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Experiences with Implementing a Spatial Decision Support System for Planning Snow Removal Operations

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ABSTRACT

This paper discusses the development of a Web-based Intelligent Spatial Decision Support system that helps efficiently plan snow removal operations. The system is designed to integrate Web and geospatial analytical techniques for asset management, routing procedures and weather information to assist effective snow removal procedures. The system includes the knowledge from snow removal experts from Blackhawk County in Iowa and the cities of Cedar Falls and Waterloo, Iowa. It manages various resources efficiently by providing expert advice to assist complex decision making for efficient routing, optimal resource allocation, while monitoring live weather information. The system has been developed as a Web-based system to facilitate ubiquitous access and ease of use.

Keywords

Spatial Decision Support System, Snow Removal, Web-based SDSS, GIS-based Routing.

INTRODUCTION

Most of the existing methods of snowplowing management are based on human experience and trial-and-error methods. Thus the majority of the agencies involved in snowplowing do not use any substantial analytical methods before planning snowplowing in order to reduce the overall costs and maximize the overall effectiveness of snowplowing operations. Also, there is no integrated use of weather information that could alert the snow removal crews and provide a scenario-based decision support. Thus, there is a significant need for developing a system that provides intelligent decision support and a set of analytical tools for snow removal planning operations, while being very user-friendly.

Our Web-based Intelligent Spatial Decision Support System provides the required decision support by utilizing the knowledge from the snow removal experts and the weather data, in combination with GIS-based data and the asset databases. The knowledge has been gathered through the process of direct interviews with the street departments in the cities of Cedar Falls and Waterloo, IA and also from the snowplow managers of Iowa DOT. Through a series of interviews, a variety of information regarding snow removal procedures like route prioritization, resource allocation procedures and the utilization of weather data for snowplowing was gathered and encoded into the system. The GIS-based road data was obtained from the Iowa DOT's website and was utilized in designing the system. The road data was available in the form of shapefiles – a GIS format – containing various types of information like traffic volumes, number of lanes, lane length, etc.

Optimizing the snow plowing operation involves determining appropriate routes for plowing; assigning the right snowplows and operators to routes; amount of salt to use; etc. By optimizing the allocation of resources, Iowa DOT can: a) minimize deadhead times based on shortest/quickest path, b) reduce errors, c) integrate up to date weather conditions, and d) reduce storage and distribution costs. Our system facilitates efficient management and optimal allocation of resources. It considers the weather forecast and changing weather conditions to alert and change existing allocation strategies. Management of personnel, material and equipment is optimized so as to minimize, or ideally, get rid of, the wastage of resources that result from double allocation, unavailable inventory, etc. Further, our system provides expert advice for the user in a scenario-based condition, suggesting the optimal resource allocation for a particular weather condition. In addition to these, our system is

also capable of generating automatic routes (either the quickest or the shortest route) and driving directions from the snowplow station to the route. The system has been designed to be Web-based so that it provides all the advantage of web-based systems such as platform independence, centralized storage, zero distribution costs, etc. Moreover, the system provides anytime-anywhere access so that it can be accessed across different computing platforms and environments. This paper presents the methodology used in implementing the system, its features and architecture, as well as several screen-shots for better understanding of the system.

LITERATURE REVIEW

Cohen & Steward (1981) discuss the need to plan and predict the high costs of snow removal operations. They have devised a system that assists the budget planning of Illinois Department of Transportation to overcome the problem of snow removal budget exhaustion and the utilization of emergency funds for snow removal. Hintz, Kettlewell, Shambarger & Sweeney (2001) stress the high costs involved in snowplowing operations. Flambard, Lasserre, & Mohnen (2002) note that the costs of snow removal are high, citing the example of the city of Montreal. Mangold (2000) describes the cost of snowplowing, considering the usage of road salt and its importance for snow removal. Several newspaper reports also reveal the high cost factor involved in snow removal operations (Roddy, 1997; Wagar, 2004).

