

Artificial-Intelligence-Based Optimization of the Management of Snow Removal Assets and Resources

Final Report—October 2002

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16. Abstract Geographic information systems (GIS) and artificial intelligence (AI) techniques were used to develop an intelligent snow removal asset management system (SRAMS). The system has been evaluated through a case study examining snow removal from the roads in Black Hawk County, Iowa, for which the Iowa Department of Transportation (Iowa DOT) is responsible. The SRAMS is comprised of an expert system that contains the logical rules and expertise of the Iowa DOT's snow removal experts in Black Hawk County, and a geographic information system to access and manage road data. The system is implemented on a mid-range PC by integrating MapObjects 2.1 (a GIS package), Visual Rule Studio 2.2 (an AI shell), and Visual Basic 6.0 (a programming tool). The system could efficiently be used to generate prioritized snowplowing routes in visual format, to optimize the allocation of assets for plowing, and to track materials (e.g., salt and sand). A test of the system reveals an improvement in snowplowing time by 1.9 percent for moderate snowfall and 9.7 percent for snowstorm conditions over the current manual system.			
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ARTIFICIAL-INTELLIGENCE-BASED OPTIMIZATION OF THE MANAGEMENT OF SNOW REMOVAL ASSETS AND RESOURCES

MTC PROJECT 3-A

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EXECUTIVE SUMMARY

This report presents the results of research on the development of an intelligent system to integrate a generation of snowplowing routes and the optimization of resource/asset allocation for snow removal. The developed system, known as the snow removal asset management system (SRAMS), is an expert system containing the logical rules and expertise of the Iowa Department of Transportation's snow removal experts in Black Hawk County, Iowa, and a geographic information system to access and manage road data. The system is implemented on a mid-range PC by integrating MapObjects 2.1 (a geographic information systems package), Visual Rule Studio 2.2 (an artificial intelligence shell), and Visual Basic 6.0 (a programming tool).

The main goal of the study was to build a knowledge-base that allows the Iowa Department of Transportation and other agencies to optimally manage snow removal assets and resources. The SRAMS was designed to be fully interactive and include provisions for entering meteorological observations and field data to refine the snow removal plan. The system is able to run various scenarios and generate prioritized snowplowing routes in visual format, and to optimize the allocation of assets and resources for snow removal. A test of the system reveals an improvement in snowplowing time by 1.9 percent for moderate snowfall and 9.7 percent for snowstorm conditions over the current manual system. Another major benefit of the system is its ability to track inventory of materials such as salt and sand.

This report also documents knowledge acquisition and system design, the algorithms used for optimization, and system validation and field testing. Several appendices with more detailed information are provided at the end of the report.

INTRODUCTION

This report summarizes the results of research on the development of an intelligent snow removal asset management system (SRAMS) to optimize resource allocation. The SRAMS uses MapObjects 2.1, a geographic information system (GIS) package, to access and manage road and bridge data; Visual Rule Studio 2.2, an artificial intelligence (AI) shell, to create a knowledge base; and Visual Basic 6.0, a programming tool, for its user interface.

Keeping roads clear of snow and ice during the winter months is a major expense for many regional and local governments. Thus, there is much interest in the development of analytical tools to support improved resource allocation, since even marginal cost efficiencies can yield very high aggregate benefits. The essential issues to be considered in snow removal are the allocation of personnel resources (drivers, mechanics, supervisors), the distribution of materials (road salt, road sand, other ice/snow removal chemicals), the deployment of equipment (snowplows, dump trucks, supervisor trucks), the observance of financial constraints (salaries, materials, repair costs), and the maximization of overall effectiveness (e.g., minimizing dead-heading or the movement of plows on roads already plowed, ensuring that safety-critical and time-critical roads such as access points to hospitals, schools, and major employers are plowed quickly). Because the movement of assets becomes difficult or impossible once snow has accumulated, a great deal of planning and preparation is needed to ensure that adequate stocks are in place at the right times and in the right places. Prediction focuses on several factors including meteorological data and geographic information. Knowing how much snow is expected and in what time frame is important for allocating resources.

Both a knowledge base and a GIS database were developed to support the SRAMS. In order to build the knowledge base, an advisory board consisting of road maintenance engineers, supervisors, and managers was assembled. Through the knowledge elicitation process, a series of interviews was conducted with local and state winter maintenance personnel on a wide variety of issues related to their snow removal procedures. Personnel from the city, county, and state levels of government were interviewed to consider any difference in standard operating procedures by type of agency or scale of operation. Typical issues discussed during these formal interviews included route prioritization, procedures for managing drivers and vehicles, treatment of the roads with salt and sand, inter-agency and intra-agency communication and coordination, minimum snowfall thresholds to mobilize equipment, and other decision-making procedures related to the management of snow removal assets. The responses were formalized and incorporated into the SRAMS.

The system also required roadway data to support the allocation of routes, drivers, and other resources. For this, a GIS database for all roads in the case study area (Black Hawk County, Iowa) was obtained from the Iowa Department of Transportation (Iowa DOT). This database consisted of a GIS shapefile and several related database files with traffic volumes, roadway inventory information, and other data. The data elements required for the SRAMS were extracted from this database and a new shapefile was generated for incorporation into the system.

This report documents the development of SRAMS and its components. A literature review of the state-of-the-art and practice is provided. The report presents the functional specifications and architecture of the system, followed by a description of the program development, system implementation and testing. Evaluation of field testing and conclusions are included, and future research directions are outlined. Several appendices of more detailed information are also provided.

REVIEW OF LITERATURE

A considerable amount of literature on transportation asset management has been completed. Recent publications have outlined the general case for applying asset management tools in the transportation construction and infrastructure maintenance industries [11, 12, 15, 29, 47]. Ruben and Jacobs [36] and Spalding [39] have approached asset management problems in transportation from a more applied perspective by exploring the use of asset management for the supply of construction materials. Iraqi et al. [21] have described the implementation of computer resources for construction-site management and applied real-time site-based sensors for monitoring potential construction logistics problems.

A substantial amount of research on the integration of databases and expert systems, the application of GIS in transportation asset management, and basic principles of applying optimization techniques is available. In the area of expert system development, recent papers include the work of Begur et al. [2], who integrated GIS information in the optimization of routing for visiting nurses, and Weigel and Cao [49], who optimized the routing of Sears service vans using operations research methods combined with GIS to save \$42 million per year. In the area of municipal public works projects, Tsai and Frost [45] have integrated a GIS database with a knowledge base for toxin remediation, and Kamler and Beckel [23] have illustrated the integration of GIS with other databases for public transport management.

Several agencies' efforts in implementing transportation asset management systems have been documented recently [9, 30, 40]. In the area of integration of GIS in asset management for public works, relevant works include that of Chang, Lu, and Wei [4] in municipal solid waste removal, Yeh and Tram [51] in electric power delivery, and Taher and Labadie [43] in municipal water distribution. The Federal Highway Administration of the United States Department of Transportation [13] has conducted research to develop programs that are capable of integrating urban planning travel models and GIS packages such as ArcView, AtlasGIS, MapInfo, and Maptitude. Loomis [27] has developed a computerized asset management system integrated with GIS. A paper in this area is that of O'Neil [32], who described the use of GPS in municipal transportation planning.

Several papers have contributed to the literature describing the application of optimization theory to transportation problems, including the work of Powell and Sheffi [34], describing probability techniques of stochastic methods for public transit service optimization, and Hall [16], discussing the generalization of these techniques to study travel times of vehicles. The application of heuristic techniques in optimizing of transportation problems has been reported in many publications [3, 5, 6, 44, 46]. In addition, there have been several studies using AI techniques to optimize transportation problems. For instance, Stiles and Glickstein [42] have described the use of low-level but highly scalable programming elements called "cellular automata" to solve this class of problems, and Kaufman et al. [24] have applied a proprietary IBM software package called "OSL Branch and Bound" to optimize public transit for the city of Sioux Falls, South Dakota. Pattnaik et al. [33] have used genetic algorithms, and Holmes and Jungert [18] have used geometric pattern analysis, to solve similar problems.

As an AI tool, expert systems have been used by several researchers in transportation. For example, Ljunberg [26] has developed an expert system for the selection of deicing material for winter road maintenance. Hung and Jan [19] and Jia [22] implemented knowledge-base techniques for construction problems, and Melhem et al. applied such systems to steel bridge construction [28].

The implementation of an expert system for asset management requires careful consideration and the selection of appropriate algorithms. Sayed and Razavi [38] compared several AI-based algorithms with more traditional mathematical approaches. Cortina and Low [7] developed a computer program, Snowman, for the town of Brighton, New York to improve snowplow routes. Walker [48] discussed advances in materials, application techniques, equipment, and operations, and suggested to maintenance and operations managers that they review new technologies and practices and select methods that are appropriate for their agencies.

With all the literature existing related to transportation asset management and optimization, the use of GIS for planning snowplow routes, expert systems for transportation infrastructure maintenance, the importance of and interest in these topics is evident. Researchers have also discussed the possible use of decision-science tools for optimizing asset management [3, 5]. The software that is developed in this project combines and integrates GIS spatial information, asset, resource, and traffic information in existing databases, and AI decision-science optimization tools to optimally manage assets for snow removal by the Iowa DOT in Black Hawk County.

SRAMS ARCHITECTURE

The provision of snow removal services during winter months on a consistent basis requires informed decision making at a variety of levels, from the planning stages, to the selection of routes and assignment of snowplows and required materials, and finally to operation and maintenance activities. The allocation of resources at each level of the asset management process entails unique considerations, but common issues emerge throughout all levels. In Black Hawk County, individual maintenance stations for the city, county, and state are responsible for snow removal. Currently, snow plans used by maintenance personnel are done manually, and consist of one or more plowing routes. Each route, in turn, consists of one or more segments of roads. City, county, and state personnel use different criteria to prioritize routes (e.g., interstates are assigned priority A by the Iowa DOT). Priority A routes must be cleared before priority B routes, if simultaneous plowing is not possible due to the unavailability of plows, and so on. Once prioritized snow plans are available, snowplows are assigned to the routes, and materials such as salt and sand are allocated, if necessary. During heavy storm events, new snow plans and routes are created that are different from the snow plans for normal snowfall. Decision making for snowplowing problems needs to be agile in its response to unpredictable circumstances such as weather. Most important, snowplowing problems involve large numbers of variables, large numbers of constraints, and complex interactions. As such concerns make snowplowing problems intractable by conventional mathematical optimization and AI techniques, they require novel methods.

Figure 1 shows the general paradigm of the intelligent (expert) system developed for snowplowing. The creation of an expert system begins with a series of detailed interviews of experts in the application area, in this case transportation managers, planners, and engineers. The questioning takes the form of both qualitative discussions and quantitative surveys. Knowledge engineering is the process of analyzing this information and developing a knowledge base. The knowledge base consists of a set, often very large, of predicate-calculus format rules:

Format—

If (input variables → input tests), then (predicates → output variables).

