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Achievement in Operations Research

Taking the Politics Out of Paving: Achieving Transportation Asset Management Excellence Through OR

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The New Brunswick Department of Transportation (NBDoT) maintains over 18,000 kilometers of roads, 2,900 bridges, various ferry crossings, and other assets. Because of its limited budget, NBDoT faced significant challenges in rehabilitating its infrastructure assets valued at several billion dollars. Its goal was to develop transparent, defensible, long-term plans for managing New Brunswick's highway infrastructure, and secure commitment from decision makers and support from the public for these plans. The operations research component of the asset management framework uses a unique combination of linear programming and heuristic techniques. The model incorporates long-term objectives and constraints from an operations perspective—it weighs all options; considers costs, timings, and asset life cycles; and produces optimal treatment plans and schedules of activities. NBDoT anticipates $72 million (discounted) in annual savings, amounting to $1.4 billion (discounted) over the next 20 years. NBDoT has become a global leader in the field of asset management, and the success has attracted the attention of transportation officials around the world.

Key words: asset management; transportation; roads and bridges; linear programming; heuristics; decision optimization.

Across North America and globally, jurisdictions struggle with their aging infrastructures. A recent report states, "While the American Reinvestment and Recovery Act of 2009 will provide $27 billion for highway projects, that money will barely make a dent in highway maintenance, preservation, and reconstruction need... Saving America's highways demands more than short term stimulus funds and quick fixes based on available funding. It will require a greater and smarter investment of transportation dollars to ensure a new and better transportation program" (American Association of State Highway and Transportation Officials 2009, p. vi).

Infrastructure debt, the accumulation of unmet construction and maintenance needs, is a pressing issue. Using preliminary estimates for the period 2006–2016, a Canadian strategy paper identified that $97 billion would be required Canada-wide for capital investment in transportation priorities for all modes (Council of the Federation 2005). Deferring maintenance and delaying repairs leads to much higher rates of deterioration and to repair bills that can equal the cost of the original asset (American Association of State Highway and Transportation Officials 2009). Securing long-term, sustainable, sufficient funding to meet development, rehabilitation, and maintenance requirements for civil infrastructure is a key challenge for public service entities such as the New Brunswick Department of Transportation (NBDoT).

NBDoT is the public agency charged with management, maintenance, and repair of roads and highways in the province of New Brunswick, Canada (see Figure 1). A key departmental mandate is to support the economic and social goals of the province by maintaining, managing, and providing a quality, safe, and effective transportation system. Compared to other jurisdictions in Canada and the United States, New Brunswick is largely rural and relatively small in area (28,150 square miles); its population is just over 750,000. However, the 18,000 kilometers of provincial highways and local roads, 2,900 bridges, ferry crossings, and other assets for which NBDoT is responsible represent the highest cost-per-capita transportation network in Canada. At $3 billion, the replacement cost for the highway pavement infrastructure represents a substantial portion

Figure 1: The map shows New Brunswick's highway system. ***Source*****: New Brunswick Department of Transportation (2009).**

of the province's asset base. NBDoT manages a capital transportation infrastructure construction budget of approximately $400 million annually; this budget is specifically for upgrading and rehabilitating infrastructure within its extensive transportation network.

Within NBDoT, it was generally accepted that the existing level of funding for infrastructure renewal was insufficient to maintain the highway infrastructure in an acceptable condition; however, NBDoT staff lacked the means to clearly demonstrate this to government leaders. Informed decision making and effective resource allocation are significant and complex challenges to any organization when it must deal with aging assets, large diverse inventories, and insufficient funding. Add in competing priorities and asset life cycles that stretch across decades, and the problem seems almost insurmountable. As a result, civil infrastructure agencies often resort to a management protocol commonly known as "fix the worst first."

By the new millennium, NBDoT's use of this protocol had resulted in the simultaneous deterioration of many New Brunswick roads to a failed state; they would require complete—and expensive—reconstruction. Looking forward, NBDoT projected an increasingly worsening situation; by the time it reconstructed one kilometer of road, two or three additional kilometers of road would have entered the failed state and would also need replacement.

The graph in Figure 2, which shows a significant proportion of pavement beyond the 17-year age mark (the maturity age for asphalt pavements), illustrates the problem. It also shows that another group of pavements was nearly mature and would require investment in the near term (5–10 years). NBDoT recognized the need for a radically different approach; at a certain point, this asset class would become unsustainable and require complete reconstruction.