Literature on GIS-based winter maintenance decision support systems is sparse. Mahoney & Myers (2003) describe a winter road maintenance decision support system that focuses mainly on using weather data for maintaining roads during winters. A similar work has been presented by Pisano, Stern, & Mohoney (2004) with winter maintenance DSS that uses complex winter prediction data for planning snow removal operations. However, these systems do not integrate asset management modules and automatic routing with real time weather data. The use of software agents for GIS-based systems is well documented (Tsou, 2002; Shahiari & Tao, 2002; Odell et al., 2003). Sengupta, Bennett, & Armstrong (2000) discuss an Agent-Oriented Modeling environment for Spatial Decision Support, and describe agent architecture for decision making.

Existing literature on asset management discusses the need for cost-cutting and improving efficiency. Salim, Timmerman, Strauss, & Emch (2002) discuss asset management in detail in the context of snowplowing and demonstrate that various computing algorithms like the Hungarian algorithm, the max-flow algorithm can be adapted using desktop based software for snow removal purposes. Kane (2000) discusses efficiency of asset management under constantly changing technologies and emphasizes the need for information systems. Cohen (1981) also underscores the importance of resource allocation in the context of snow removal.

There is increased interest in pursuing the development of SDSS on the Web to support better decision-making and policy formulation. Examples include: HYDRA - a Spatial Decision Support System for water quality management in urban rivers (Taylor, 2002), development of a decision support system for a fish and wildlife assessment in the Columbia river (Parsley et al., 2000), Agricultural Farm Analysis (Vernon et al., 1999), and environmental decision making (Sugumaran et al., 2005). The literature on GIS-based routing demonstrates that there are many advantages. Shad, Ebadi, & Ghods (2003) evaluate various route finding methods for a GIS-based application. Batty, & Jiang (1999) illustrate how software agents can be programmed to find network paths, shortest routes –both ad hoc as well as in a structured way. Christian Kray (2001) shows that a multi-agent based system offers flexibility and extensibility for spatial reasoning problems. A similar approach is adapted for developing a GIS based routing for large sized vehicles (Osegueda, Garcia-Diaz, Ashur, Melchor, Chang, Carrasco, et al, 1999).

The existing literature supports the development of GIS-based Intelligent Decision Support Systems that provide analytical tools to increase efficiency of planning operations. The knowledge gained is put to use in developing our snow removal planning decision support system that utilizes technologies like GIS, the Web, and intelligent software components

METHODOLOGY

The methodology that we used for developing the system encompassed the following four steps: a) Knowledge Elicitation, b) GIS-based website design, c) Intelligent software component development, and d) GIS and intelligent software component integration. Each of these steps is briefly described below.

Knowledge Elicitation

The first step in building our decision support system was to gather knowledge from the county officials. The street department officials from the cities of Cedar Falls and Waterloo, IA were interviewed regarding various snowplowing and resource allocation procedures. Also, the snow removal experts from the Iowa DOT were interviewed on various standard operating procedures for snow removal. The knowledge thus gained was embedded into the system using Visual Rule Studio and is referenced as a DLL during spatial data analyses. The expert knowledge is very crucial for arriving at an accurate decision and therefore, the system designed will be able to replicate the human knowledge.

GIS-based website design

A website was designed containing the GIS-based road information of Blackhawk County, the study area, in the form of shapefiles. The Iowa department of transportation has a website from where all the road related information was downloaded. These maps were converted into a form suitable to be published on the Web. In effect, the GIS-based road map file was converted into an ArcIMS AXL (ArcXML) file that can be published on the Internet. The website also provides a way to perform various analyses on the road data like a route creation, assigning material to each route, etc. From within the website, live weather data can be read and various scenario based analyses can be performed. Also, there is a provision to manage various resources like material, drivers, and vehicles. The website integrates the GIS-based analytical and routing tools, and weather data into a single interface, providing a set of analytical tools for providing intelligent decision support.

Intelligent Software Component Development

A major emphasis of this research was the use of intelligent software components for decision support and integrating them into a web-based GIS system. These intelligent software components can work with minimal user input and sometimes autonomously without any user intervention. In our system, the intelligent software component helps in decision making using a set of rules and by reading the forecast weather data. It can read the current and forecast weather data and help make an advised decision regarding generating shortest paths, generating prioritized routes, and allocating resources optimally for the snow plowing purposes. The intelligent software component was designed using knowledge gathered from the snow removal experts in the cities of Cedar Falls and Waterloo, Iowa and also the Iowa Department of transportation. These rules were encoded into a computer usable form using Visual Rule Studio. Various ASP Scripts and the Rich Simple Syndication or Really Simple Syndication (RSS) technology were used to obtain live weather data. The live weather data, in combination with the encoded rules help make intelligent decisions for snow removal and resource management and allocation.