Example—

If (climate = torrential rain), then (work location = inside).

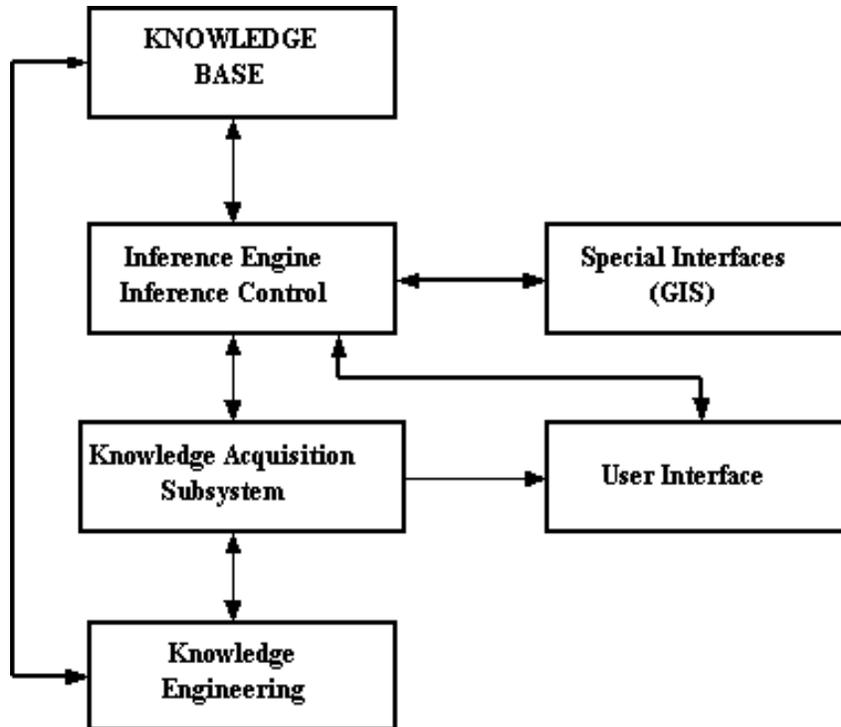


Figure 1. General Paradigm of the Expert System for Snowplowing

These predicate-calculus format rules can be used either sequentially or simultaneously, depending on the nature of the knowledge to be implemented. The inference engine portion of the software implements these rules. The implementation can be quite complex as the rules may be interrelated both sequentially and simultaneously in unobvious ways. Clearly, the causality and direction of information flow must be carefully monitored.

The user interface portion of the expert system secures input variable information from the users of the system and delivers output variable instructions to the users. The user interface translates the information content of the output variables into useful formats such as personnel rosters, bills of materials, and route maps for drivers. Special interfaces include connections with GIS databases, asset databases, and material inventory systems. As all of these databases and information streams use different protocols and conventions, exceptional challenges occur for programming the interface and translation engines of this subsystem.

The knowledge acquisition subsystem serves three distinct functions. First, this subsystem allows the knowledge engineers to formulate and enter predicate-calculus based rules. Second, this subsystem implements learning functions. The predicate-calculus based rules are not static, but are dynamically refined and modified to implement new knowledge. The knowledge engineers can use information such as statistical analysis of rule firings to eliminate or inactivate rules. Similarly, problems and suggestions reported by the users can be used to modify and expand the knowledge base. Third, this subsystem serves as a front-end for the knowledge base. It arbitrates queries from the user interface, and secures and delivers information as requested by the system users. As the knowledge base deals exclusively with formal variables and is programmed using Lisp or proprietary AI languages, it is not suitable for direct access by the users. The subsystem uses programming constructs such as menus, radio buttons, and related graphical displays to make the system accessible to non-specialist users.

Figure 2 shows the architecture of the system that was developed. The function of this system is to optimize the allocation of resources for snow removal. Both a knowledge base and a GIS database were developed to support the expert system. The expert system also requires roadway data to support the allocation of routes, drivers, and other resources. For this, a GIS database of all roads in the case study area (Black Hawk County) was obtained from the Iowa DOT. This database consisted of a GIS shapefile and several related database files with traffic volumes, roadway inventory information, and other data. The data elements required for the snow removal management system were extracted from this database and a new shapefile was generated for incorporation into the expert system.

The knowledge base, GIS database, and programming efforts were integrated into an expert system with a user-friendly interface. The interface, created in Visual Basic 6.0, provides a series of features to guide non-expert users in inputting the required information.

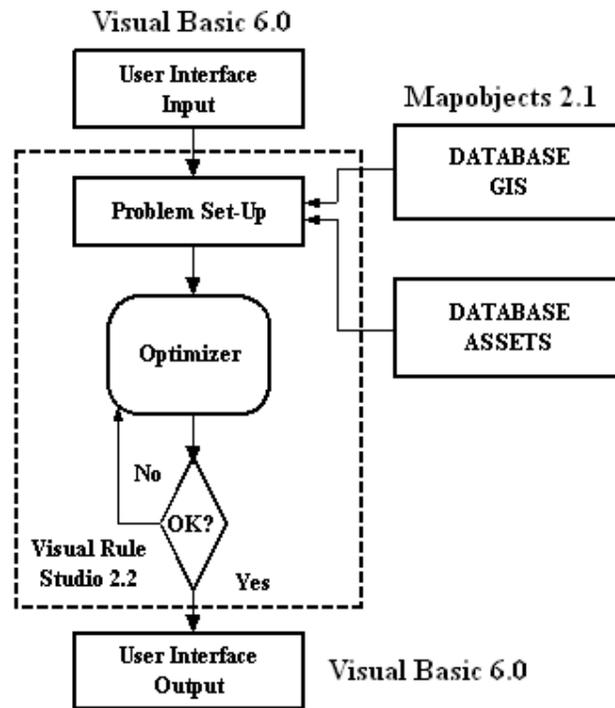


Figure 2. SRAMS Architecture

KNOWLEDGE ELICITATION

The process of knowledge elicitation, sometimes referred to as knowledge acquisition or knowledge engineering, is the most important task in the development of an expert system. This is required to reduce a large body of knowledge to a precise set of facts and rules. The term “knowledge engineer” is used for the person responsible for acquiring knowledge for specific system development. The following is a brief job description for knowledge engineers:

Knowledge acquisition is a bottleneck in the construction of expert systems. The knowledge engineer’s job is to act as a go-between to help an expert build a system. Since the knowledge engineer has far less knowledge of the domain than the expert, however, communication problems impede the process of transferring expertise into a program. The vocabulary initially used by the expert to talk about the domain with a novice is often inadequate for problem solving; thus, the knowledge engineer and expert must work together to extend and refine it. One of the most difficult aspects of the knowledge engineer’s task is helping the expert to structure the domain knowledge, to identify and formalize the domain concepts [17].

Thus, the basic model for knowledge engineering has been that the knowledge engineer mediates between the expert and knowledge base, eliciting knowledge from the expert, encoding it for the

knowledge base, and refining it in collaboration with the expert to achieve acceptable performance. Figure 3 shows this basic model with manual acquisition of knowledge from an expert followed by interactive application of the knowledge with multiple clients through an expert system shell:

- The knowledge engineer interviews the expert to elicit his or her knowledge.
- The knowledge engineer encodes the elicited knowledge for the knowledge base.
- The shell uses the knowledge base to make inferences about particular cases specified by clients.
- The clients use the shell's inferences to obtain advice about particular cases.

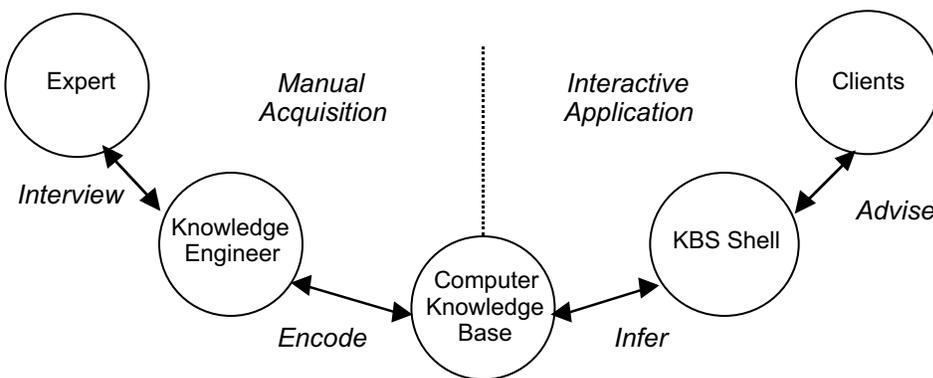


Figure 3. Basic Knowledge Acquisition and Representation Model

In order to build the knowledge base, an advisory board consisting of road maintenance managers, supervisors, engineers, and a GIS coordinator was assembled. Several structured interview sessions were held over the course of preparing the knowledge base. Although the development of the system was geared toward the use by Iowa DOT in Black Hawk County, personnel from the city, county, and state levels were interviewed to consider any difference in standard operating procedure by type of agency or scale of operation. In addition, several follow-up interviews were conducted by telephone. Some experts (e.g., the snow removal expert of the Iowa DOT in Waterloo, Black Hawk County) were available for several interviews. In the follow-up interviews, the knowledge engineer summarized what was discussed in the interviews and presented the rules that had been derived. These follow-up interviews eliminated any sort of inconsistencies, misunderstanding, and misrepresentation of the rules. Guidelines for knowledge acquisition are available in many publications [17, 22, 28] and are not reported here. Interviews were tape-recorded and encoded transcripts were used to formalize the knowledge in the form of rules.

The main factors that need to be considered in optimizing the allocation of snow removal assets are (1) annual average daily traffic (AADT), (2) route prioritization, (3) number of lanes, (4) operation time for each vehicle, (5) pavement type (concrete or bituminous), (6) availability of vehicles and drivers, (7) treatment of roads with salt/sand, and (8) minimum snowfall thresholds to mobilize equipment. These factors were identified by the experts during the knowledge elicitation process. On completion of the knowledge elicitation process, the knowledge engineer or the system developer needed to structure the key concepts, rules, and knowledge, and transform them into a representative scheme suitable for the selected AI shell, i.e., Visual Rule Studio 2.2. The knowledge base and sample representation of rules are discussed in more details in the "System Implementation" section of this report.

PROGRAM DEVELOPMENT

Generation of Route Map

The main purpose of planning routes for the plows is to remove snow using the least amount of resources such as driver time, plows, sand, and salt. In doing so, it is important to reduce and possibly eliminate “deadhead” travel for snowplow, i.e., travel time without plowing. Since Dijkstra’s shortest path algorithm is well studied and documented, we have selected this algorithm to solve the problem of generating routes [7]. The employment of Dijkstra’s shortest path algorithm ensures minimization of deadhead travel.

