractable and precludes the use of strictly object oriented approach to design. The simulation capability provided by RePast allows users to examine the forward implications of a causal map facilitating the understanding of often counter-intuitive situations.

Forward Analysis: Agent-based modeling and simulation using RePast

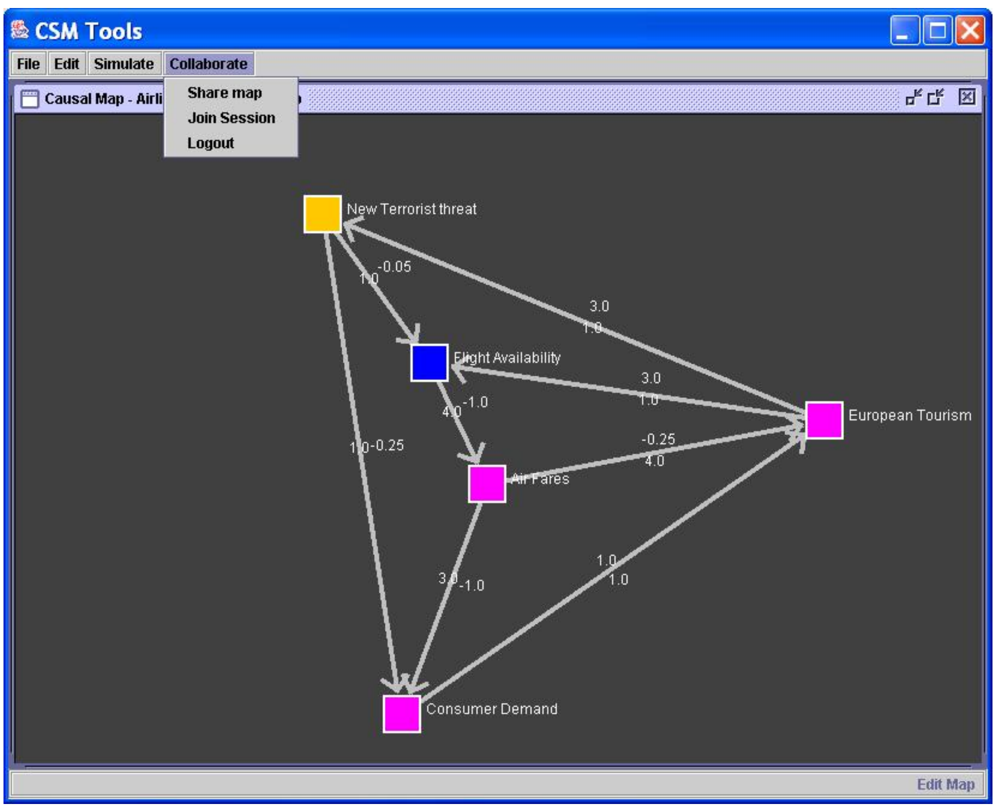

Figure 2. Editing and conferencing interface

Figure 2 shows a hypothetical scenario developed for demonstration purposes. The system is currently undergoing usability testing and several test scenarios have been developed. This test scenario studies the dynamics of tourist travel to Europe and the impact of terrorist threats on flight availability, air fares and consumer demand for travel to European destinations. Nodes and Links are placed on the map interactively using the mouse. Object properties (for nodes and links) are edited using a property sheet. Map modifications are transmitted to other joint session users by agents. In the example map, increased terrorist threats impact both consumer demand and flight availability as flights are canceled. The link notation shows that increased terrorist treats cause a decrease of -.05 (-5%) in available flights and a decrease of -.25 (-25%) in consumer demand for travel to Europe. A time lag of 1 week is indicated for both of these links. Fewer available flights forces fares higher which also affects consumer demand. Decreased consumer demand means fewer people travel to Europe. Fewer people traveling to Europe makes threats to air travel less attractive to terrorists, decreasing the threat level.

The link coefficients and time lags are only for illustration and are not based on empirical studies. Empirical validation of simulation models is an outcome of the process. At an early stage of map development, the best estimates of decision participants are used to construct individual models. A primary future thrust of this research is to enable agent based validation of quantifiable assumptions in the model through data mining or other data analytical methods.

Forward analysis (simulation) of maps can be done at any time to test the implications of created maps. RePast provides a robust simulation environment and the linked editing interface provides an easy to use graphic model building tool for RePast simulations. Causal nodes, implemented as agents, transmit changes to other agents through defined linkages. These cascading changes are graphically represented (see Figure 3 and 4).

