PAPER 2

A FEEDFORWARD DECISION FRAMEWORK FOR CLIMATE CHANGE ADAPTATION

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ABSTRACT: The Adaptation and Impacts Research Division of Environment Canada has developed, or has access to a large number of climate change related, predictive models capable of analyzing the implications of various climate change policy options upon socio-economic, ecological systems. Until now most of these models have not been employed in an integrated fashion. This paper chronicles the initial methodological considerations of developing an integrated adaptation, mitigation, sustainable development (AMSD) decision support system (DSS), to be used in an adaptation planning exercise undertaken by Halton Municipality, in Ontario, Canada. A systems approach is used to develop a conceptual, agency-centered framework (Agent ENvironment, *AEN*), within which major modeling systems, techniques and information are to be structured. From this basis, several existing climate change impacts and adaptation research tools/concepts will be assessed in terms of their applicability to the specific context of Halton regional municipality.

Keywords: climate change, adaptation, integrated modeling, municipalities, Halton, Canada

1. Introduction

Future-oriented, feedforward planning frameworks are typically assumed to offer greater opportunities for the efficient attainment of multiple social objectives (e.g. an equitable distribution of risk (Beck, 1992)), than are feedback systems (i.e. the market, political and even biological systems). Unfortunately, in the case of climate change adaptation, the planning domain is enormous; a particular locality or region is subject to numerous ecological, social, economic and political influences. As a political entity it is one piece within a larger set of hierarchies, both imposed (i.e. within the context of the Canadian political system (Alastair, 2004) and implied (i.e. Gunderson and Holling's panarchy (2003). Within this domain, administrators must find the knowledge, expertise, resources, political willpower and consensus to proactively deal with the uncertainties associated with climate change. To address this complexity, the following approach will start with as simple a planning system as possible by adopting a systems perspective as derived from earlier work (MacLellan and Innes, 2002) and consistent with the literature on systems planning and engineering (Sommerville, 2002).

The 'systems' approach is used heuristically to aid comprehension of complex environmental phenomena, (social or natural) by dividing the environment into digestible components which are grouped together, and ordered. We take as our system components, the tools, methods and information developed by researchers at the Adaptations Impacts Research Division (AIRD) of Environment Canada. AIRD has been instrumental in developing expertise and knowledge in the field of climate change adaptation (CCA) since its inception in the early 1990s. In collaboration with partners from various levels of government, industry, and academia, AIRD has pursued research in climatic modeling and scenarios development; impact assessment; and adaptive strategies development.

Case studies have been employed throughout AIRD's history, to verify findings, integrate system components, disseminate research results, to garner information and ideas, and to maintain the relevance of the research (e.g. the MacKenzie (Cohen, 1997) and Great Lakes Basins (Mortsch *et al.,* 1997). In this instance, we will develop and apply our decision support system in the context of the Regional Municipality of Halton (see Fenech for an overview). In the following sections we develop an integrated modeling framework, which we then relate to the information, methods and tools offered by AIRD in the context of the Halton planning exercise.

2. An Integrated Modeling Framework

A decision support system is a purposeful collection of interrelated components that work together to obtain some objective (Sommerville, 2002) (i.e. to build adaptive capacity in an urban environment). The scaffolding allows systems components to be organized in a standard fashion so as to facilitate integration and communication among inter-related parts. In Figure 1, we have devised the simplest system imaginable: a *Human Agent* is separated from *Environmental Systems* (both natural and human) and sensations\perceptions (i.e. the red arrow-tail) are separated from actions (i.e. the red circle). The essential elements of this Agent/ENvironment system (*AEN*) are: dynamic models of agency, the environment (i.e. two distinct branches of science (Mill, 1874)), and the rules governing their interaction (MacLellan, 2006). In this system, an agent senses its environment, and then acts upon it as influenced by an interpretation (perception) of those senses.

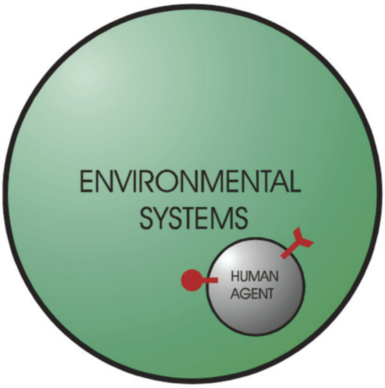

FIGURE 1
To facilitate the development of an AMSD decision support system, the world is interpreted as simplistically as possible. Human Agent are separated from Environmental Systems, and sensations/perceptions (i.e. the red arrow-tail) are separated from actions (i.e. the red circle).