GIS and intelligent software component integration

A website was designed for publishing street maps, as well as receiving user input. Different routes are color coded to effectively present the route information. Thus, the website serves as a user interface and a way to publish the resultant maps and show the results. Till now, the usage of traditional GIS was restricted to a community of trained experts, whereas the Web now makes GIS technology accessible for many people. The greatest advantage of Web-based GIS is its online feature; it not only provides the general GIS functionality, such as zoom, pan, point and query on Internet, but also has some statistical and spatial analysis capabilities (Osegueda, Garcia-Diaz, Ashur, Melchor, Chang, Carrasco, et al, 1999). Once the initial prototype of our system was implemented, it was demonstrated to the county and city officials and their feedback was sought for improving and refining the system. The system was tested to see if it meets the required performance and requirement specifications. Once we obtained their feedback, the system was further improved and implemented.

Features of the System

A key feature of this system is network routing and generating shortest paths. The application allows the user to identify the road segments and assign priorities to these selected segments. Further, the application generates shortest or the quickest path circuits from the nearest snow plowing stations. The system uses ArcIMS RouteServer Extension to provide quick and easy way to generate routes and driving directions. Additionally, the system is also capable of producing automatic prioritized routes depending upon some pre-fixed priorities used by Iowa DOT. Snow plowing stations can be defined on the map either manually or automatically by choosing some pre-defined locations.

The next important feature of the system is the optimal resource allocation. During snow fall, resources like salt, plowing vehicles and drivers should be assigned depending upon the current and future weather conditions. Decisions should be made on the basis of the severity of snow fall, snow accumulation, wind intensity, wind direction and storm prediction factors. Also, resources should be allocated on the basis of the road priority. For example roads like highways and the roads that lead to emergency services like fire stations and hospitals should be plowed first.

The knowledge base in the system helps in making all the decisions for prioritized route generation and resource allocation. A GIS asset database stores the road information along with traffic volumes, roadway inventory information, etc and assists the user in decision making. Thus the system combines Geographic Information Systems with Intelligent software components and facilitates its usage through a web-based interface. The web browser provides the communication between the map display and the spatial server and other server side components over the Internet.

SYSTEM ARCHITECTURE

The architecture of our intelligent SDSS consists of the following three main components: a) intelligent software component, b) GIS-based website, and c) databases for spatial and non-spatial data. These components are briefly described below.

The intelligent software component comprises of the expert knowledge base and the module that automatically reads current and forecast weather data to assist in planning and major resource allocation decisions. The knowledge-base containing expert knowledge of county and city officials has been implemented using Rule Machines Corporation's Visual Rule Studio. Visual Rule Studio provides for encoding expert knowledge in the form of "If-then" rules. These rules can be "fired" depending upon various factors and can help make a decision, rivaling a human expert knowledge.

The website hosts a GIS-based road map and provides information on various roads in the Blackhawk County. Also, the website provides a place for providing user-friendly interaction and result dissemination. All the asset databases are managed through the website and the website also serves as a central location for all planning and decision making.

The Asset Databases contain information about various transportation assets that are utilized in snow removal activities such as characteristics of snowplows, capacity, mileage for equipment maintenance, Odometer reading prior to assignment of the machine, details of the materials available at the central storage for snow removal, available quantity, unit cost of the material, reorder point, assignment of the operator to preferred machines, etc.

SYSTEM IMPLEMENTATION

The system has been implemented by creating a website using ArcIMS, the most popular web-based GIS software produced by ESRI Inc. The system utilizes the ArcIMS ActiveX Object Model, XML, ArcXML, and Visual Rule Studio. The GIS software component sits on the server and provides GIS functionality to the user through a web browser. ArcIMS has got several servers such as the application server, query server, image server, and feature server that use the underlying data. These servers, in conjunction with the spatial/non-spatial data, produce and render maps through the browser. The communication between the map display and the spatial server is performed via a standardized and proprietary XML format called ArcXML. The system primarily uses Active Server Pages technology for programming the server side components. Figure 1 shows the various components of the system that has been implemented.