Determining the Number of Routes

In the route generation process, priority levels are considered independently. For each priority level, the total plowing time is estimated by using the information available in DOT databases. The number of vehicles to be assigned for each priority level is determined as follows:

$$N = \frac{T_p}{T_{\max}},$$

where N is number of routes, T_p is total estimated plowing time, and T_{\max} is maximum allowable operation time for each vehicle.

Then the SRAMS determines the actual plowing time for each available snowplow:

$$T_a = \frac{T_p}{N},$$

where T_a is actual plowing time per vehicle.

This is the leveling of load distribution and it is used to ensure distributing the load of snow removal to assigned trucks evenly.

Creating Route Maps

To begin the process, SRAMS looks for segments of roads that are connected to an initial segment defining an edge on the map. These segments are starting points for each priority level in the selected map. Next, all of the segments that are connected to the starting segment are determined and placed in a stack in order of priority. The top one is picked for the process of adding segments. If the connection of segments is finished, SRAMS generates a jump in the route and uses Dijkstra’s shortest path algorithm to determine the next road segments to be added to define a specific route. This continues until the total plowing time of the route exceeds the T_a (actual plowing time).

After defining N routes, SRAMS generates maps with color codes for the easy identification of routes. For example, routes in color codes as shown in Figure 4 was accomplished by creating the following shapefiles:

DOTLAYERA.shp
ROUTE1.shp
ROUTE2.shp

These names are given automatically by the program. Note that the combination of ROUTE1.shp and ROUTE2.shp constitutes DOTLAYERA.shp as presented in Figure 4.

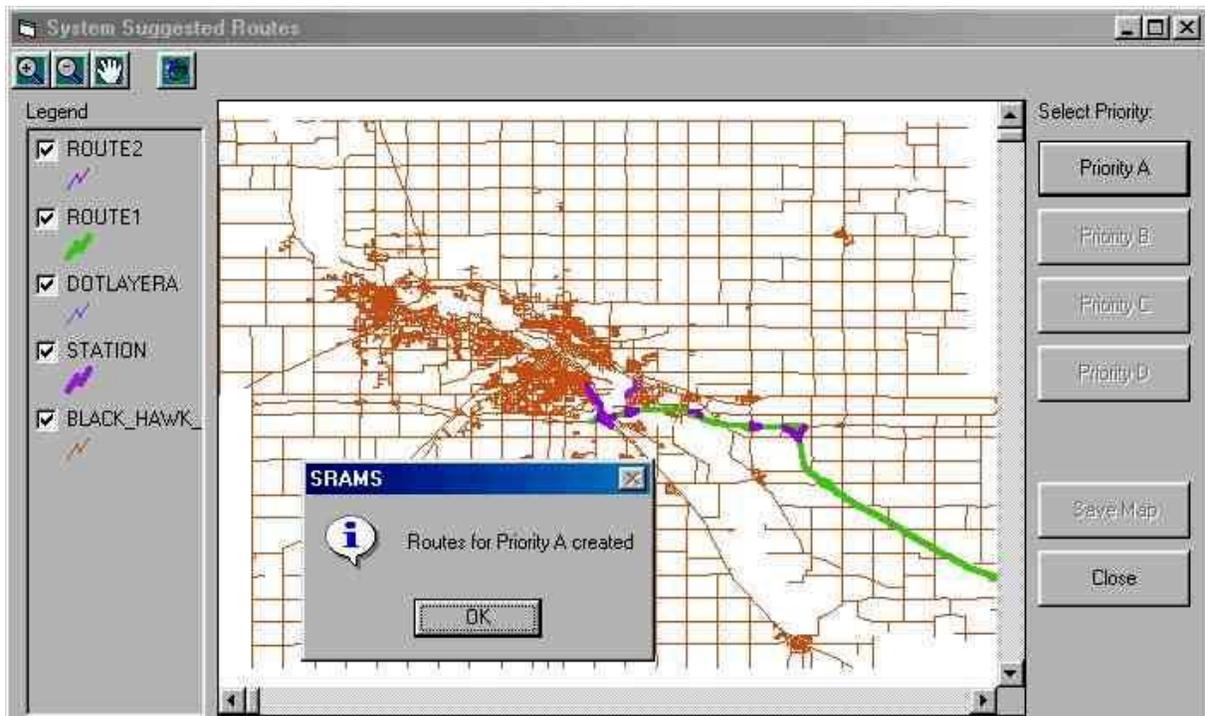


Figure 4. Color-Coded Routes for Priority A

Resource Allocation

Snowplows, operators, and materials are resources for the snow removal process. Once routes are created, snowplows are assigned to each route using two different methods:

1. A vehicle cannot be assigned to more than one route, and a route cannot have more than one vehicle assigned.
2. A vehicle can be assigned to more than one route, and a route can have more than one vehicle assigned for snowplowing.

These two (1 and 2 above) distinctive optimization problems are known as the Assignment Problem and the Transportation Problem, respectively. The user has control on the SRAMS to decide which type of optimization problem is to be solved. The “Use Vehicle on multiple Routes” field in the Routes tab under the Option menu is specified for this purpose (see Figure 5).

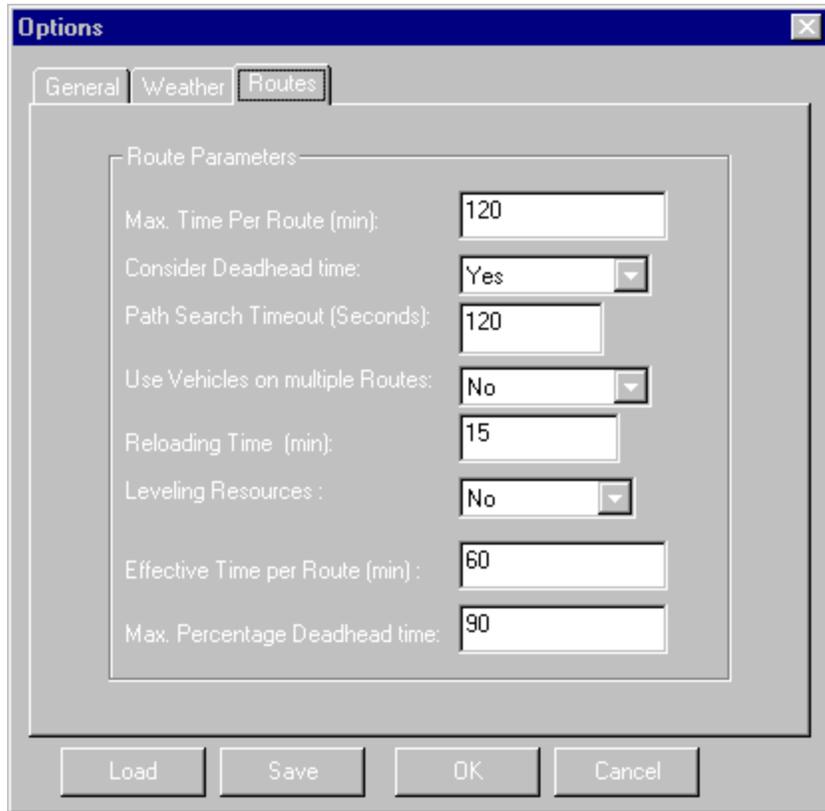


Figure 5. Routes Tab Under Options Menu

Assignment of Truck/Snowplow

The Hungarian Algorithm is used for square ($n \times n$) assignment problems in which n -snowplows and n -routes are available [41]. This is an algorithm for solving a matching problem. The Hungarian Algorithm is actually a special case of the Primal-Dual Algorithm. It takes a bipartite graph and produces a maximal matching. In case of non-square problem—i.e., the number of snowplows does not match the number of routes, it is still possible to use the Hungarian Algorithm by introducing slack routes or slack snowplows. Note that if some slack routes are introduced, the same number of operators will remain idle; similarly, if some slack operators are introduced, the same number of routes will not be snowplowed during the operation. The formulization of the assignment problem is as follows:

$$\text{Minimize } \sum_{i=1}^n \sum_{j=1}^n C_{ij} X_{ij} ,$$

where $i = \text{truck}; j = \text{route}; C_{ij} = \text{total cost per route for the assigned snowplow/vehicle};$ and $X_{ij} = \text{assignment of vehicle } i \text{ to route } j \text{ where } 0 = \text{not assigned and } 1 = \text{assigned}.$

Constraints:

$$\sum_{j=1}^n X_{ij} = 1 \quad i = 1, \dots, n \quad (\text{For each vehicle, only one route can be assigned.})$$

$$\sum_{i=1}^n X_{ij} = 1 \quad j = 1, \dots, n \quad (\text{For each route, only one vehicle can be assigned.})$$

Transportation Problem

The formulization of general transportation problem is as follows:

$$\text{Minimize } \sum_{i=1}^m \sum_{j=1}^n C_{ij} X_{ij}$$

Constraints:

$$\sum_{j=1}^n X_{ij} \leq S_i \quad i = 1, \dots, m$$

$$\sum_{i=1}^m X_{ij} \geq D_j \quad j = 1, \dots, n$$

where $C_{ij} = \text{unit cost (dollars/minute) coefficient for } i\text{th snowplow working on } j\text{th route}, X_{ij} = \text{time in minutes that } i\text{th snowplow on } j\text{th route}, S_i = \text{the operating time of } i\text{th snowplow}, \text{ and } D_j = \text{the required operating time for } j\text{th route}.$

Note that the unit cost (dollars/minute) will not just depend on the route that the vehicle is assigned to. Thus, $C_{i1} = C_{i2} = \dots = C_{in} = C_i.$ The objective function can be simplified as follows:

$$\text{Minimize } \sum_{i=1}^m \sum_{j=1}^n C_i X_{ij}$$

Usually the transportation problem is set up within the context of a tableau (see Figure 6). Each cell in the tableau represents the allocated time for each vehicle (row) on the route (column). The small box within each cell contains the unit snowplowing cost (C_i) of the vehicle on the route. The last column and

the last row represent the allowable operating time for each vehicle and the required plowing time for each route, respectively.

	Route1	Route2	Route3	S_i
Snowplow1				
Snowplow2				
Snowplow3				
D_j				

Figure 6. The Transportation Tableau

The stepping-stone solution technique can be used to solve $(n \times m)$ transportation problems [9]. Prior to applying this technique, an initial solution must be determined. As Russell and Taylor [37] state, “In a transportation model an initial solution can be found by several alternative methods, including the *northwest corner method*, the *minimum cell cost method*, and *Vogel’s approximation method*.” The Vogel’s approximation method (VAM), which is very well established to find a consistent initial solution for the transportation problem, is selected to be coded for SRAMS. The steps of VAM are given by Russell and Taylor as follows:

1. Determine the penalty cost for each row and column by subtracting the lowest cell cost in the row or column from the next lowest cell cost in the same row or column.
2. Select the row or column with the highest penalty cost.
3. Allocate as much as possible to the feasible cell with the lowest transportation in the row or column with the highest penalty cost.
4. Repeat steps 1, 2, and 3 until all rim requirements have been met.