Separation and isolation of components and processes, is merely heuristic (i.e. we cannot neatly disconnect sensation\perception from action), nevertheless, it may be justifiable in a pragmatic sense (MacLellan, 2006). In our crude representation, the human agent can sense\perceive the environment and act in accordance with that information. Many organisms survive with simple feedback systems no more complicated than this (see Holland's classifier systems (Holland, 1986)). Nevertheless, it should be remembered that such a representation hides the complexity of the environmental processes in which these agents are embedded (e.g. natural selection for instance). For Herbert Simon (1981) human adaptive behavior is not complex, but merely an indication of the complexity of the working environment.

The organism must develop correlations between goals in the sensed world and actions in the world of process. When they are made conscious and verbalized, these correlations correspond to what we usually call means-ends analysis. Given a desired state of affairs and an existing state of affairs, the task of an adaptive organism is to find the difference between these two states and then to find the corresponding process that will erase the difference. (Simon, 1981)

By consciously seeking knowledge about environmental processes, humans have increasingly been able to eliminate the differences between current and future desired states (externalities aside). Interacting with each other through complex working associations, storing and manipulating knowledge with ever more powerful tools, humans have been able to exert increasing control over the natural environment (Kareiva *et al.,* 2007). Knowledge production increases this power by enabling us to manipulate environmental components to meet our desired (implicit) ends. In Figure 2, knowledge production (in the context of a management system) may be represented by two basic components: *Descriptive Data* which are any data describing past (over a scale relevant to management ends) biotic or abiotic environments including social/cultural conditions; and *Predictive Models* which are any model which attempts to describe a future state of the environment (social or natural). This process starts with the classification of elements within the environment from which relationships amongst elements can be inferred, leading to the creation of predictive models. From these models, environmental conditions can be linked to both natural processes, and human interventions.

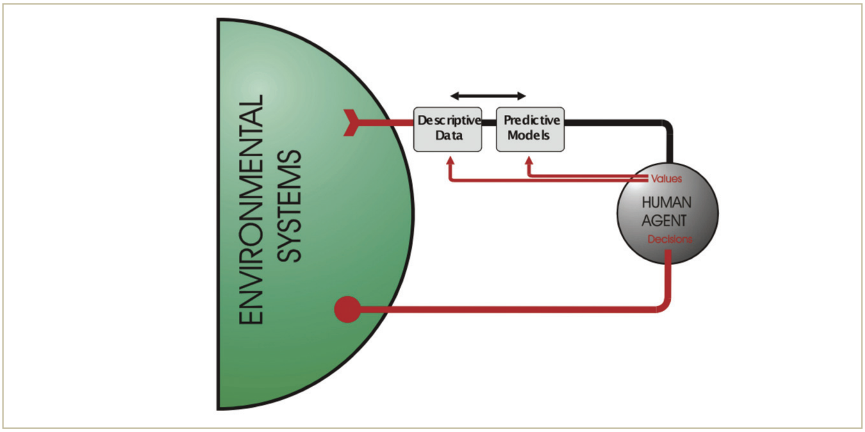

FIGURE 2
Artificially, human agents are moved outside environmental systems and the sense\agency process studied separately. Environmental information is collected and classified from which relationships between components are inferred. The process is not uni-directional (i.e. Descriptive Data to Predicative Models); requirements and results from Predictive Models influence the type of Descriptive Data collected (i.e. represented by the black two-directional arrow) and used for validation and future inference. Model output may even be used as model input (climate change model results into economic models and vise versa). The entire process is ultimately guided by human interests (values).

Although Figure 2 suggests that these elements are causally linked in a progressive, sequential sense, they overlap and interact amongst each other. For instance, 'criteria' represent the subjective measures against which the environmental state is to be assessed. Associated 'indicators' are the data which must be collected so that the current state of the environment can be assessed, as well as the future state projected. Hence, criteria selection is important in evaluating which data to measure store and evaluate. Data inventories represent the essential starting point for an AMSD-DSS. Knowledge begins with data, from which inferences of relationships between elements can be formed. Such theoretical relationships (as represented in predictive models) require information about current conditions to project future possible system states. Knowing which data to choose, given infinite possibilities, is critical from both a theoretical and practical perspective.