The ActiveX Connector of ArcIMS was chosen over HTML and Java Connectors for its ease of use and provision for web programming with ASP, a server side scripting language. Also, the expert knowledge system created with Visual Rule Studio can be easily integrated into the system. For reading weather data, the RSS feed technology was used to read in the XML data containing live and forecast weather information. This information is automatically used to make decisions regarding resource allocation, generating weather alerts and providing suggestions for resource allocation. For efficient resource allocation, various asset management and assignment algorithms are employed and coded into the system using ASP.

SAMPLE INTERACTIONS WITH THE SYSTEM

User Interface

The system provides an uncluttered interface, divided neatly into various "areas" (see Figure 2). For example the menu and the tool bar appear on top, and the map and map layers area are beneath the menu, and a "message area" displays detailed messages to the users. The interface is mainly menu driven, making it very easy to use. All the menu options are given appropriate, non-technical names so that a naïve computer user can also utilize the system. The system generates verbose and detailed alerts, warnings, tips and other messages that help a non-technical user better understand the system. Most of the commonly used menu options are provided as tools on a separate tool bar and can be used by clicking on the appropriate icon. When the user clicks on particular tool, a message is displayed in the message area of the window. A detailed help system is available, which avoids technical jargon and provides the user an easy guide to use the system.

Routing

The routing module essentially deals with generating routes for snowplowing. The system provides two options for routing, namely manual and automatic. Manual routing is the process where the user selects the route to be plowed, starting from the snowplow station, whereas automatic routing produces the maps for the user automatically.

For manual routing, the system provides tools to create, manipulate, and delete routes. To start, the user selects Route > Create > Start Route from the menu. The user can select a route by clicking on the road segments on the map. The user can also choose if a segment will be snowplowed or just traveled upon. The "Delete > Segment" option lets the user delete