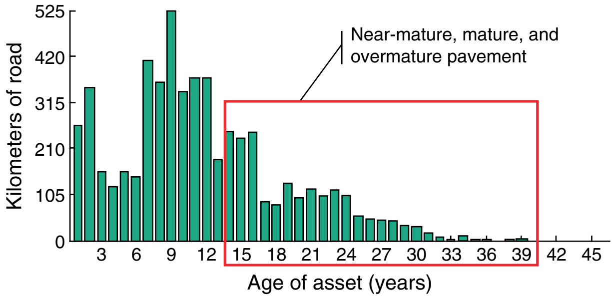


Figure 2: The graph shows the age distribution of New Brunswick asphalt highways in 2007. Many roads were close to an age at which complete replacement would be required.

In 2002, NBDoT decided to make transportation asset management a strategic priority. It turned to operations research (OR) for potential solutions. NBDoT's goal was to develop a comprehensive asset management system (AMS) to manage New Brunswick's nearly century-old infrastructure in a cost-effective, sustainable manner. Between 2004 and 2009, it allocated $2 million toward the consulting, software development, and software purchase required to develop AMS. Prior to AMS implementation, NBDoT's average annual funding for pavement rehabilitation was in the range of $50 million. Based on early analyses using AMS, funding for the pavement and bridge rehabilitation capital program would be approximately $180 million annually, with $120 million allocated to pavement rehabilitation. Despite this increased rehabilitation budget, NBDoT projected that it would realize savings of $1.4 billion (discounted) over the next 20 years by applying the optimal least life-cycle approach of AMS, rather than the worst-first planning protocol it had used previously. In this paper, we present the methodology we used to develop AMS, describe the details of its application and implementation within NBDoT, and present the substantial qualitative and quantitative benefits that NBDoT has accrued since it adopted AMS.

Developing the Asset Management System

NBDoT undertook AMS development with full recognition of budgetary and staffing limitations; its guiding principle was that any new solution had to be implemented without additional staff or layering of additional business processes. In 2002, it established a small project team comprising NBDoT staff and outside consultants, and recruited subject matter experts for various parts of the project, such as corridor management, pavement design, bridge management, and change management.

The project team's first task was to compile the available data sources and current processes within NBDoT. It gathered information from multiple sources and in various formats; the data came from a mix of legacy systems, new systems, and systems in transition. The team determined that NBDoT had technology to track and manage its diverse asset base, but it lacked the decision support tools to address the range of assets and scope of issues that had to be analyzed together to ensure optimal planning. The existing system allocated budget and projects separately for each asset class (e.g., roads, bridges, culverts, signs), resulting in "silos," limiting the interaction and collaboration between the different asset groups. NBDoT needed an approach to network-level planning that would allow trade-off analysis and optimization across all asset classes over the long term. The internal review also included consideration of asset use over time (because of changing populations and fluctuating traffic characteristics) and adjacency issues (e.g., the proximity and interrelationships with regard to pavements, culverts, sewers, curbs, sidewalks, pipes, signs, and other corridor features).

The new planning approach would have to demonstrate how NBDoT would preserve assets, optimize investments, and minimize life-cycle costs. As a public organization accountable to the taxpayers, it had to ensure that its plans would be transparent and defensible, and it had to secure commitment from decision makers and support from the public for its plans.

The team's next task was to investigate the state of planning, best practices, and new technology approaches worldwide. It found that other agencies and industries had encountered issues similar to its own: incongruent data, separate information systems, and a general inability to model trade-off scenarios—especially across asset classes. A number of solutions existed for individual asset classes, such as Pontis® for bridges (Golabi and Shepard 1997); however, given the asset-specific nature of these solutions, the team determined that they did not deal with cross-asset analysis in a sufficiently comprehensive manner, nor did they project sufficiently far into the future for NBDoT's needs.

A number of alternative approaches that included an OR component were also assessed; however, these solutions exhibited large footprints, had diverse and demanding data requirements, lacked the required flexibility and comprehensiveness, and did not provide the expansion and customization features that NBDoT would need in the coming years.