Predictive Models allow us to identify possible environmental and human futures. In our case, the most critical predicative models are the climate models, which project change in climatic weather patterns given estimations of past and future human influence (i.e. CO_2 increases in the atmosphere). The scenarios these models define, form the basis upon which we will assess human responses, whether adaptive, or maladaptive. In most cases, the outputs from climate models will act as input to other environmental models, such as hydrological models, productivity models, successional models, etc. For human systems such models include: hazard models, energy models, demographic models, industrial output models, etc. Though forecasting is often thought of as solely derived from computer simulation models, it should be remembered that *Predictive Models* also include knowledge-based systems (individual human cognition) wherein lies the vast majority of what we 'know'.

In the final stage of interpretation\deliberation of human adaptive futures, *Vetting Possibilities* describes the process of choosing an adaptation\mitigation, sustainable development strategy based upon a given set of values (Figure 3). In our case we are predominantly interested in the values held by the current constituents of Halton region, but we must also be aware of provincial, national and international interests which may be expressed as constraints upon municipal agency (i.e. ethical imperatives, mores, laws, policies and regulations). Such preferences are manifest in terms of how we perceive and weigh the future. Possibilities are often discounted in recognition of the fact that the future does not mean as much to us as the present, although even here the necessity of maintaining the environment for our descendants may outweigh current, egocentric values.

The vetting process covers the whole range of interpretation/deliberation activities including discerning the types of models and methodologies utilized (MacLellan, 2006). Thus advantages exist in formalizing this process so that values can be more directly tied to choices. The vetting process includes: all aspects of informing stakeholders (i.e. using visualization techniques, mailings, web-based forums, interviews, advertisements, various media, etc), techniques to search through the realm of projected human possibilities (i.e. optimization methods, heuristic search techniques, competitions), and methods for determining choice (i.e. democratic forums, ranking of choices by given criteria, etc). Approaches, which integrate analytical modeling and value solicitation, are clearly required in an AMSD-DSS. The process of value solicitation, value weighting, and assessing tradeoffs is often considered to be the most difficult part of management (Bormann *et al.*, 1994).

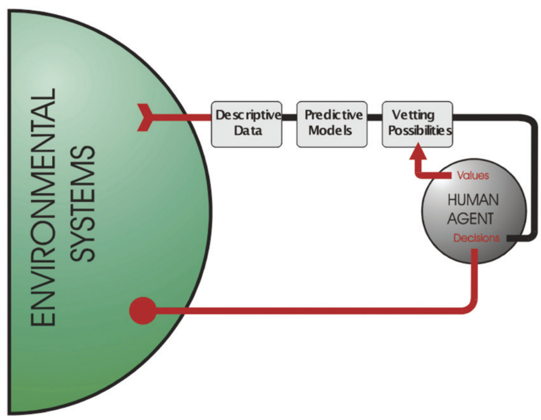

FIGURE 3
Output from Predictive Models is used to describe possible futures and our influence over them. In an ideal sense, there exists an infinite spectrum of possibilities of which only an exceedingly small fraction can be represented. Nevertheless the large state spaces created by Predictive Models must be searched to reveal feasible, valued, possibilities. This requires various biological, economical, political, or algorithmic search techniques. Through data\model combinations, and search protocols, we ignore feasibilities that are of little value to us, or those that cannot be represented. By formalizing this vetting process, we can tie values to choices more directly.