Once the initial solution is obtained, the stepping-stone method can be employed to find the optimal solution. The summary of the stepping-stone method provided by Russell and Taylor is given below:

1. Determine the stepping-stone paths and cost changes for each empty cell in the tableau.
2. Allocate as much as possible to the empty cells with the greatest net decrease in cost.
3. Repeat steps 1 and 2 until all empty cells have positive cost changes that indicate an optimal solution.

Cost Parameters

Two main cost categories are considered for SRAMS: operating cost (C_{oi}) and material cost (C_{mi}).

The unit operating costs of snowplows are entered by the user and stored in the Machine.dbf database. The user can open and edit this database by selecting Vehicles from the Edit menu (see Figure 7). Once the route assignment is accomplished, the operating durations (T_{oi}) for each piece of equipment are determined by the SRAMS. Thus, the total operating cost (TOC) is calculated as follows:

$$TOC = \sum_{i=1}^n C_{oi} * T_{oi} \text{ where snowplow } i = (1, \dots, n)$$

Similarly, the unit material costs (C_{mj}) are stored in Material.dbf and can be reached from the Edit menu (see Figure 8). The quantity of material (Q_{mj}) use is determined by adding necessary material for each route, and then the total material cost (TMC) is calculated as follows:

$$TMC = \sum_{j=1}^k C_{mj} * Q_{mj} \text{ where material } j = (1, \dots, k)$$

Total cost (TC) = TOC + TMC.

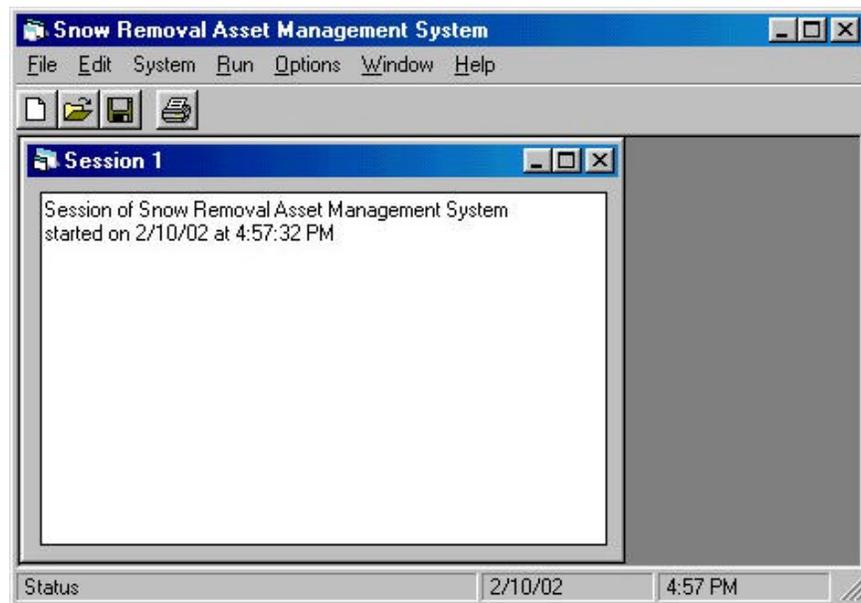


Figure 7. SRAMS Edit Menu

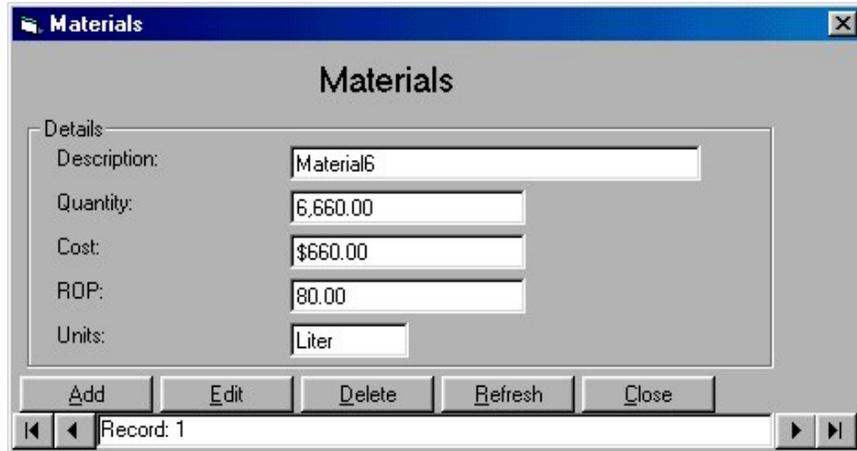


Figure 8. Editing Materials Database

Database Development

The SRAMS uses the following databases for Black Hawk County: Black_hawk_roads.shp, Dirlane.dbf, Info.dbf, Inventor.dbf, and Traffic.dbf. These database files are available from the Iowa DOT for download over the Internet. Using a common denominator called Mslink for each road segment, all of these five databases were integrated. Black_hawk_roads.shp is a shape file containing a polyline for each road segment so that it can be viewed using many GIS tools. Each shape file is accompanied by two other files with the same file name as the shape file but with the file extensions of .dbf and .shx.

The attributes of the files are as follows:

Shape:	Includes polyline for each road segment.
Mslink:	Auto increment variable. Key element for linking with databases created by SRAMS.
Jurisdic:	Indicates the jurisdictional responsibility for the segment of road.
Stateroute:	Indicates whether road is primary, secondary, municipal, or institutional.
Nineoneone:	Street name.
Gradesigna:	The number of automatic traffic signals at grade intersections in the road segment of road that is being traveled.
Gradestop:	The number of stop signs at grade intersections in the road segment being traveled.
Gradeother:	The number of intersections in the road segment that is being traveled with no signals or stop signs.
Aadt:	This field indicates the AADT on this road segment. This is applicable for primary, secondary, and municipal roads.
Laneleng:	Length of a road segment.
Surfwidth:	Width of the road.
Citynum:	Identifies if road segment is within the city.
Urbanarea:	This field identifies if the road segment is within an urban area.
Interstate:	Indicates whether or not a road system is classified as an interstate.
Truckrte:	Indicates whether or not the road is on a truck route on the primary road system only.
Lanetype1-9:	Identifies the type of each lane from the left side of the road segment to the right side. There are nine possible values.

	1: Through lane (lane used for traffic continuing in main direction).
	2: Climbing lane (lane signed for such use).
	3: Right turn lane (lane constructed for right turns only).
	4: Left turn lane (Lane constructed for left turns only).
	5: Center turn lane (painted lane used by both directions for left turns).
	6: Exit lane.
	7: Entrance lane.
	8: Reversible lanes (electronically controlled lane direction).
	9: Other.
Hwyresp:	Indicates the level of service provided by the highway. A, B, C or D.
Numlanes:	Number of lanes.
Planclass:	Five level classification for planning and programming the primary road system.
	1: Interstate.
	2: Commercial and industrial network.
	3: Area development.
	4: Access roads.
	5: Local service.
Surftype:	Type of road surface.

Resource Databases

Additional databases are required for the management of resources such as materials, snowplows, and personnel for operating the equipment. As such, three additional databases—Material.dbf, Machine.dbf, and Operator.dbf—are created. If these databases are not available in the same folder of the selected shape file, they will be created automatically by the SRAMS.

The database file Machine.dbf contains information on available snowplows, which includes the following attributes:

Descriptio:	String description of the snowplow, which may include brand and general characteristics.
Capacity:	Snow removal capacity of the snowplow. It may include cutting width in inches or overall height of the snow removal tool. For this project, the overall height of the removal tool is used.
ID:	Represents the license plate of the truck.
Cost:	Hourly cost (dollars) of operation of the machine.
Maintenanc:	The mileage for equipment maintenance.
Current:	Odometer reading prior to assignment of the machine.

Material.dbf incorporates the details of the materials available at the central storage for snow removal. It may include chemicals, sand and other materials. The structure of the database is as follows:

Descript:	String description of the chemical/material.
Qty:	Available quantity at the central storage facility before the start of the operation.
Cost:	Unit cost of the material.
ROP:	Reorder point
Units:	Units of measure truck as liter, pound, or ton.

Operator.dbf is a database that includes information about the operators who will be assigned to each snowplow. It considers operator preferences. The structure is as follows:

Operator:	String containing the name of the human operator.
Pref1:	Assignment of the operator to the first preferred machine.
Pref2:	Assignment of the operator to the second preferred machine.
Pref3:	Assignment of the operator to the third preferred machine.

Additional Databases

In order to improve the functionality of the computer program, other databases are created runtime by SRAMS. The controls of these files are not given to the user. These files are listed below:

- Station.dbf
- Stationd.dbf
- Assgdrv.dbf
- Assgmach.dbf
- DOTLayerA.shp
- DOTLayerB.shp
- DOTLayerC.shp
- DOTLayerD.shp
- Map.shp
- RouteX.shp where ($X = 1 \dots n$: number of routes)
- Valmach.dbf

User Interface Design

The Rationale

The user interface is the means by which the user and the expert system communicate with each other. Barnett et al. [1] pointed out that, although all computer programs have user interfaces (no matter how primitive), the expert system's user interface must be extremely sophisticated in order to allow more complicated dialogue between the program and the user. The interface of SRAMS is designed to handle this inevitable sophisticated dialogue easily and intuitively by employing powerful graphical user interface (GUI) components. Several key requirements have particularly shaped the user interface design:

- user control
- flexibility

User control is cited as “good tool” principle number one by Cox and Walker [8]. Galitz [14] has defined it as “feeling in charge” and “feeling that the system is responding to your actions.” Because of the dynamic characteristic of weather conditions and asset allocation, this design principle becomes essential for snow removal problems.

Flexibility is the system's capability to respond to individual differences in people. In this sense, it contributes to increased user control. SRAMS is designed to support snow removal managers in devising and maintaining snowplow plans for three different organizations: state, county, and

city (see Figure 9). Flexibility is required not only to solve the problem at three different levels, but also to serve users with different knowledge, skills, and experience. It should be noted the SRAMS has been developed for Iowa DOT use in Black Hawk County; however, modules for county and city analyses are added for future inclusions in the system.