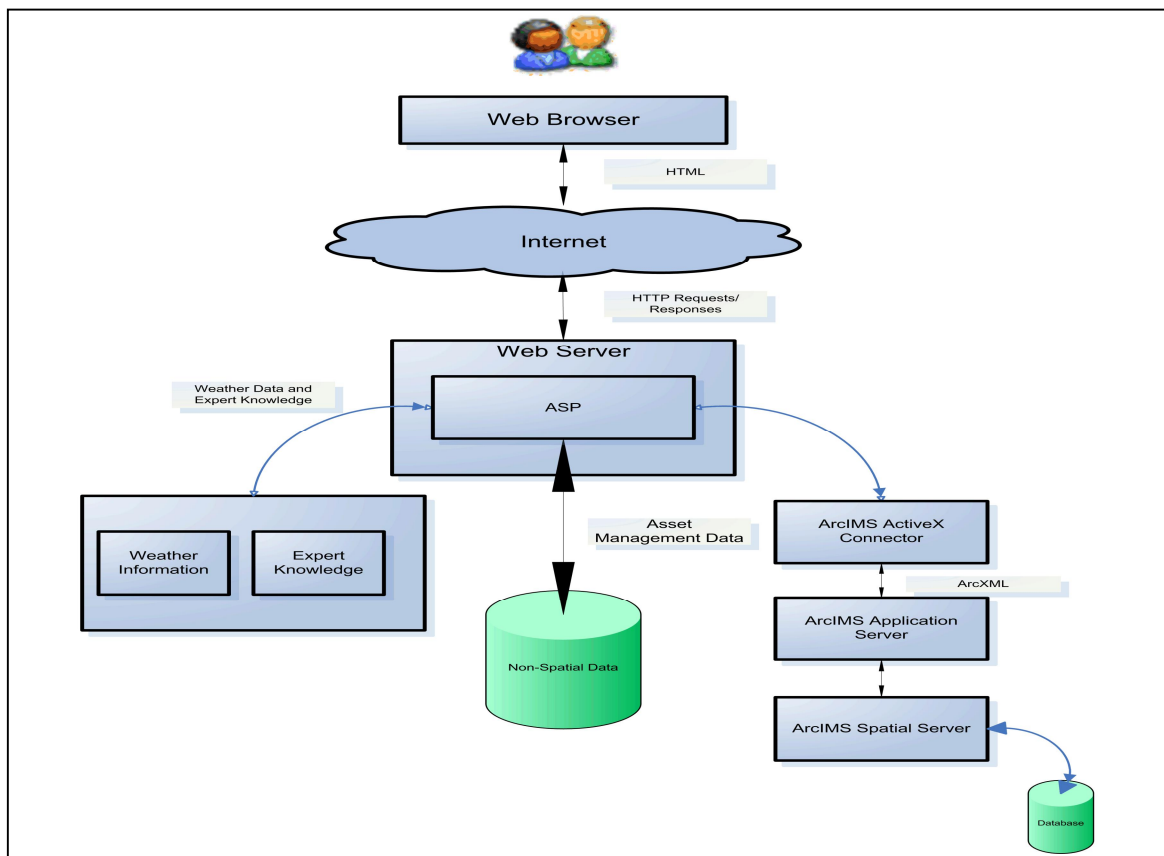


Figure 1. Architecture of the system

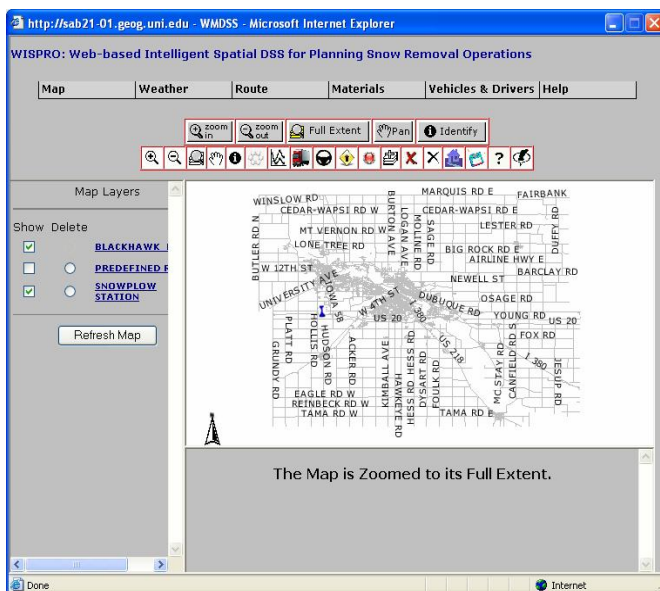


Figure 2. The Main Interface Window for the System

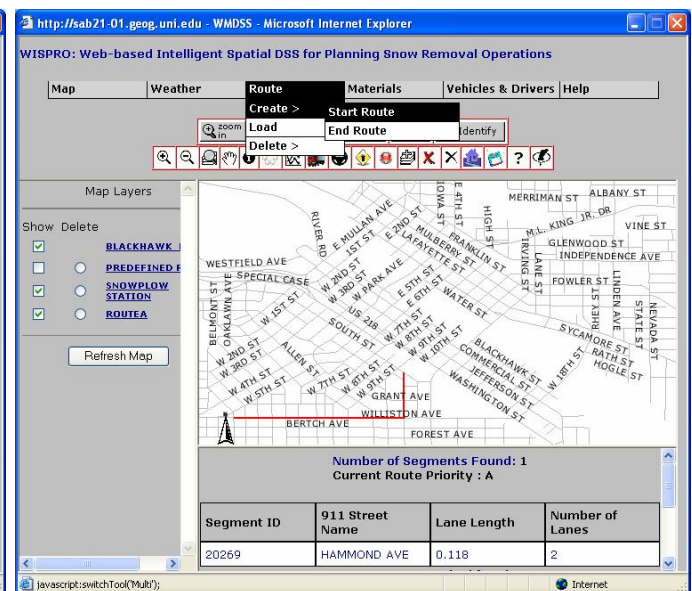


Figure 3. Process of Creating a Route Manually

individual segments while route creation. Once the route selection is done, the route can be saved by choosing "Route > Create > End Route" from the menu. Figure 3 shows the procedure. Alternatively, the user can click on "Start Route" and "End Route" icons on the toolbar.

Automatic Routes are shown on the map as predefined routes. They are the standard routes used by the Iowa DOT to snowplow, based on a priority (see Figure 4). The manual route creation tool helps add new routes as necessary. For creating a route, expert knowledge is used to determine the estimated snowplowing time, number of runs and the total snowplowing time. The program utilizes expert knowledge encoded as business-rules and embedded as a DLL to obtain the results.