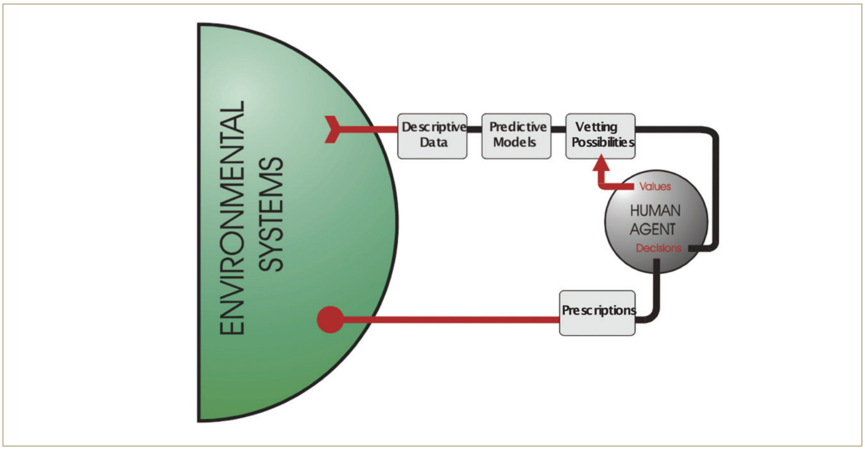

FIGURE 4
Once a desired future state has been chosen, a strategy is devised for attaining it. Given this sought state of affairs and the existing state of affairs, the task of an adaptive organism is to find the difference between the two and then find a corresponding process that will erase the difference (Simon, 1981).

Once a choice is made among future possibilities, a strategy must be determined for its attainment (Figure 4). Typically the strategy is implicit in the predictive modeling structure which was used to identify it. If a single act cannot achieve the goal, a sequence of actions which, given the initial state, the goal, a set of operators for changing the given state, and tests for determining when the goal, or sub-goals have been reached, are determined to bring the agent towards its ends (i.e. 'problem solving') (Newell & Simon, 1972; Simon, 1976). A *Prescription* describing the activity or sequence of activities the agent must undertake to attain the goal is not the final act of the agent. Numerous occurrences may happen that would frustrate goal attainment: the strategy may not be realizable; the relationship between means and ends may reveal more appropriate means or ends (Hitch, 1960); externalities not accounted for by the Predictive Models may appear; or the individuals or institutions responsible for implementation may not undertaken their tasks as prescribed. As such a monitoring program must be established to close the loop by providing information from which system improvements may be derived (Figure 5).

One shortcoming of the *AEN* conceptual framework (Figures 3-7) is that it suggests humans seek only well defined ends, or goals in their relationship with

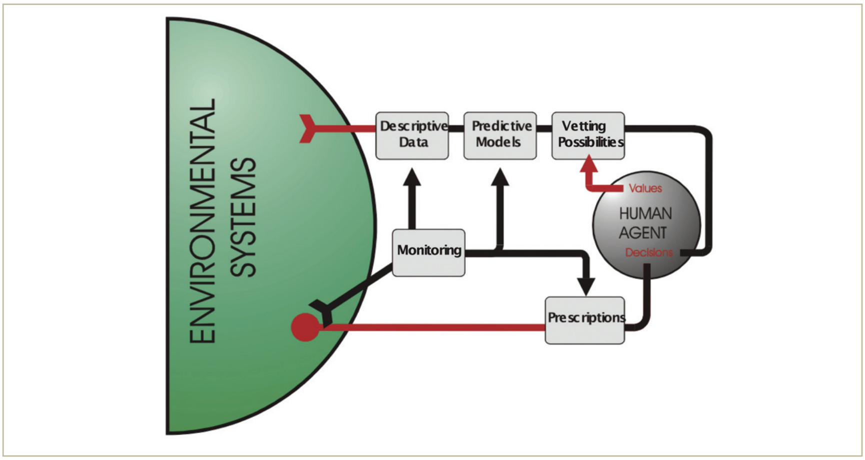

FIGURE 5
As part of a continuously evolving system, all elements of the management process are monitored, evaluated, to facilitate improvement. Identifying a strategic plan or prescription is not the same as implementing it: the strategy itself may not be realizable; the relationship between means and ends may reveal more appropriate means or ends (Hitch 1960); externalities not accounted for by the Predictive Models may appear; or individuals within institutional agents, responsible for implementation may not have undertaken their tasks.

the environment. In traditional management formulations attempts are made to predict future possibilities with as much accuracy as possible, then sift through them to provide an "optimal" strategy of management prescriptions constrained by specific environmental factors. Such methods are powerful precisely because they define a well structured problem which has unambiguous objectives, firm constraints and establishable relationships between causes and effects (Rosenhead, 1989). As Ackoff (1979) suggests they are "mathematically sophisticated but contextually naive". Ecosystem Management (EM) and its variants, focus on process; they shift our vision from the manipulation of single resources over economic horizons, to the maintenance of complete human\nature ecosystems over extended scales. This is less goal-seeking than optimal control of human interactions with the environment (see Optimal Control Theory) (MacLellan, 2006).