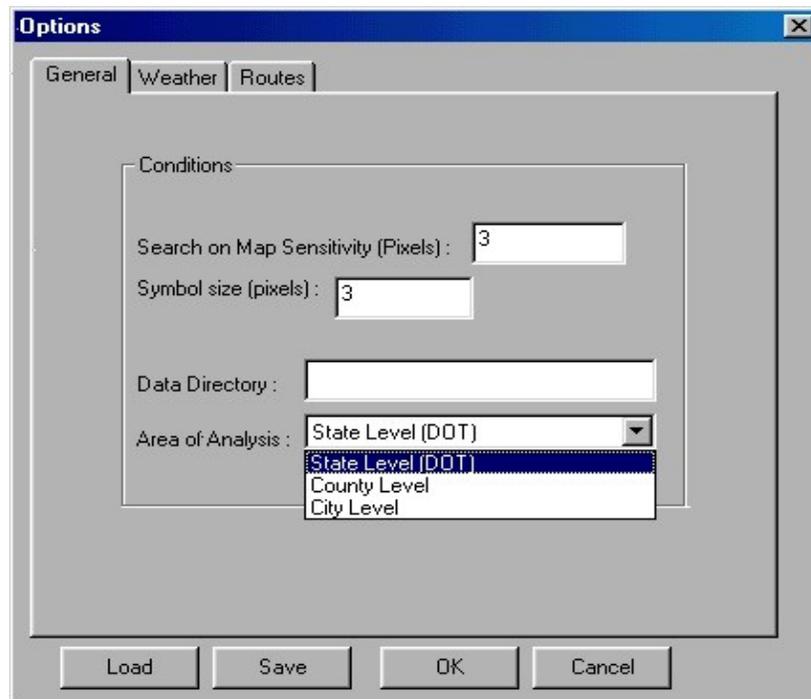


Figure 9. Selection of Organization for Road Identification

The Design

The general interface organization is around a standard window (see Figure 10) that the user can find in most standard Microsoft Windows menu options. Additional specific menu items are also created to enhance decision making for snow removal. Assets (material, operator, and snowplow) can be analyzed and controlled by a similar window (Figure 11). Data entry by the user is very simple. SRAMS has the flexibility of allowing the user to create routes either manually or automatically. When the user requests a route definition by selecting the proper menu option, the program asks which type of definition is preferred (Figure 12).



Figure 10. SRAMS Main Window

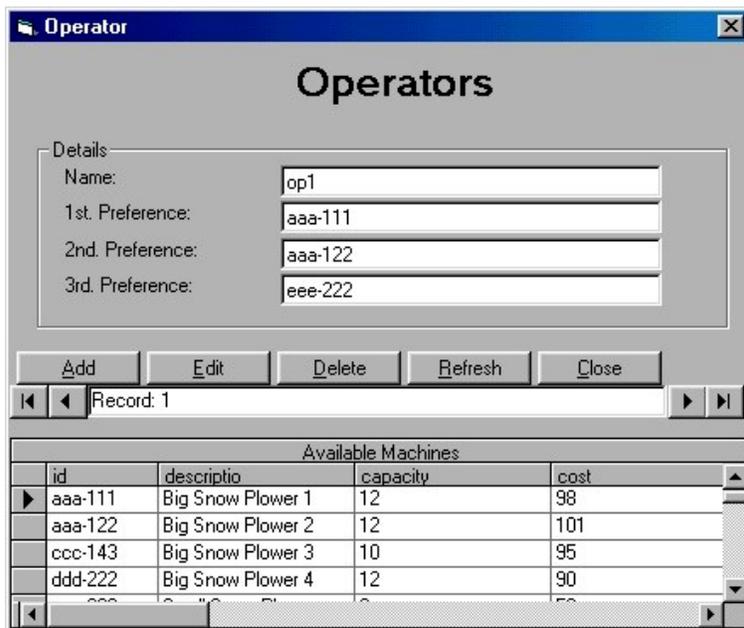


Figure 11. Example Window for Asset Management

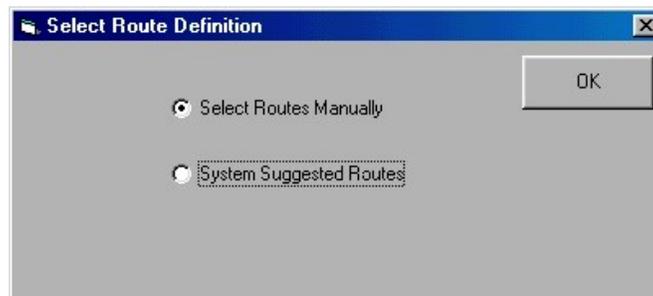


Figure 12. Selection of Route Creation

In the design of the output screen, the graphical display capabilities of MapObjects 2.1 are used. A legend is provided to the user to enable/disable the display of the route layers as well as control their thicknesses, and colors. In order to manipulate the display of the resulting map, toolbars, scrollbars, and buttons are conveniently provided, as presented in Figure 13.

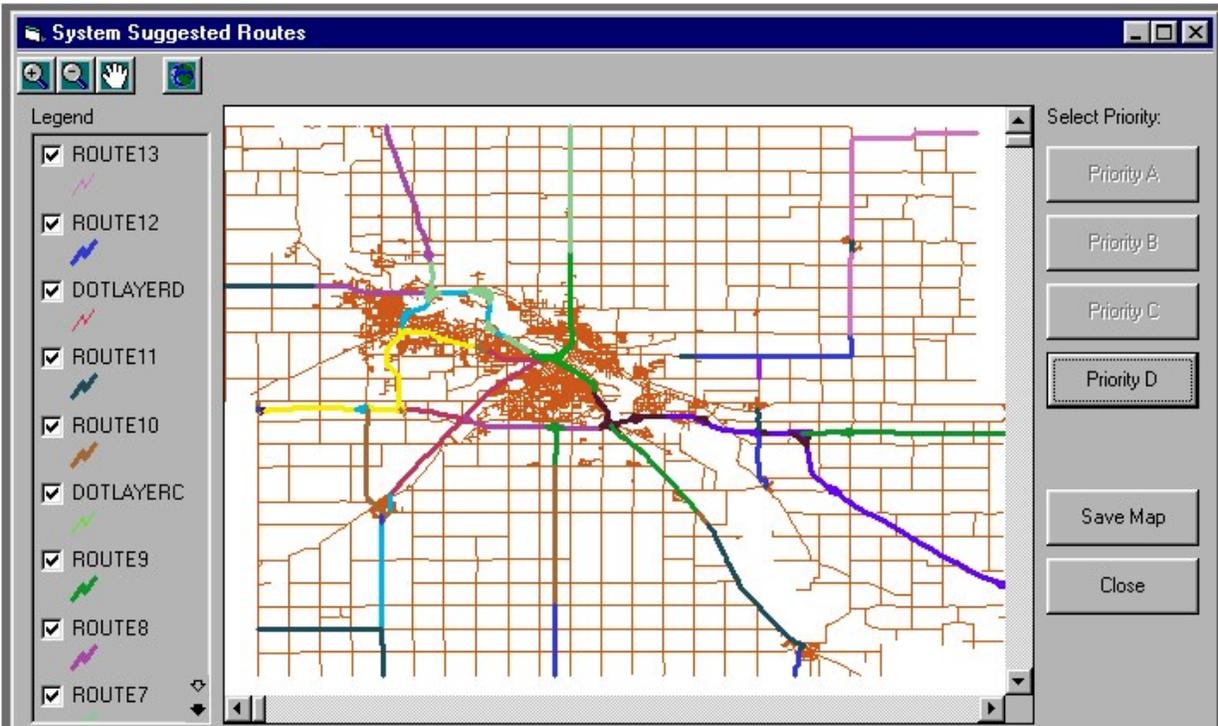


Figure 13. Display of Prioritized Route Map

SRAMS IMPLEMENTATION

SRAMS was implemented by integrating Visual Rule Studio Professional 2.2 (expert system shell) running under Microsoft Windows, Visual Basic 6.0, and MapObjects 2.1 (GIS package). Programs were written in Visual Basic to support the user interface. Visual Rule Studio provides dynamic rule generation and expanded database facilities, and permits the creation of reusable business rule objects. The knowledge base, knowledge acquisition subsystem, and inference engine were all programmed in the proprietary system language used by the Visual Rule Studio expert system shell. MapObjects 2.1, produced by Environmental Systems Research Institute, Inc., was used to sort, format, and import geographical roadway information into the Visual Basic platform to generate road maps, and other graphical outputs for the user interface.

Program Implementation

The program runs under the Microsoft Windows environment. At the start of any session, the user is required to select the GIS shapefile for a specific county. Then the program automatically links all of the related GIS databases using the MSLINK field, which has distinctive data for each road segment. The shapefile is displayed as a map using MapObjects. The data for materials, operators, and snowplows/trucks are stored in DBF format, and are retrieved from the databases when needed through the Visual Basic interface. The logic is stored as rule sets in Visual Rule Studio. The Visual Rule Studio is integrated with Visual Basic and can be called up

in Visual Basic as an Active Designer. Visual Basic acts as a user-friendly interface. The system configuration is shown in Figure 14.

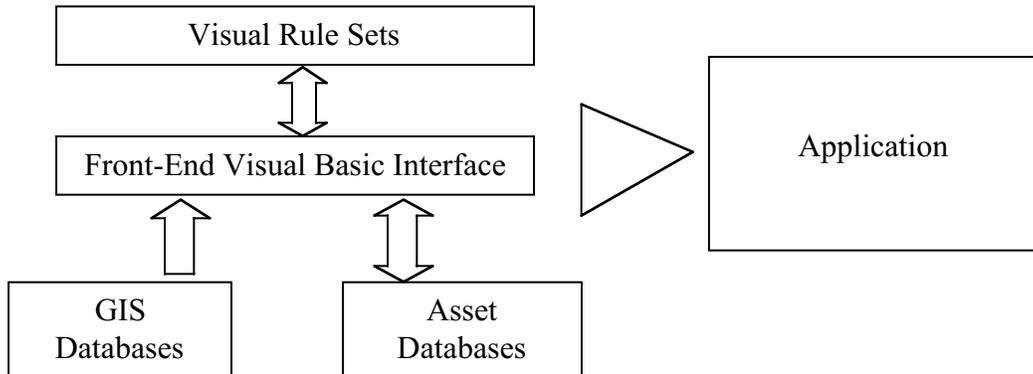


Figure 14. SRAMS Configuration

Example rules from Visual Rule Studio are shown in Figure 15. Rule sets are located under Active Designers, and can be reached by using object oriented technology. The rule set—namely, RuleSet1—is developed to make the two decisions: “suggstatus” (suggested status) and “expcond” (expected condition). Their possible values are listed in Table 1.