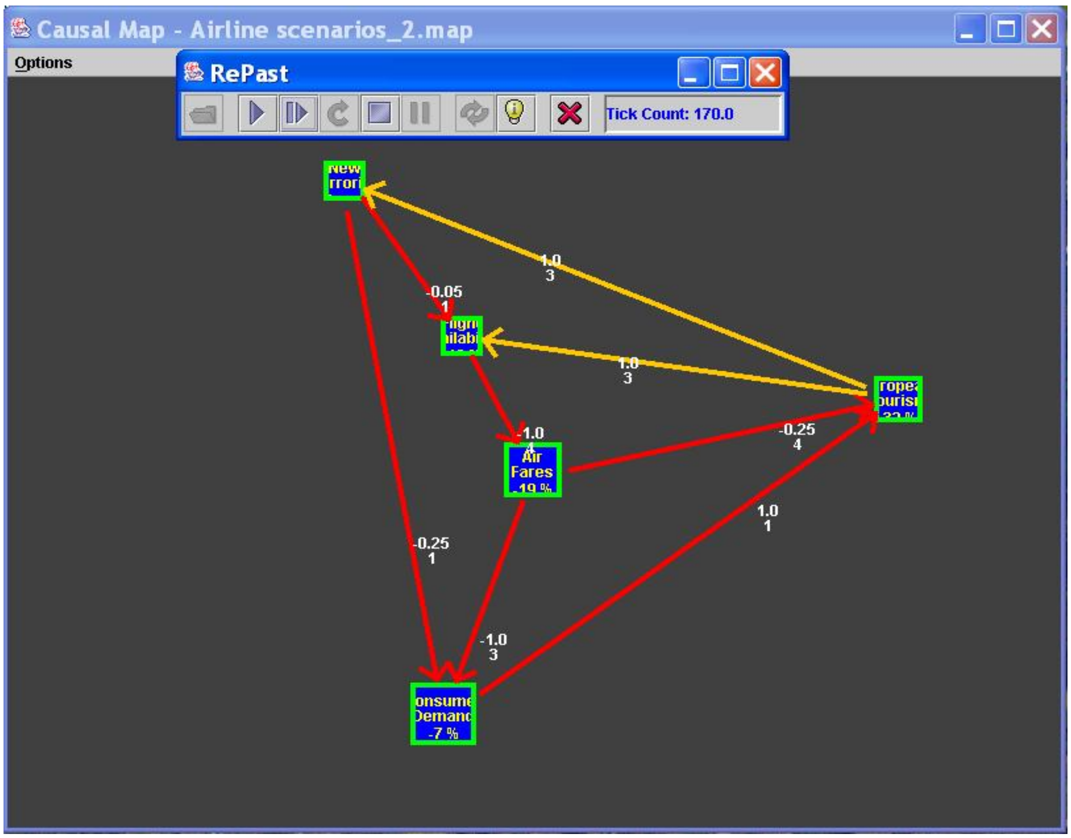

Figure 3. Repast simulation of edited map – Simulation Time 170 weeks

Emergent patterns of interaction are viewed and analyzed through animations, custom charts and graphs, and other functionality provided by RePast (see Figure 5.) This represents an advance over traditional causal mapping methods which are static representations of situational dynamics. The ability to easily animate maps and set their dynamics visually into motion is a critical development that makes causal mapping an engaging, dynamic and interactive support tool for strategic decision support.

The propagation of change through the network is color coded to enable visualization. Figure 3 shows Airline scenarios model at 170 weeks of simulated time. The initial point of change in this scenario was an initial increase of 1% over the status quo of terrorist threats against air travel to Europe. As the change propagates through the system, links are colored orange (light colored links) when changes are loaded onto the link and red (dark colored links) when they activate. At 170 weeks, terrorist threats have subsided, consumer demand for travel is on the rise and air fares have fallen. This can be compared with Figure 4., which is the map at 177 weeks of simulated time. Terrorist threats have once again increased as available flights were increased due to increased demand. More available flights provide richer targets of opportunity, etc.