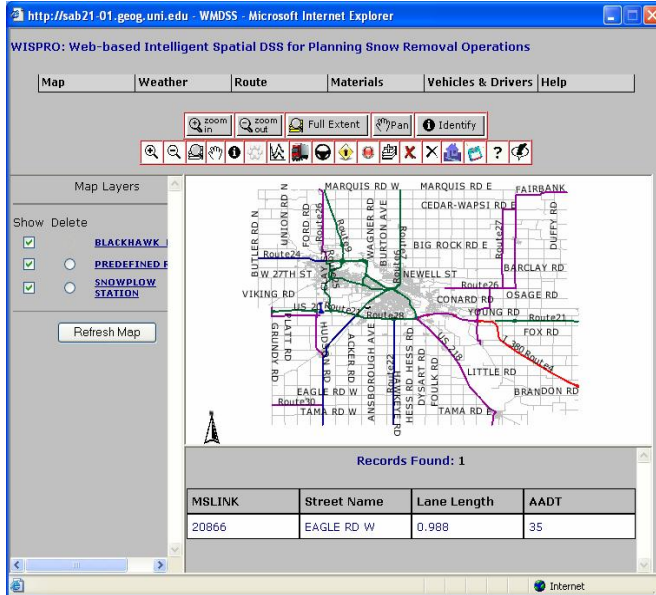


Figure 4. Predefined, Color-coded Routes of the System

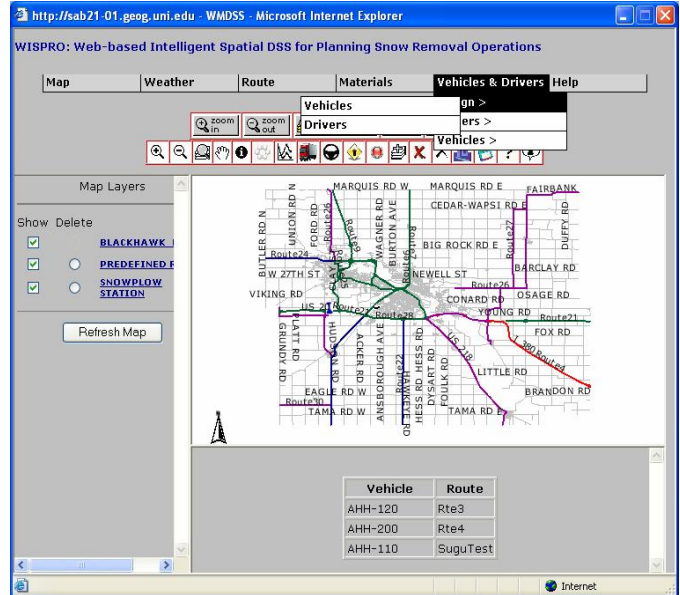


Figure 5. An Example Vehicle Assignment

Resource Allocation

Vehicles

Upon the creation of routes, vehicles can be assigned to snowplow these routes. The Vehicles & Drivers > Assign > Vehicles option from the Menu lists all the available routes and available vehicles will be displayed in the message area. Upon clicking the "Assign" button, vehicles are assigned to the routes, depending on the priority and the total snowplow time for each route.

In order to assign the vehicles, the Hungarian algorithm was employed. The Hungarian algorithm is well tested and proven for assignment problems of $m * n$ matrices, which precisely represents the current problem of allocation of vehicles to the routes. ("m" vehicles to "n" routes). An example of vehicle assignments is shown in Figure 5.

Drivers

Once the routes are created and vehicles are assigned to these routes, drivers are allotted a route. The "Vehicles & Drivers > Assign > Drivers" option from the menu can be used to assign drivers. Each driver has a choice of three vehicles that he or she can drive and these choices are stored in the drivers' database. The allocation of drivers to the vehicles is based upon a heuristic-based algorithm. The algorithm works the following way:

The algorithm first assigns the drivers that can drive only one vehicle, and then the drivers that can drive two vehicles and then, the drivers the can drive three vehicles. In case of drivers that can drive more than one vehicle, the "cost" factor for a driver to drive a vehicle is taken into consideration. Since this is a heuristic based algorithm, the system provides facilities for overriding the assignments and allocating the drivers manually. An example of driver assignment is shown in Figure 6.