As such, it is useful to think of the *AEN* diagrams as existing along a number of dimensions. The first dimension expands Figure 5 by considering time: Figure 5 does not represent one sequential series of events, but is a process which evolves through the inclusion of monitoring, and continuous improvement. In this case, the choice of environmental goals may be perceived as regulative in the sense that we may never attain certain goals (i.e. ideals regarding adaptive capacity) but should seek them as a means of constantly improving our relationship with the environment (MacLellan, 2006).

A second dimension stretches across planning methodologies: imagine Figure 1 as one end of a continuum and Figure 5 as the other. In the first system, a feedback method is employed to adapt to the environment and in the second a feedforward is used. Although we typically imagine environmental management as a process of preparing the future for our needs, methods exist which can "*omit prediction entirely, relying wholly on feedback*" (Simon, 1981). Planning for distant futures becomes possible because we can combine predictive control (feedforward) with homoeostatic and feedback mechanisms (Simon, 1981) for a more robust adaptive strategy.

3. AIRD Models and Integration

The goal of this project is to test several existing climate change impacts and adaptation research tools/concepts developed by the Adaptation and Impacts Research Division (AIRD) of Environment Canada within the specific context of Halton. AIRD has developed, or has access to, a number of climate change related, predictive models capable of analyzing the implications of various climate change policy options upon socio-economic, ecological systems. The ultimate intent is to bring these tools together in an integrated manner so as to increase the decision-making capacity of municipal planners and decision makers.

3.1 Models of Future Climate Scenarios

At the core of all AIRD models are Global Climate Models (GCMs) that various international agencies have developed to examine the effects of increased carbon dioxide upon longer term climatic patterns. GCMs use mathematical models to simulate the functioning of the global climate system in three spatial dimensions and in time. Modern climate models, such as Canada's GCM, include coupled atmosphere, ocean, sea-ice and land-surface components. Constraints on the availability of computing resources dictate that coupled models, such as Canada's GCM, must operate at modest resolutions which are insufficient for detailed projections of local climate impacts. Climate impact studies (as necessary for Halton region) usually require detailed information on present and future climate with high resolution and accuracy (spatial resolutions of the order of 100 km or less). At this lowest end of the spatial resolution scale, with one or a few grid distances, the global climate models have little or no skill.

A method often used to refine results from global models is to nest a regional climate model (RCM) within a GCM. In this approach, information from the global model is used to drive a higher resolution limited area model at its boundaries. The RCM in turn simulates climate features and physical processes in much greater detail within its limited area domain. The success of the nested approach depends on the accuracy of the large scale model (at the scales that it represents) and on the quality of the regional model. Scenarios of future climate change have become available from the Canadian Regional Climate Model (Caya *et al.,* 1995) recently, and no assessments have been made of their usefulness in local climate impact studies.

A number of alternate methodologies have been developed for deriving more detailed regional and site scenarios of climate change for impacts studies. These downscaling techniques are generally based on GCM output and have been designed to bridge the gap between the information that the climate modelling community can currently provide and that required by the impacts research community (Wilby and Wigley, 1997). The literature presents downscaling techniques as generally divided into spatial (deriving local scenarios from regional scenarios) and temporal (deriving daily data scenarios from monthly or seasonal information) classes (Giorgi and Mearns, 1991; Robock *et al.,* 1993; Hewitson and Crane, 1996; Wilby *et al.,* 1998; Murphy, 1999; IPCC, 2001).

3.2 AIRD Sub-ordinate Models

AIRD has produced a whole series of predictive models sub-ordinate to the aforementioned series of climate models which produce future climate change scenarios. A good example of this form of predictive model is AIRD's work in natural hazards. As a response to demand from municipalities who seek atmospheric hazards information, and as compliance with Ontario's *Emergency Management Act*, Environment Canada developed a website to consistently present packages of data, documentation and peer-reviewed maps for atmospheric and climatological hazards in Ontario (**www.hazards.ca**). The site contains maps of various weather hazards, their trends, Environment Canada Weather Warning criteria and guidance on potential impacts of specific hazards which include extreme heat and cold, drought, extreme rainfall, fog, hail, heavy snow, blizzards, lightning, hurricanes, ice storms, tornadoes, wind storms, smog, UV radiation and acid rain.