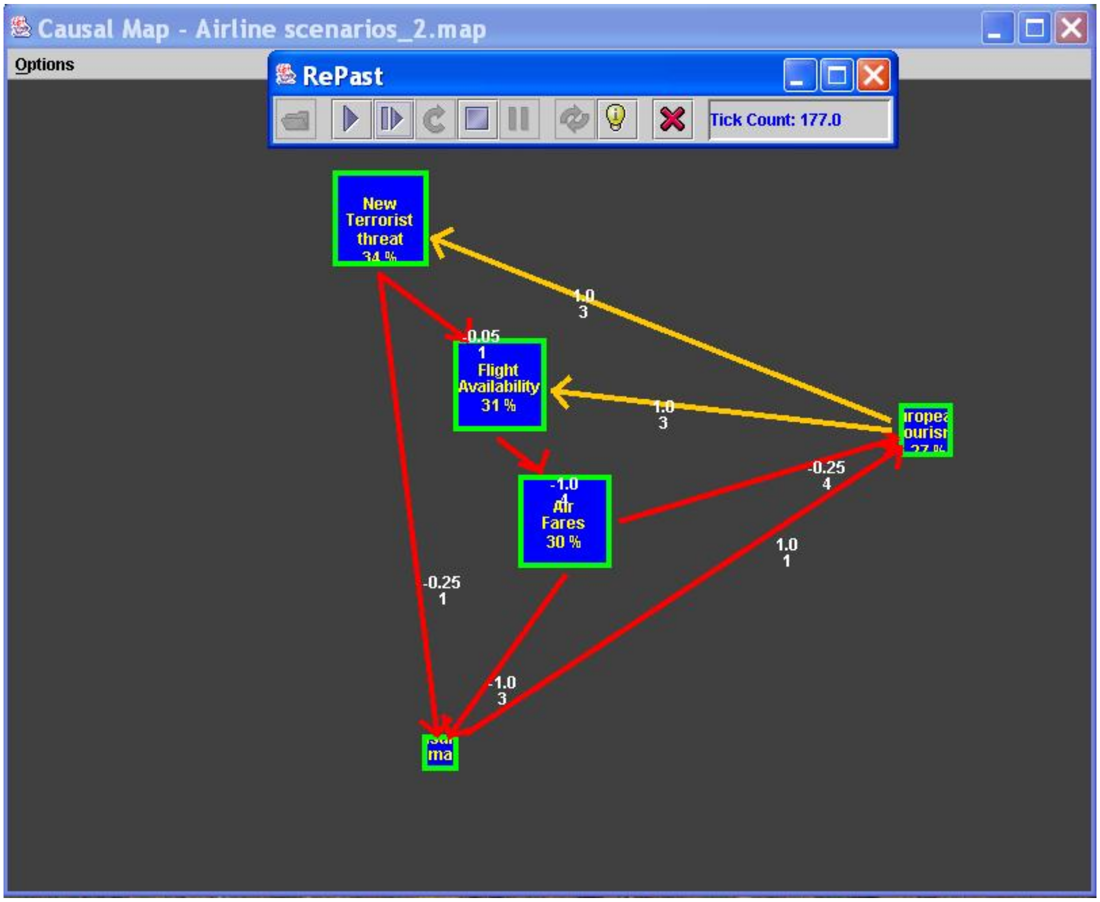

Figure 4. Repast simulation of edited map – Simulation Time 177 weeks

Initially in a simulation all nodes have a status quo level of 0. As changes are accumulated by each node, the status quo is changed either positively or negatively. The nodes are either visibly increased or reduced in size and the current change from status quo is indicated inside the node as a percentage. This scenario is unstable, viewing Figure 5. one can see a graph depicting the levels of the various nodes as the simulation progresses through time. The swings between positive and negative values get larger and larger as change reverberates through the system. This of course might represent the hope of terrorism: destabilization of an economic system and constant disruption and economic disaster.

Users examine simulation output to help refine assumptions and check the face validity of the model. The simulated outputs are the implications of the situation as it is currently modeled. An iterative process of backwards assumption modeling and forward simulation analysis allows decision makers to understand the nature of the strategic situation and problem at hand. Alternate scenarios (changes in the initial conditions or changes in map structure) can be created and stored as separate maps.

IMPLEMENTATION ISSUES

Dynamic model construction

A RePast model is dynamically constructed from the graphically edited map with individual nodes represented as agents. Links between agents constitute the environment of the system, analogous to a communication network. The graphic modeling interface facilitates an interaction between modeling of assumptions and simulation of the implications. Mapping models are easily updated, saved and shared.