The market scan identified OR-based modeling software that had been successfully implemented in the natural resources sector at hundreds of sites worldwide by both industry and government. The New Brunswick Department of Natural Resources had successfully used it for many years to sustainably plan for and manage forest activity. The software could be adapted to NBDoT's transportation asset management needs with no additional customization. Furthermore, Remsoft, the solution provider, had been in existence since 1992, and comprehensive training, technical support, and ongoing software updates were available.

Modeling Transportation Assets

In developing a plan for the rehabilitation of all transportation assets, four key considerations are asset deterioration, treatment choice, adjacency and proximity, and consideration of both network-level and segment-level decisions for all asset classes together.

The deterioration rate of a given asset is a function of several factors, including time, weather, use patterns, and construction standards; it is not typically linear. New assets have a relatively slow rate of deterioration; however, without preventative maintenance, the rate of deterioration accelerates. In addition, the cost to rehabilitate rises as the assets deteriorate (see Figure 3).

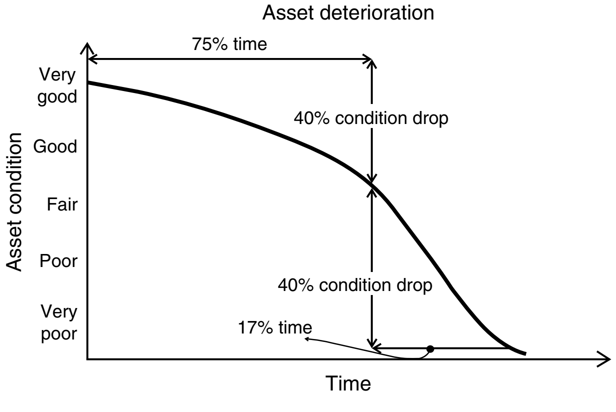


Figure 3: A sample deterioration curve shows that rehabilitation costs change according to the point on the curve. The choice of when to treat the asset can significantly impact both the overall quality and cost.

Consider a new highway. Although it is smooth and defect-free in the early stages of its life cycle, it also exhibits evidence of minor deterioration. As the highway ages, small cracks in the surface allow water to penetrate into the road bed, accelerating the deterioration process. In these early stages, a relatively inexpensive intervention treatment (e.g., crack filling) can slow the rate of deterioration, thereby extending the highway's life. Waiting to treat the surface can lead to much higher costs.

As an asset deteriorates, the number and choice of treatments available to maintain the asset change (see Figure 4). Appropriate actions for improving a relatively new asset differ greatly from actions for improving an older one; if the deterioration is too great, few options short of reconstruction may be available.

Where an asset is located and where it is located relative to other assets are important considerations for scheduling work; we refer to these as adjacency and proximity issues. Adjacency and proximity of assets can affect decisions in two ways. The first involves scheduling maintenance work on a single asset type (e.g., road segments) together when it makes sense from a geographic and timing perspective. For example, when a decision is made to rehabilitate one section of road that is in poor condition, the optimum solution may also include simultaneously treating a neighboring segment of the road. Although the neighboring road segment may be in better condition, there may be benefits and savings related to scheduling contractors and equipment, easing traffic congestion, and economies of scale.

The second location-related consideration is the treatment of different asset classes together. The simultaneous rehabilitation of culverts *under* a road scheduled for paving can offer cost savings and improve overall safety and road quality (see Figure 5).

Operational realities (e.g., current network condition, budgets, available staff, available data) constitute constraints on what can be accomplished in a given period. Given an unlimited budget and no resources constraints, the optimal decision may be to rebuild all older assets immediately; unfortunately, such ideal situations are exceedingly rare; thus, other options must be explored.

Selecting the optimal treatment for a bridge or a section of road in isolation is a relatively simple matter. The problem becomes complex when treatments for all network assets must be determined simultaneously and over an extended period, resulting in a large number of decision variables. Rather than only determining the best treatment option for the asset in its current condition, the best series of treatments for the next 20 years must be determined, with activities in the later years reflecting decisions and treatments made in the earlier phases of the planning cycle. Problems of this nature can be easily addressed using linear programming (LP), although the resulting matrices tend to be quite large.