In particular, the site can be used by municipalities and Regional ministries to determine the frequency or probability of occurrence of each hazard. The web site and publication (Auld *et al.*, 2004) reference a collection of maps from the Environment Canada led project known as Integrate Mapping and Assessment Project or IMAP (Fenech *et al.*, 2005 and **www.can-imap.ca**), as well as peer-reviewed maps developed by many other agencies. All maps (predictions) included in the Atmospheric Hazards collection are scientifically defensible (for example, journal publication, meeting World Meteorological Organization requirements for weather data archiving and analyses).

These maps, graphs and information were then assembled and assessed by themes. For example, maps assembled under the theme of extreme heat included information on record extremes, as well as the frequencies of temperature values exceeding thresholds deemed to be significant (for example, high temperatures that could typically trigger municipal heat response programs aimed at reducing health risks for susceptible populations). Other themes included frequencies for selected periods of record (for example, past 15 years), the average number of days per year with conditions exceeding specific thresholds, extreme precipitation and temperature records, probabilities of an event at a location, most recent occurrences of an extreme, return period estimates, climatic design values for engineering codes and standards, etc.

Each map theme is accompanied by documentation describing its information holdings, the data used to develop the mapped fields, uncertainties and limitations for use of the maps and references. The documentation for each hazard theme also provides listings of historical events having significant impacts on communities and hazards trends information. The project is now moving towards more probabilistic maps of natural hazards under future climate change. These maps will be used in the project for the Halton Region as a means for planning for future natural atmospheric hazards. This work is also related to research undertaken to determine extreme-weather related mortality for four selected cities in Canada (Toronto Public Health 2005).

Other *Predictive Models* available for this research include modeling systems that analyze energy type, utilization, production, and associated externalities. The *REAM* (Regional Energy Adaptation Mitigation model) suite of energy models include a provincial level (i.e. electric power grid), optimization model which examines long-term, energy mix decisions, as constrained by environmental factors. This model exists both in a spreadsheet version and a more powerful GAMS version. It allows for numerous constraints on output and energy types to be considered, and various demand scenarios to be emulated. Additionally, the Canadian Regional Energy Model operates at a regional scale in a more encompassing manner, weighing various forms of energy (petroleum, renewable, power, etc.) in the context of the production of atmospheric pollutants.

HHES (House Hold Energy System) examines optimal energy decisions at household scale (see Liu (1998) for a discussion of the merits of this level of statistical aggregation), enabling researchers to examine issues dealing with changes in consumptions patterns, energy storage systems, incentive programs and policy options that can be tied to dynamic market prices of energy. This work is of particular interest in terms of distributed demand loading and the effect this has upon provincial decisions (see Butler (2007)). Also at this micro scale, the Environmental Services Performance-research (*ESP-r*) model simulates energy consumption at the building scale and is currently being used to assess the thermal performance of green roofs. Finally, AIRD has developed *COBWEB*, which is a flexible agent-based software platform for simulating adaptation across a social, hierarchical context and can be used to examine demographic relationships with energy usage, transportation patterns, emissions, and land use patterns. Along these lines, AIRD also has access to *ABEN* which examines natural resource management issues in the face of climate change.

Numerous other models exist which will be of direct relevance to the Halton region study. Part of the goals of this exercise will be to collect and reference all the available tools for adaptation assessment at regional level. Currently numerous data management packages, predictive models, and techniques for stakeholder engagement have been produced over the history of AIRD. Relevance of each model or system is dependant upon the case study under consideration, and will have to be assessed as the project evolves. As such, *AEN* provides a simple means of integrating and categorizing these tools, allowing us to place each product in its proper conceptual framework, thus allowing it to be presented to stakeholders where appropriate.

3.3 System Integration

System integration, which involves taking independently developed systems and joining them together, represents the greatest effort in a DSS development activity. Integration not only concerns integrating modeling components, sub-components, but providing the conceptual framework upon which the system is founded, as well as structuring of essential supporting elements such as documentation, personnel, and institutional policies and practices. Given the associated complexity, an incremental integration process usually represents the most effective means of detecting compatibility errors (Sommerville, 2002).

In developing an AMSD DSS, technical considerations will be a central aspect of the process. Earlier work (MacLellan and Innes, 2002) suggests that technical integration occur in two general manners. Nelson proposes that decision support systems be built upon advanced data management systems capable of handling large data sets (Nelson, 2001). A slightly different approach is to focus upon 'model management' which provides a platform for system integration. Model management creates a consistent framework into which models of many different origins and styles can be placed (Rauscher, 1999). There are subtle differences between the two approaches. In one, system integration is left to the devices of the sub-component developer, in the other integration is a conscious objective and is 'forced' upon the developer.