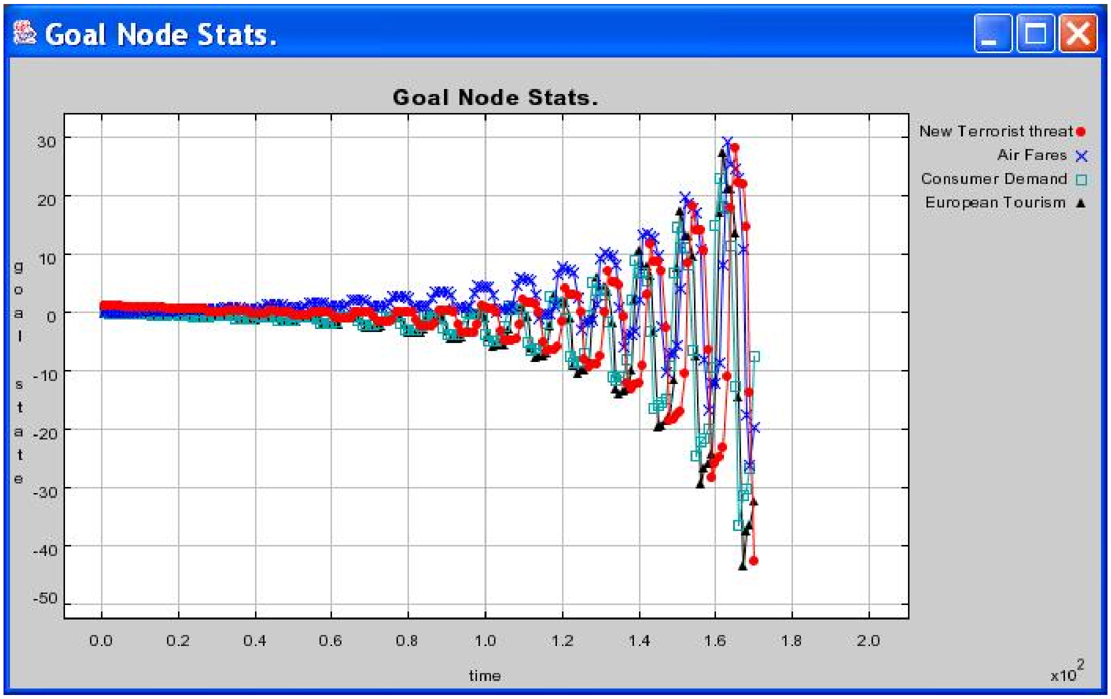

Figure 5. Repast simulation of edited map – Node graph

Agent behavior

Agents listen on incoming links for changes from associated agents. When changes "arrive", after the time lag indicated on each link, each agent updates its state by adding the new change value times the change coefficient on the link to the status quo level of the agent. Changes are thus cumulative and since link coefficients can be negative or positive the status quo level of the agent will increase or decrease. Changes do not automatically affect the agent however. Threshold values are defined that allow the agent to block or drop changes from propagating through the system. Received changes are then transmitted on outgoing communication links. Thus agents are both interactive and autonomous.

Links are implemented with a vector structure since successive waves of change can be present on a link at the same time due to the time lags and loops of specific models. As changes mature with the progression of time they become "Hot" and activate the link. The attached agent then gets the change and updates its state. The change element is deleted from the link and the agent processes the change. Links are not implemented as agents.

The different kinds of links also affect agent behavior. Agents will process *full channel* linkages if threshold values allow. *Partial channels* on the other hand are only processed if all incoming *partial channels* are activated. Agents hold activated link values in memory and when all *partial links* are active the change is processed. *Partial link* processing is not additive in the sense that the change values on each link are added together. These links represent necessary *and* sufficient conditions for a change to take place. *Partial link* changes take the minimum value of the associated links. *Restricting channels* represent qualitative factors that operate as a binary switch on the node restricting or enabling an agent. If a *restricting link* is activated the associated agent is blocked from processing changes.

Scheduling

Change is initiated in the system by the user specifying an initial level, either positive or negative, that is different from the status quo level. These changes in initial conditions are made in nodes that represent either external triggers (external agents that affect the system) and internal levers (internal agents that represent controlled agents in the system of interest.) These nodes are graphically represented in the system by a change in the node color to orange. Scenarios are run by changing the initial level of trigger or lever nodes that represent different sets of initial conditions. Primary agent behavior during each time step of simulation time is recursively scheduled. Agents must continue to process changes that cascade through the system until no new changes are present on links. This means that agent behavior must be continuous. Infinite causal loops can develop as a result. The basic problem is illustrated in figure 6.