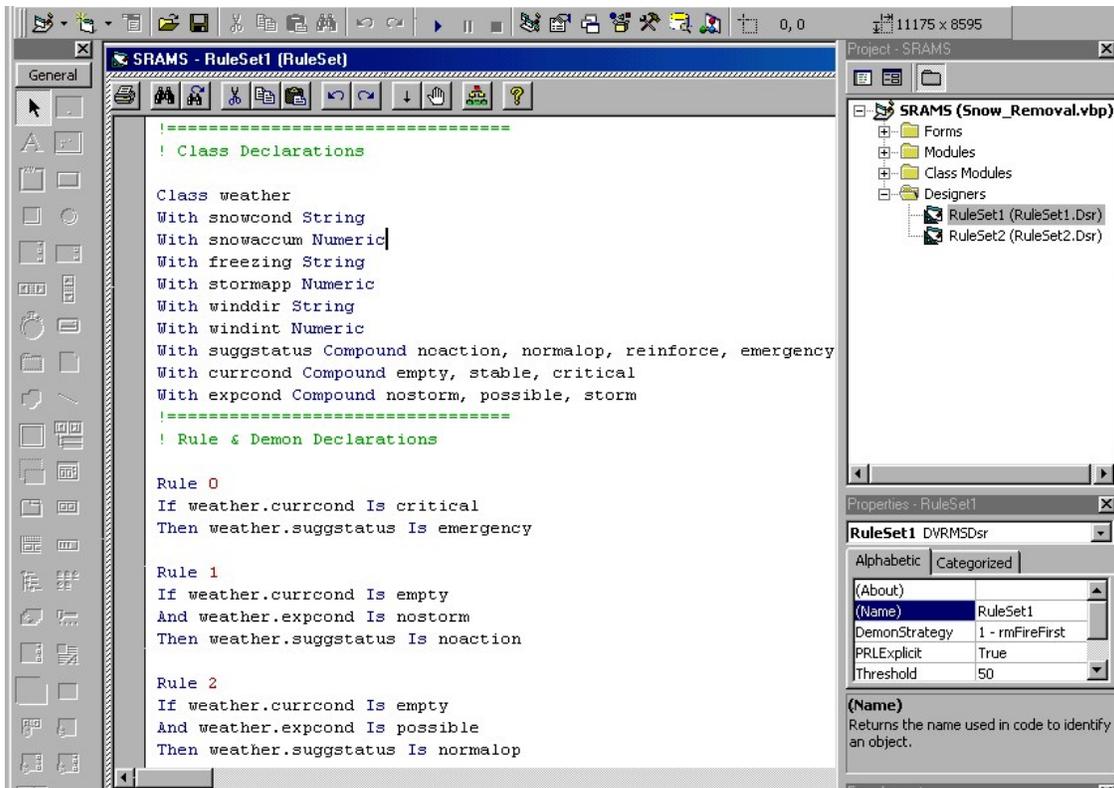


Figure 15. Example Rule from RuleSet1

Table 1. Decisions Given by RuleSet1

suggstatus (suggested status)	noaction	no action
	normalop	normal operation
	reinforce	reinforce
	emergency	emergency
expond (expected condition)	nostorm	no storm
	possible	possible storm
	storm	storm coming

In Black Hawk County, plowing starts when there is an accumulation of at least two inches of snow under normal condition, i.e., no stormy or blizzard condition. According to the experts interviewed for establishing the knowledge base, a snowplow can effectively plow 25 miles/lane of a road in an hour under normal conditions. In the case of stormy or blizzard conditions, half of the distance can be plowed, i.e., 12.5 miles/lane/hour. Again, each snowplow is deployed for two consecutive hours for the first time. A decision as to the assignment of the same snowplow for the second time depends on plowing needs and the availability of snowplows for the first time assignment.

To run the program, the user is required to locate and select the shapefile for the county, as shown in Figure 16.

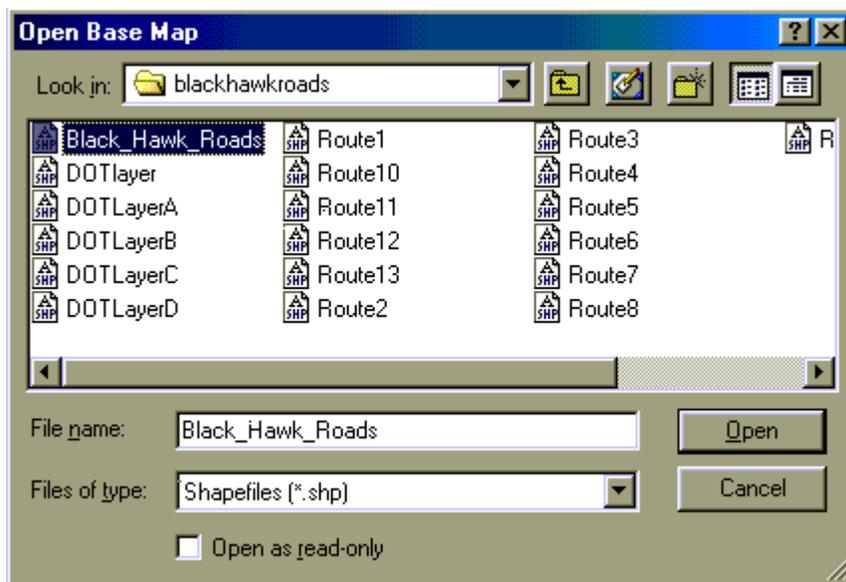


Figure 16. Selection of Shapefile

Once selected, a map displaying the road network in the selected county appears on the screen. The Iowa DOT uses four different priorities for route selection: Priority A, Priority B, Priority C and Priority D. Iowa DOT selection criteria used in prioritizing routes are presented in Table 2.

Table 2. Priority Level Criteria for DOT

Priority	Decision Criteria
A	Interstate Industrial commercial network
B	$AA\text{DT} \geq 5,000$ vehicles/day
C	$5,000 > AA\text{DT} \geq 2,000$ vehicles/day
D	$AA\text{DT} < 2,000$ vehicles/day

Automated generation of two routes (route1 and route2) for Iowa DOT priority A is depicted in Figure 17. Routes for other priorities can be similarly generated. A legend, which enables user to select the desired thickness and color, is provided for the convenience of the user. The system allows either activating or deactivating any route in the display area. For more details, refer to the SRAMS User’s Manual in Appendices A, B, and C.

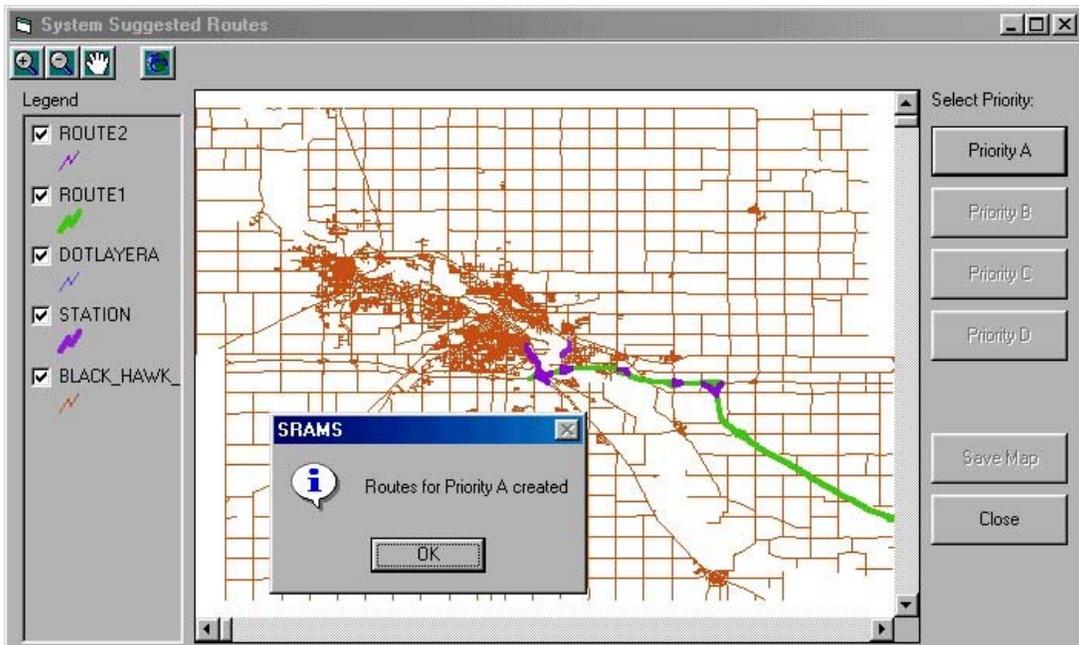


Figure 17. Iowa DOT Priority A Routes Created by SRAMS

VALIDATION AND FIELD TESTING

The validation of any developed intelligent system is necessary before using the system in real-world applications. In other words, validation is required to ensure the system or model performs with an acceptable level of accuracy. As Knauf et al. [25] have indicated, “Initially, validation efforts were not formal and highly individualized often characterized as a ‘craftsman approach’ which exercised program code against a small set of ad hoc test cases. As modeling efforts grew from rather small projects to more complex endeavors, validation complexities increased. Later, more rigorous validation techniques backed by statistical tests were developed.” Thus, validation is an imperative component of any expert system research and development. Many of the validation techniques currently in use by expert system modelers owe their foundation to early simulation and conventional software developers.

O’Keefe and O’Leary [31] have defined verification and validation as building the system right and building the right system, respectively. Verification provides a firm basis for the question of whether or not a system meets its specifications. In contrast, validation is the process of determining whether the system actually fulfills the purpose for which it was intended. The following section describes the validation of the SRAMS.

Validation of the SRAMS

The validity of an expert system determines the validity of the technical content of the knowledge represented in the system. That is, to what extent is the user satisfied with the technical details provided in the system? To what extent are the utilities provided useful? Knauf et al. [25] propose a validation methodology with the following steps:

1. Test case generation

Generate and optimize a set of test input combinations that will simulate the inputs to be seen by the system in actual operation.

There are two necessities opposing each other in this step:

- a. Coverage: ensuring that all of the possible test cases covered for completeness.
- b. Efficiency: minimizing the number of test cases to make the process more practical.

2. Test case experimentation

Since expert systems reproduce human expertise, it is more convenient to employ human opinion when evaluating the correctness of the system’s response. However, human experts may have their bias for or against the process of automation. Thus, the existence of a method is very important to fairly evaluate the correctness of the system’s outputs given imperfect human expertise. Therefore, this step consists of evaluating the test data by an intelligent system as well as by validating experts.

3. Evaluation

In this step, the results of the experimentation step are interpreted and errors recognized by the system are determined, then validity assessments related to the test cases are reported.

4. Validity assessment

Results in the evaluation steps are analyzed and conclusions are made about the validity of the system. The types of the results of this step are listed below:

- a. Validities associated with outputs (for potential users).

b. Validities associated with rules (for system developers and knowledge engineers).

c. Validities associated with test cases (for system refinement).

5. System refinement

This step constitutes the improvement of the system as a result of the previous four steps. This leads an improved rule base with respect to the examined test cases and knowledge base in general. Figure 18 provides a flow chart for the SRAMS validation process.

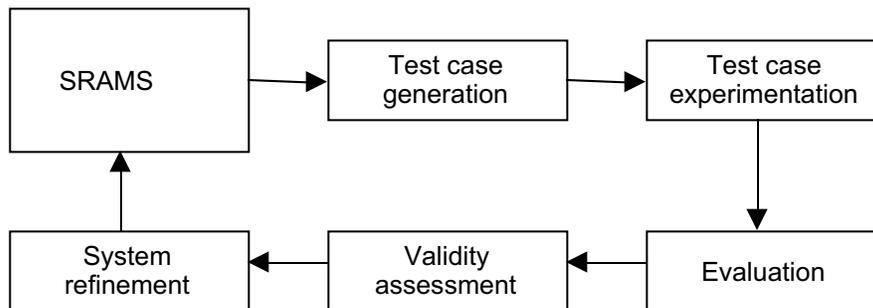


Figure 18. Validation Process

Test Case Generation

Any engineering product can be tested in one of two ways: (1) black-box testing and (2) white-box testing. Pressman [35] made this assertion and also stated, “White box testing of software is predicated on close examination of procedural detail. Logical paths through the software are tested by providing test cases that exercise specific sets of conditions and/or loops.” Creating test cases for all of the logical paths for even small software can be impractical to manage. The SRAMS is constructed with around 9,000 lines of codes in Visual Basic, excluding the codes for the knowledge base. It can be considered a large piece of software.