Material

Assignment of materials is based on the suggestions generated by the system based weather conditions. The system provides for the allocation of material by the type of material like liquid salt, sand, etc. Material for each route is assigned based on the

snowplowing time, the priority of the route, etc. Data such as the unit cost are retrieved from the materials' database and used for material assignment. For material assignments, the system uses the same assignment guidelines used by the DOT in the form of encoded expert knowledge in the system. Also, the system provides an option to perform inventory analysis in order to determine various crucial inventory parameters such as reordering point, reorder costs, economic reordering quantity, etc.

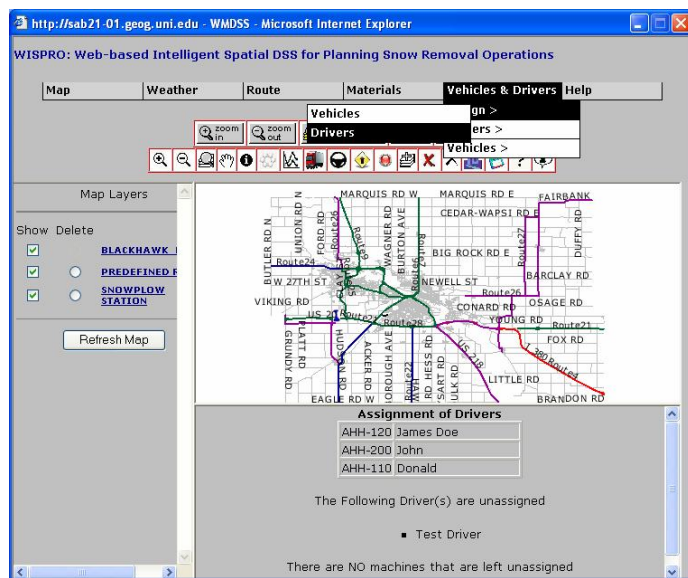


Figure 6. An example Driver Assignment

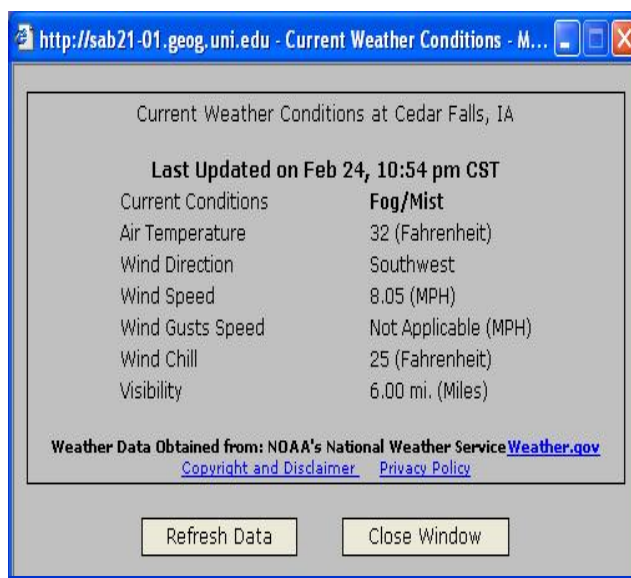


Figure 7. Live Weather data read from NOAA's National Weather Service using RSS XML Feeds

Weather

Weather data for this project is obtained using the RSS and XML feeds technology. RSS is an XML based document format for syndicating news and other timely news-like information (NOAA, 2003). Free weather feeds are available from online sources like www.rssweather.com, www.weatherroom.com, www.weather.gov, etc. By loading the XML Document Object Model (DOM) through an ASP program, various tags of the XML document can be interpreted and presented to the user. For this project, the weather data is embedded into the system by reading the free RSS and XML Weather feeds provided by www.weatherroom.com and NOAA's National Weather Service (<http://www.nws.noaa.gov>). These XML feeds essentially provide an XML document that encodes various weather parameters including the air temperature, wind speeds, wind direction, wind-chill and visibility. Live as well as the forecast weather data can be obtained and presented to the user in this fashion by reading a particular weather feed webpage, and loading its DOM. Thus, weather feeds are read directly from the Internet using RSS/XML technology. Once a user stores the weather feeds, the system responds by producing a set of suggestions. The suggestions are inferred by the expert system based on the expert knowledge stored within the system. These suggestions include road treatment suggestions, advice on initiation of snowplowing operations, etc. Further, these suggestions are utilized while allocating material (based on road treatment suggestions). Thus, up to date weather conditions help generate suggestions for material assignment and help determine the allocation of resources. The forecast data is used to generate alerts. The weather information can also be used for generating scenario based solutions. An example of live weather data retrieved for Cedar Falls, IA is shown in Figure 7.