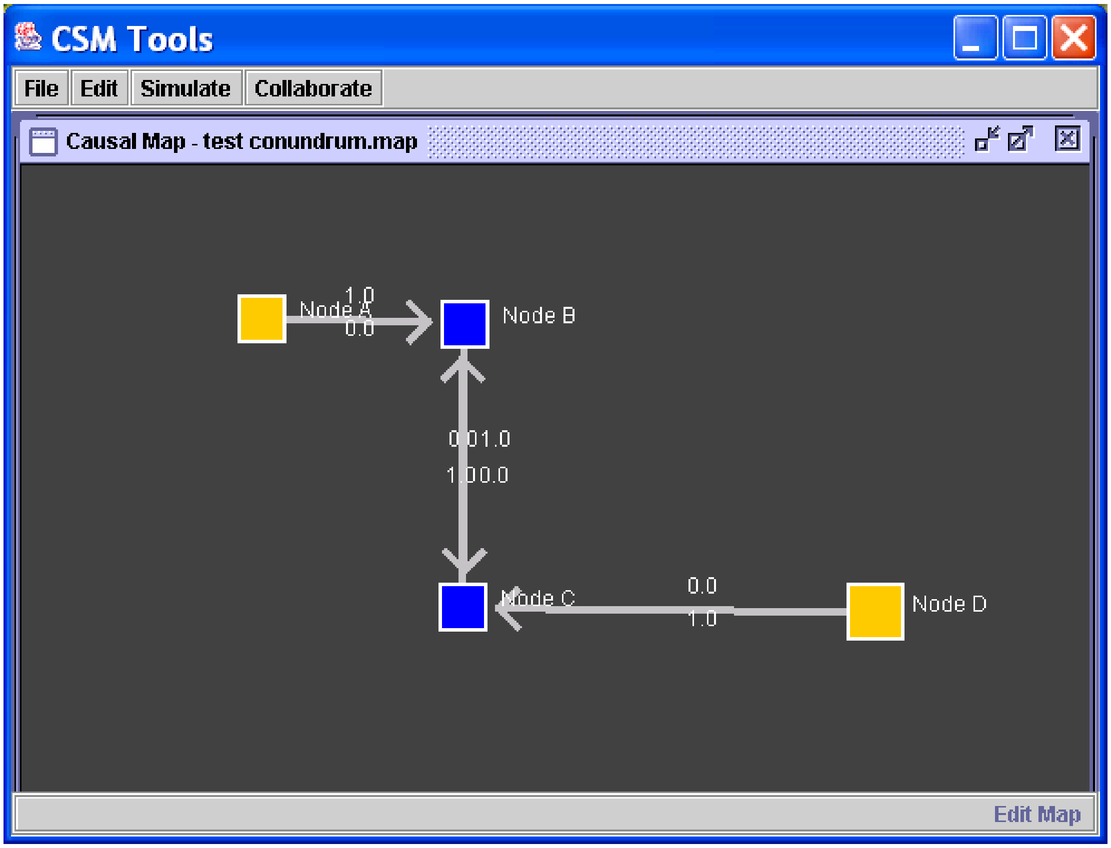

Figure 6. Test map of infinite causal loop.

Agents (nodes) are processed in order from A to D. In time step 0, agent A initiates a change to agent B. The associated channel is a full channel with a time lag of 0. The magnitude of the change coefficient is 1. Since the time lag is 0 the change is placed on the link to agent B and the link is immediately activated. Agent B is linked by a full channel with a time lag of 0 and change coefficient of 1 to agent C. The link is immediately activated. Agent C has a return link to agent B and an incoming link from agent D. Agent D is a source of change and since it has not yet had a chance to act, agent C has received no change from D. The change from A via B is present and C processes the change and places a change on the return link to B. Agent D is then processed and a change is placed on the link to C and the link is activated. If agent behaviors are only scheduled for one time activation during a time step all processing stops and the simulation time is advanced. However processing is incomplete according to the semantics of the map. There still is an unprocessed change on the D-C link and on the C-B link. The nodes should be revisited to process these new changes. After processing however, there will now be a change present on the B-C link and a second change on the C-B link. This of course leads to an infinite loop and escalating change.