Black-box testing is used at the interface to exhibit that software functions are working properly. It is also used to demonstrate that input is appropriately accepted and output is adequately produced, and that integrity of external data is preserved.

Although it seems that white-box testing produces 100 percent correct programs, it is not always practical to consider all logical paths since the number of paths increases exponentially. Thus, black-box testing was employed for the validation of the SRAMS. Testing was conducted in three different categories:

- routes
- vehicles and drivers
- materials

Testing for Routes

The test cases designed to test SRAMS for routes are given in Table 3.

Table 3. Test Cases for Routes

Case	Name	Description
1	No DOT roads	No entry for “jurisdic“ field in Black_hawk_roads.dbf has a domain value of “1” that is reserved for Iowa DOT roads.
2	Only one DOT road	Only the first record of the entire database has domain value of “1” for the “jurisdic” field.
3	One DOT road for each priority level	Priority A, B, C and D have only one road under Iowa DOT responsibility.
4	Multiple roads for each priority level	Each priority (A, B, C and D) has more than one road under Iowa DOT responsibility.

Case 1: This case is designed to test the reaction of the SRAMS if no Iowa DOT road is available in the given database. In the SMMS Metadata Report (downloaded from Iowa DOT website) for Iowa, the attribute of “jurisdic” for GIS sources is explained as follows:

Attribute:

Attribute Label: JURISDIC

Attribute Definition: indicates the jurisdictional responsibility for the segment of road

Attribute Definition Source: Iowa DOT Base Record Manual

Attribute Domain Values:

Enumerated Domain:

Enumerated Domain Value: 1 through 8

Enumerated Domain Value Definition:

- 1 Iowa DOT
- 2 Iowa DNR
- 3 Iowa Dept of SS
- 4 Boards of Regents
- 5 Federal domain
- 6 Local
- 7 Iowa National Guard
- 8 Other State Lands

Enumerated Domain Value Definition Source: Iowa DOT Base Record

In order to maintain the status of no Iowa DOT roads, all of the enumerated “1” entries for “jurisdic“ field in “Black_hawk_roads.dbf” database were modified to be “6,” which is defined as local roads. A total 1,012 fields (Mslink 14,752 to Mslink 15,763) were modified. The SRAMS has generated the response indicating that there is no Iowa DOT road in the selected database.

Case 2: This case is intended to test the response of the SRAMS, if there is only one road under Iowa DOT responsibility in the given database. The “jurisdic” field of very first record, which is MSLINK=14,752, in the Black_hawk_roads.dbf was changed to “1.” The “jurisdic” fields of remaining records have values other than 1. The SRAMS response was “only one DOT road is available in the database.”

Case 3: Four records (Mslink) are modified to have “jurisdic” field value of “1” as listed below.

Mslink	Priority	Description
14,752	A	Interstate
14,903	B	Iowa DOT priority B road
15,465	C	AADT = 3,890 (2,000 < 3,890 < 5,000)
15,615	D	AADT = 1,160 (1,160 < 2,000)

As depicted in Figure 19, SRAMS has generated four routes for four priority levels.

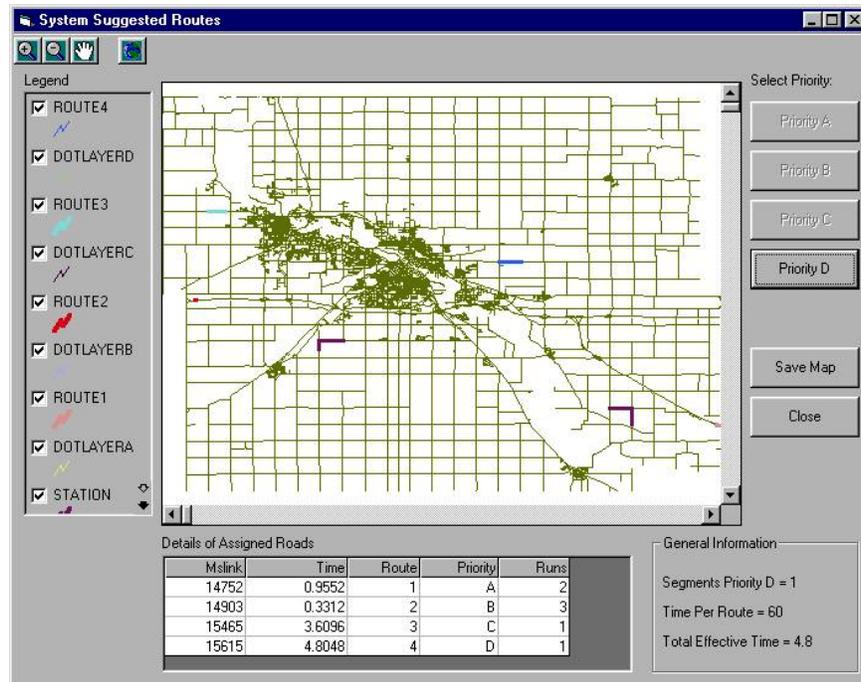


Figure 19. Snapshot for Test Case 3

Case 4: The original GIS data from the Iowa DOT database, without any modification, is used to test the SRAMS. The system generated all Iowa DOT routes and assigned priority to each route, as expected.

Testing for Vehicles and Drivers

The test cases designed to test SRAMS for vehicles and drivers are given in Table 4.

Table 4. Test Cases for Vehicles and Drivers

Case	# of Vehicles	# of Drivers	Description
5	0	m	There is no vehicle to be assigned to created routes.
6	n	0	There is no driver to be assigned to vehicles.
7	n	m	$n > m$
8	n	m	$n = m$
9	n	m	$n < m$

Case 5: Machine.dbf file was emptied to ensure that there was no vehicle to be assigned to the generated routes. The system warned that no vehicle was in the database.

Similarly, all other cases (6–9) were tested and the system performed successfully.

Testing for Materials

Case 10: Material.dbf file was emptied to ensure that there was no material in stock. The system warned that the file was empty. The system also has the ability to provide information on the status of the inventory.

Field Testing

Currently, the Iowa DOT office in Waterloo uses 32 manually created static routes for moderate snow removal operations in Black Hawk County. Precise winter weather terminology used in Arkansas is reported in the literature [50]. In Black Hawk County, Iowa, snow removal experts use somewhat similar terminology to indicate the snowy conditions. These are as follows:

No snow:	No new snow expected.
Light flurries:	Intermittent light snowfall of short duration with no measurable accumulation.
Moderate intensity:	A fall of snow of increased intensity, usually an accumulation of 2 inches or more but less than 4 inches over a 12-hour period.
Heavy snow:	Refers to 4 inches or more in a 12-hour period, or 6 inches or more in a 24-hour period.
Snow storm:	The following conditions occur for 3 hours or longer: Sustained winds or frequent gusts of 35 mph or greater, and considerable falling and/or blowing snow which frequently reduces visibility to less than 1/4 mile. This is also known as a blizzard condition.

One of the basic requirements of field testing was to gather sufficient data under comparable conditions to detect any meaningful differences between the existing Iowa DOT manual system and the developed SRAMS. Thus, to make comparative measurements in this study, it was necessary to run SRAMS twice, first considering moderate snowfall, and then heavy snow/snowstorm. Iowa DOT data for both cases are available to make comparisons. As mentioned earlier, the Iowa DOT office in Black Hawk County (our test case) uses 32 manually created static routes designated as run number in its data spreadsheet for moderate snowfall. Data for snowplowing operations in Black Hawk County in 1998–1999 is summarized in Table 5. In case of heavy snow or a snowstorm, the number of routes is doubled by the Iowa DOT (i.e., 64 plowing routes) and consequently the commitment of resources (snowplow, operators, time, etc.) is also doubled. As an approximation, the deadhead travel distance is also considered double for this heavy snowy condition compared to the distance for moderate snowfall. There is no method currently in use by the Iowa DOT for tracking actual deadhead travel during a snowstorm or

heavy snowfall. The Iowa DOT usually assigns one snowplow per route, which necessitates as many snowplows as the number of routes.

Table 5. Actual Iowa DOT Data for Moderate Intensity Snow Removal Operations in Black Hawk County (1998–1999)

Run Number	Plowing Road Length (miles)	Ramp (miles)	Total Plowing Length (miles)	Total time (hour)	Deadhead Travel Length (miles)	Deadhead Travel Time (min)
701	30.5		30.5	2.0	9.6	14.4
702	30.5		30.5	2.0	9.6	14.4
703	1.3	7.0	8.3	2.1	24.6	36.9
704	1.3	7.3	8.6	2.1	24.6	36.9
705	18.5		18.5	1.9	6.0	9.0
706	18.5		18.5	1.9	6.0	9.0
707	0.0	4.0	4.0	1.8	20.4	30.6
708	22.0		22.0	1.7	14.6	21.9
709	40.6		40.6	3.6	16.4	24.6
710	8.6	6.4	15.0	2.3	39.4	59.1
711	8.6	6.4	15.0	2.3	39.4	59.1
712	8.0		8.0	2.3	39.4	59.1
713	30.8		30.8	1.9	2.6	3.9
714	30.8		30.8	1.9	2.6	3.9
715	0.0	8.0	8.0	1.8	23.0	34.5
716	39.4		39.4	2.5	8.6	12.9
717	25.4		25.4	2.2	20.8	31.2
718	13.6		13.6	1.6	11.4	17.1
719	13.6		13.6	1.6	11.4	17.1
720	19.4		19.4	1.5	2.8	4.2
721	9.2		9.2	2.1	0.4	0.6
722	9.2		9.2	2.1	0.4	0.6
723	13.3		13.3	2.1	5.8	8.7
724	13.3		13.3	2.1	5.8	8.7
725	21.0		21.0	2.2	6.0	9.0
726	21.0		21.0	1.8	6.0	9.0
727	0.0	15.1	15.1	2.3	8.4	12.6
728	0.0	15.1	15.1	2.3	8.4	12.6
729	0.0	11.7	11.7	2.4	16.4	24.6
730	11.1		11.1	2.4	9.2	13.8
731	11.1		11.1	2.2	9.2	13.8
732	11.1		11.1	2.2	9.2	13.8
Total	481.7	41.9	562.7	67.2	418.4	627.6

The SRAMS generated data for Black Hawk County is depicted in Table 6 and Table 7 for moderate snowfall and a snowstorm, respectively.