LESSONS LEARNED AND DISCUSSION

This project provided us with many important lessons in implementing the prototype, particularly in areas of ArcIMS customization, knowledge engineering, asset management algorithms' application, real-time weather data usage, and expert systems integration with a Web-based GIS. The technology choice for the current system – ArcIMS ActiveX Connector – was made based on its availability on Windows operating platform and the wide availability and usage of related technologies like Active Server Pages and IIS. For the knowledge base, Visual Rule Studio was chosen for its tight integration with our chosen technology of Widows, IIS and ASP. Visual Rule Studio provides the ability to integrate a knowledge-base as a Windows DLL within the ASP pages on the server.

There were several technical issues that we dealt with during the development of this prototype. On the server side, managing various ArcIMS virtual servers and services was challenging and a good learning experience. A "Virtual Server" is a logical grouping of spatial servers (e.g., Image Server, Feature Server, etc) that is used to manage and balance the load across several

spatial servers. Since the application is web-based, and involves map rendering and routing, it is desirable that the response times are lower. Employing a virtual server architecture ensures that the application responds faster by balancing the load across multiple servers. An important lesson learned while administering ArcIMS Servers was that an optimal balance of virtual servers can handle constant traffic to the website without hogging memory resources. Another issue was the slow response of the ArcIMS servers. This can also be solved by adding or deleting virtual servers as necessary. Further, there were some issues dealing with obtaining live weather data in the form of XML feeds. Since most of the weather feeds are provided for free, the updates are less frequent, which inhibits our ability to provide actual “real-time” weather data at all times. However, there are weather services with paid subscriptions from where current and historical weather data can be accessed instantly. Also, the updates are being provided for an entire area like a city or a county. If weather data is obtained by each road segment, more customization is possible. With the knowledge component, embedding the business rules into a DLL made the project “distributable”. If the client (e.g. DOT) plans to use it on multiple machines, there is no need to purchase several versions of Rule Studio’s inference engine to use the system. A major issue with the knowledge component was knowledge engineering - the process of knowledge elicitation and knowledge representation. Since the knowledge gathered was in the form of “a set of conditions resulting in a set of actions”, we concluded that Rule-based representation knowledge was the most appropriate for the current system.

For extending this prototype, ArcGIS Server 9.x can be used in conjunction with ArcObjects to provide advanced functionality like adding new features (e.g. new roads) and advanced geo-analytical tools. Additional solutions based on “intelligent technologies” such as agents can be explored to extend the fundamental rule-based system to a full-scale “Intelligent Agent” based system. Also, the usage of commercial weather data service that provides frequent updates and segment-wise conditions can improve the efficiency of the current prototype by generating very accurate snowplow routes and by cutting costs further. Currently the prototype is optimized to work with the Microsoft Internet Explorer browser. This prototype can be further expanded to work with other browsers such as Netscape, Mozilla, and Firefox by carefully considering the cross-browser functionality issues.

CONCLUSION

The maintenance of snowplowing operations during winter is a major challenge for many governmental agencies. Existing methods for snowplowing planning operations are either manual or stand-alone single user systems that are not efficient for optimal resource allocation and effective snowplowing. The Web-based Intelligent Spatial Decision Support System presented in this paper overcomes the disadvantages of the existing systems by providing intelligent decision support for effectively planning snow removal operations. The system has been designed integrating ArcIMS ActiveX Connector with ArcIMS RouteServer Extension and web technologies like ASP, XML, RSS, etc. The system provides prioritized route creation, inventory management, resource allocation and provision for embedded weather information. The sample test runs show that the system could effectively plan snow removal planning based on live and forecast weather data, and thus can improve snowplowing efficiency, thereby cutting costs for the parties involved in snow removal procedures.

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