These feedback loops are common in causal maps and systems dynamics and while problematic for automated processing, are essential to modeling complex systems. From the standpoint of scheduling, the infinite regress is what should happen given the semantics of the situation. Scheduling of agent behavior therefore needs to be recursive and not just a single pass polling of agents. Even without feedback loops agent D's changes would not be processed by Agent C because of the sequential ordering. Random processing could be used but with a single pass system the problem still remains. So recursive scheduling is necessary but can lead to the infinite causal loop problem.

Working solutions

Two basic approaches can be taken. One approach is to limit the semantics so that time lags of 0 are not allowed. This keeps the system from hanging and allows the loops to play out over time. Part of the problem is that we are using discrete units of time which could be 1 minute, 1 hour, 1 day, etc. Causal systems take place in continuous time but our representation is discrete. If the basic unit of time in the simulation is 1 month, a time lag of 0 means something less than 1 month. True simultaneity is not a feature of causal networks. The cause is prior to the effect (unless we are considering quantum mechanics) in social networks.

The second solution involves a more intelligent use of threshold values by the agent. Agents can keep track of time and only allow so much change during a single time step. This would allow a certain amount of recursion during a single time step but stop short of infinite progression. In the current development we have chosen the former solution while working on alternatives to the latter.

CONCLUSION

The research describes a practical linkage between scenario driven planning for strategic management and the latest distributed artificial intelligence modeling tools. Scenario driven planning is revolutionizing the way decision makers manage uncertainty and change. The development of an easy to use distributed tool for creating and simulating causal maps demonstrates the synergy of well designed methods for strategic thinking combined with intelligent support from DAI. It sets the stage for the development of a system using human/agent-based conceptual models to guide intelligent searches of internet, intranet and extranet space, thus combining ABM systems with more traditional MAS approaches.

The research discussed in this paper underlies the feasibility of using agent-based modeling and simulation to support scenario development and simulation. It provides the basic tools for combining a user-friendly interface for graphically developing scenarios and simulation models. This puts the design of the simulation model squarely in the hands of the user of the system and provides for the collaborative development of scenarios via standard internet technologies. Until this development, computerized modeling and simulation was deemed too difficult for the ordinary user and was left to specialists. Decision makers themselves can now develop and exploit the power of agent-based modeling and simulation at minimum cost and maximum effectiveness. The research also opens the door to using an agent-based conceptual model to guide intelligent searches of internet, intranet and extranet space to support backward analysis of causal factors, coefficients and relationships. Given the wealth of information available from such sources, the development of a human-artificial conceptual map will be an invaluable guide to selecting relevant information for strategic decision making.

Future research

Many research questions remain. Key aspects of the system still need to be researched and developed.

- **User acceptance.** Usability testing of the system is underway to refine the user interface and reporting capabilities of the system. The human-agent interface must be intuitive and easy to use for widespread adoption. Graphic representation of dynamic situations should lead to new insight and the formulation of useful strategies. User acceptance is also dependent on the overall design of the strategic decision making process of which software is only a part. The larger context of Scenario-Driven planning must be carefully designed to both lead into and follow from the developed tool. The development of strategies from analyzed strategic scenarios and the refinement of the inquiry system that leads to the development of causal maps is an integral part of user acceptance. This indicates the need for a succession of field research projects using this methodology, refining the basic process and contributing to the development of an effective decision tool. How can different maps from different stakeholders be compared? What role can multi-agent systems play in making such comparisons and negotiating the process of consensus that allows divergent decision makers to converge mental models in a single causal map?
- **Management cognitive models and decision processes.** Causal maps are representations of a manager's perception of the underlying causal structure of strategic situations. Investigation of decision makers' cognitive models and strategic decision formulation in specific contexts contribute to the understanding of strategy and strategic theory. What is the relationship between managerial cognition and firm performance? What processes contribute to or counteract the phenomenon of group think that can lead to strategic blunders and disasters? To what degree does situational formulation solve this problem?
- **DAI integration and application**. The developed system is an experimental system in the coordination of multi agent systems and human interactions. Research is needed to extend the system capabilities, including intelligent searching of internet, extranet, and intranet space and the integration with standard business intelligence technologies. How can the cognitive structures currently implemented as a set of linked agents be used to guide information searches that confirm or deny causal linkages and support key assumptions about change coefficients and time lags? How can cognitive models represented as agent structures be used to filter relevant information from the overwhelming amount of information in the environment?

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