Table 6. SRAMS-Generated Data for Moderate Snowfall in Black Hawk County

Route	Effective Plowing Time (min)	Actual Plowing Length (miles)	Deadhead Time (min)	Total Miles (Actual Plowing + Deadhead Travel)	Priority
Route30	19.0	7.9	36.5	29.7	D
Route29	52.2	19.5	100.5	74.3	D
Route28	65.8	17.7	63.9	52.4	D
Route27	93.7	39.0	57.8	65.2	D
Route26	75.2	15.6	113.9	41.0	D
Route25	1.5	0.6	25.5	16.4	C
Route24	73.8	17.7	84.1	57.4	C
Route23	67.8	21.4	92.2	71.9	C
Route22	101.2	27.7	57.2	59.3	C
Route21	64.5	26.9	41.6	51.7	B
Route20	93.1	22.7	39.3	43.0	B
Route19	39.2	8.8	105.5	32.5	B
Route18	68.2	9.7	68.2	24.7	B
Route17	51.8	13.6	78.7	36.6	B
Route16	64.4	20.8	153.4	91.9	B
Route15	65.0	20.5	64.6	45.0	B
Route14	27.3	6.2	101.6	29.0	B
Route13	90.3	22.6	38.3	37.6	B
Route12	95.0	21.5	35.8	33.6	B
Route11	99.0	24.5	30.1	33.3	B
Route10	85.0	17.1	43.9	28.2	B
Route9	60.1	14.3	71.7	29.9	B
Route8	97.6	19.1	31.1	30.0	B
Route7	109.7	29.9	20.8	37.7	B
Route6	110.4	23.8	25.1	31.1	B
Route5	65.3	11.9	66.5	25.9	B
Route4	23.5	5.9	46.6	31.6	A
Route3	63.2	26.3	66.1	67.8	A
Route2	94.3	35.1	39.2	53.6	A
Route1	94.7	23.1	44.5	41.7	A
Total	2,111.9	571.4	1,844.3	1,303.8	—

Table 7. SRAMS-Generated Data for Snow Storm in Black Hawk County

Route	Effective Plowing Time (min)	Actual Plowing Length (miles)	Deadhead Time (min)	Total Miles (Actual Plowing + Deadhead Travel)	Priority
Route53	19.0	4.0	43.3	29.7	D
Route52	68.1	14.2	125.0	87.5	D
Route51	98.0	14.3	33.8	29.6	D
Route50	73.6	10.4	62.5	44.1	D
Route49	69.7	13.5	60.0	41.8	D
Route48	125.0	26.1	8.4	28.1	D
Route47	63.7	9.1	121.4	41.9	D
Route46	94.8	8.2	33.8	20.6	D
Route45	51.8	9.0	122.1	56.3	C
Route44	86.3	8.0	46.0	27.6	C
Route43	60.7	6.4	70.7	38.9	C
Route42	87.3	16.3	47.8	45.2	C
Route41	95.2	15.6	87.2	66.3	C
Route40	107.3	12.1	22.9	18.2	C
Route39	22.5	4.7	61.1	47.3	B
Route38	90.4	18.8	51.7	47.1	B
Route37	84.1	12.4	49.4	38.6	B
Route36	116.3	13.5	14.4	17.5	B
Route35	35.6	4.1	107.1	37.4	B
Route34	93.7	9.1	35.3	21.0	B
Route33	58.9	6.8	84.3	22.4	B
Route32	98.2	4.9	62.3	17.9	B
Route31	79.6	10.1	74.4	29.1	B
Route30	51.8	7.7	77.3	29.4	B
Route29	49.3	8.3	81.2	33.5	B
Route28	62.1	8.5	158.4	84.1	B
Route27	78.9	15.4	52.7	38.8	B
Route26	84.1	10.5	44.4	29.1	B
Route25	61.9	7.7	81.0	27.3	B
Route24	83.0	10.4	51.4	22.9	B
Route23	96.4	9.2	34.0	18.9	B
Route22	90.3	10.2	44.9	20.3	B
Route21	106.6	12.4	26.5	20.6	B
Route20	106.3	13.3	32.5	24.9	B
Route19	91.2	11.4	38.4	26.5	B
Route18	88.1	11.0	46.9	29.6	B
Route17	67.5	8.4	68.4	35.2	B
Route16	31.6	3.8	97.8	27.3	B
Route15	32.8	2.9	109.3	27.3	B
Route14	94.6	8.4	34.8	21.4	B
Route13	107.4	9.8	21.8	18.1	B
Route12	102.1	17.7	28.5	29.9	B
Route11	126.4	15.8	13.9	19.5	B
Route10	120.4	12.0	22.5	17.8	B
Route9	93.1	8.1	44.5	18.0	B
Route8	66.7	6.7	66.5	20.7	B
Route7	59.0	8.4	60.2	44.9	A
Route6	50.9	10.6	78.9	63.9	A
Route5	78.9	16.4	55.9	48.6	A
Route4	81.2	16.9	48.2	42.0	A
Route3	91.8	15.0	39.2	33.5	A
Route2	100.7	12.6	30.6	26.1	A
Route1	88.7	10.5	44.5	29.1	A
Total	4,223.4	571.4	3,060.1	1,783.6	—

Evaluation of Field Data

A comparison of results between the Iowa DOT's existing manual system and SRAMS is presented in Table 8.

Table 8. Comparative Study Results

		Number of Routes	Total Plowing		Deadhead Travel		Total	
			Distance (miles)	Time (min.)	Distance (miles)	Time (min.)	Distance (miles)	Time (min.)
Iowa DOT Existing Manual System*	Moderate intensity	32	562.7	3,404.4	418.4	627.6	981.1	4,032.0
	Snow storm	64	562.7	6,808.8	836.8	1,255.2	1,399.5	8,064.0
SRAMS	Moderate intensity	30	571.4	2,111.9	732.4**	1,844.3	1,303.8	3,956.2
	Snow storm	53	571.4	4,223.4	1,212.2	3,060.1	1,783.6	7,283.5

* Data are taken from the Iowa DOT Manual System (Table 5) and include Priority A, B, C and D routes.

** Total deadhead miles for SRAMS solution can be calculated by taking the difference between total miles, 1,303.8 (Table 6), and total effective miles, 5,71.4 (Table 7) = 732.4 miles.

As can be seen in Table 8, for moderate-intensity snow conditions, the Iowa DOT and SRAMS use 32 and 30 routes, respectively. The plowing distance generated by SRAMS is 571.4 miles, whereas the existing Iowa DOT manual system covers 562.7 miles. The exact cause of this small difference (8.7 miles) is not known. However, after running SRAMS and looking at all road segments under Iowa DOT responsibility in Black Hawk County as identified in the existing Iowa DOT road database, it appears that 571.4 is the correct plowing distance. The most important aspect of Table 8 is the total time for plowing and deadhead travel because the cost of many resources is time dependent. For snowfall of moderate intensity, SRAMS-generated routes will require 1.9 percent less time for plowing operations compared to the existing Iowa DOT manual system (4,032 minutes vs. 3,956.2 minutes), as can be seen in Table 8. This is certainly an improvement over the existing system. Even more dramatic improvements for SRAMS are noticeable for snowstorm conditions (9.7 percent).

As mentioned elsewhere in this report, the essential problems to be considered in snow removal are the allocation of personnel resources, the distribution of materials (road salt, road sand, other ice/snow removal chemicals, the deployment of equipment, and the maximization of effectiveness in snow removal (e.g., Priority A roads are plowed quickly). SRAMS is capable of automatically generating snowplow routing based on priority, and also assigning needed resources for snow removal operations. Intermediate database files contain information on the allocation of assets and other parameters such as cost, time, and kilometers (miles) of roads to be plowed. The automatic generation of routes and the assignment of snowplows and operators can be done in less than an hour using SRAMS on mid-end Pentium PCs. In addition, SRAMS is capable of material tracking and inventory analysis.

TECHNOLOGY TRANSFER

Because of the applied nature of the project, an advisory committee was consulted throughout the development of SRAMS. To date, presentations have been given at three prestigious international conferences and one paper has been published in a peer-reviewed academic journal:

- Salim, M., T.R. Strauss, and M. Emch. AGIS-Integrated Intelligent System for Optimization of Asset Management for Maintenance of Roads and Bridges. *The Fifteenth International Conference on Industrial*

and Engineering Applications of Artificial Intelligence and Expert Systems, IEA/AIE 2002, Cairns, Australia, 2002, pp. 628–37.

- Salim, M., and M.A. Timmerman. A Communication-Based Paradigm for Construction Asset Management. *The Second Worldwide ECCE Symposium on Information and Communication Technology in the Practice of Building and Civil Engineering*, Finland, 2001, pp. 55–60.
- Salim, M., and M.A. Timmerman. Software to Simulate and Optimize Asset Management in Construction and Manufacturing. *The Journal of Technology Studies*, Vol. 27, No.2, 2001, pp. 64–101.
- Salim, M., and M.A. Timmerman. Optimization of Construction Logistics Using AI-Based Heuristic Asset Management Tools. *The Eighth East Asia-Pacific Conference on Structural Engineering and Construction*, Singapore, 2001, pp. 1–6.

The project team will continue to promote technology transfer through the distribution of software and user manuals, meetings with the advisory committee and other winter maintenance personnel, and the development of an educational interactive web site. In addition, the project team will disseminate results through conferences and the academic literature.

CONCLUSIONS

This report describes the development of analytical tools in a transportation asset management context through knowledge engineering methods. Specifically, software (SRAMS) was developed to generate prioritized snowplowing routes in color-coded visual format and to manage the allocation of snow removal assets and resources. SRAMS was implemented on a mid-range Pentium personal computer system by integrating a commercial expert system shell (Visual Rule Studio 2.2), a GIS package (MapObjects 2.1), and a programming tool (Visual Basic 6.0). Initial studies reveal that such a system could efficiently be utilized to optimize allocation of assets for plowing snow, especially in the northern part of the United States. Although the case study presented in this report is specific to the allocation of assets/resources for snow removal operations on Iowa DOT roads in Black Hawk County, Iowa, as well as to the concerns of colder climates, the methods may also be employed to other areas of management (e.g., inventory control). SRAMS has the ability to provide on-line information on the status of inventories and to warn users when materials are depleted beyond their re-order level.

Future developments could include the following:

- enhancement of the SRAMS for handling snow removal asset/resource management problems at the county and city levels,
- use of artificial intelligence learning techniques such as genetic algorithms to allow the knowledge base to learn new rules and refine existing rules without manual assistance by the operators,
- implementation of optimization techniques based on knowledge engineering to allow for an improvement in the ratio of costs to benefits of the expert system's generated asset management plan,
- use of predictive artificial intelligence techniques such as neural networks or fuzzy systems to allow the expert system shell to predict future conditions (e.g., meteorological changes and road conditions) based on current real-time data and stored historical data.

It is hoped that this work will be of interest to a broad audience in the civil engineering research community.

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