Currently no comprehensive, theory based interoperability standards exist for achieving integrated operations of DSSs. These issues are relevant because systems are produced with: different data sources; different process visions; decision making methods; and solution strategies (Liu, 1998). Attempts to develop stand alone, integrated systems are not generally well received by developers who shy away from building 'big' monolithic systems, given the spectacular failures of the 1980s and 1990s. Rather, work continues upon building standards from which all sub-components can operate. Interoperability systems provide a software standard that promotes communication between components and provides for integration of legacy and newly developed components.

Data standards are developed by the Federal Geographic Data Committee (FGDC) which has a series of related programs to define standards for metadata content **http://www.fgdc.gov**. Also, standards in terms of what environmental data are reported by industry, and governments are being developed by the Global Reporting Initiative (2007). But more than any other technical development, it is the explosive growth of Web-based development tools that seems the most promising for system integration. This not only occurs at the data level (the definition of data standards which some see as the doorway to the much anticipated Web 3.0) but in terms of how results are reported (*Vetting Possibilities*). One promising avenue is the concept of an 'environmental dashboard.' In it, the results from various modeling exercises are presented in a way that is immediately discernable to stakeholders, decision-makers and developers alike.

In our case, it may be possible to represent the results of our climate modeling exercises by presenting two or three small graphs in relationship to each other, which show projections of future climate scenarios in terms of temperature, precipitation, and weather extreme events. Beside these graphs will rest other graphs showing projected demographic increases in Halton over the same time horizon, economic output, household energy consumption, etc. The dashboard would be made up of both real time data (weather reports) and long term projections. Resting behind each graph will be a series of screens arranged in a hierarchy starting with the most informative graph, data, or statement, and receding towards greater complexity in terms of results, web linkages and ultimately the actual data used to make projections.

4. Conclusions

For the most part, AIRD climate change impacts and adaptation models have been designed as stand-alone tools to inform planning processes on an *ad hoc* basis. As such, they rely upon the implicit structure of larger, meta-planning systems as described in *Mainstreaming*. These separate models will be integrated using the *AEN* conceptual framework (Data; Predictive Models; Vetting; Prescriptions; Monitoring) developed earlier to identify synergies between models, required data standards and data management practices, as well as gaps in AIRD's adaptation toolkit. The goal will be to develop an AMSD decision support system to "amplify the power of the decision makers" while at the same time recognizing that human judgment makes the final choice (Rauscher, 1999).

A decision support system (DSS) is an artificial construction which is used to aid decision-makers in their pursuit of 'good' decisions. The DSS represents a combination of decision-makers, data, projection models, and a vetting process to sift through potential choices utilizing inherent judgment or analytical search techniques (MacLellan and Innes, 2002). Each sub-component is further composed of individuals with specific expertise, as well as software, documentation and configuration data needed to operate the sub-component. As with any complex system existing within a 'stochastic' or 'uncertain' environment, the DSS must incorporate the ability to adapt to changing societal and ecological conditions. It must also recognize the innate limitations of the sub-components that make up the system.

The aim is to build a AMSD decision support system, using models developed at AIRD, Environment Canada. This is both a pragmatic as well as a theoretical exercise. It is meant to offer Halton planners useful information about adapting to climate change, as well as guidance to future research and development within AIRD. The hope is to build upon the theoretical framework developed earlier, so as to better comprehend adaptation in the urban context. In terms of *Descriptive Data*, several things must be determined: appropriate criteria and indicators, database management format, emission patterns, demographics, transportation patterns, socioeconomic infrastructure, environmental and ecological footprint, GIS potential, data Standardization and data integration with other systems.

In terms of *Predictive Models* we must determine the relevance of each mode in the context of the overall goal, the necessity of model integration (regional to provincial models, ecological to economic models, etc), and the requirements of flexibility in usage. In terms of *Vetting Systems*, the stakeholder process needs to be examined and utilized. Finally, how do the elements of *Prescriptions* and *Monitoring*, efficiently fit into an evolving architecture for AMSD-DSS? One guiding principle we can take from software systems engineering, is the importance of using an incremental integration process, as it represents the most effective means of detecting compatibility errors (Sommerville, 2002).

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