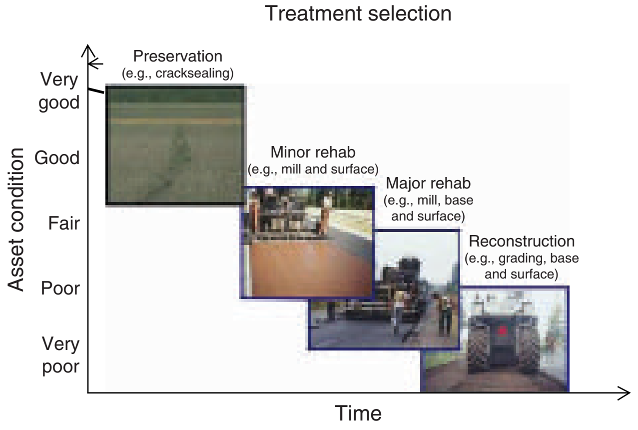


Figure 4: As roads or other assets deteriorate over time, the treatment required to bring them back to the desired level of service changes, with corresponding increased costs and related implications.

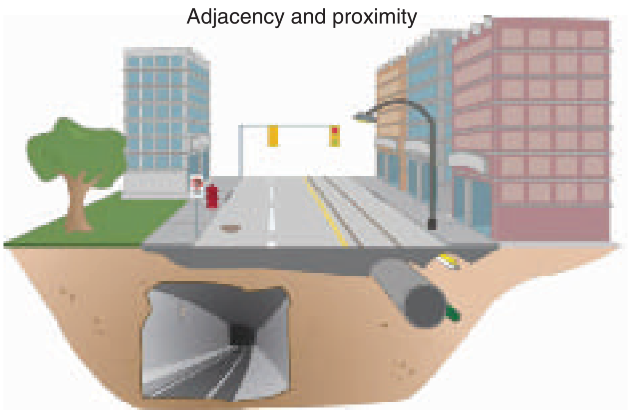


Figure 5: Grouping projects together based on location can provide benefits, such as avoidance of later disturbance or removal of a newly placed pavement surface.

Incorporation of spatial relationships among asset classes often results in coordinated allocation choices: decision variables that are binary in nature (e.g., culvert x is repaired in period 2 if the adjacent road segment y is also repaired in period 2). Given that the existing asset management LP problem was already large, adding coordinated allocation choices to the model resulted in a combinatorial optimization problem, defying a solution by exact methods. These issues are analogous to those faced in the forestry sector, which has contributed a great deal to the OR literature; these contributions, which include numerous papers on exact methods, heuristics, and decomposition approaches to spatial planning, can be applied equally to transportation asset management (Weintraub and Cholaky 1991, Borges et al. 1999, Baskent and Keles 2005).

Hierarchical Planning Approach

Because of the highly spatial nature of the problem, the number of assets under consideration, and the long time horizons involved, incorporating all the spatial and temporal aspects of the problem would have created a model too complex to solve by exact methods. Instead, NBDoT adopted Remsoft's hierarchical approach (Feunekes et al. 2009), which is based on problem decomposition, and results in separate but linked models to solve the problem in stages and at increasing levels of spatial resolution.

In the first stage, an LP model is constructed to address the long-term strategic aspects of the problem; adjacency and proximity relationships and constraints are generally omitted. Inputs at this level include performance measures, deterioration curves, operational windows, and costs within aggregate quantities by treatment strategy (i.e., preservation, minor rehabilitation, major rehabilitation, and reconstruction), as Figure 6 shows. Outputs from the optimization include detailed schedules of when and what actions should be performed to meet objectives and constraints, as well as the projected values for all key performance indicators. The underlying premise behind this hierarchical approach is that LP can be used to tackle many decisions necessary for the global planning problem, and the resulting optimal schedule of activities will form a good basis for the subsequent tactical and operational planning stages that incorporate increasing levels of spatial resolution over shorter planning horizons.

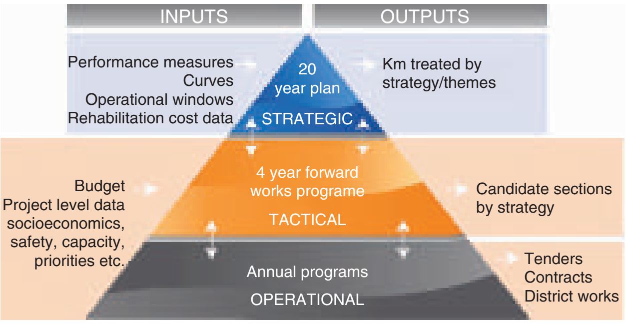


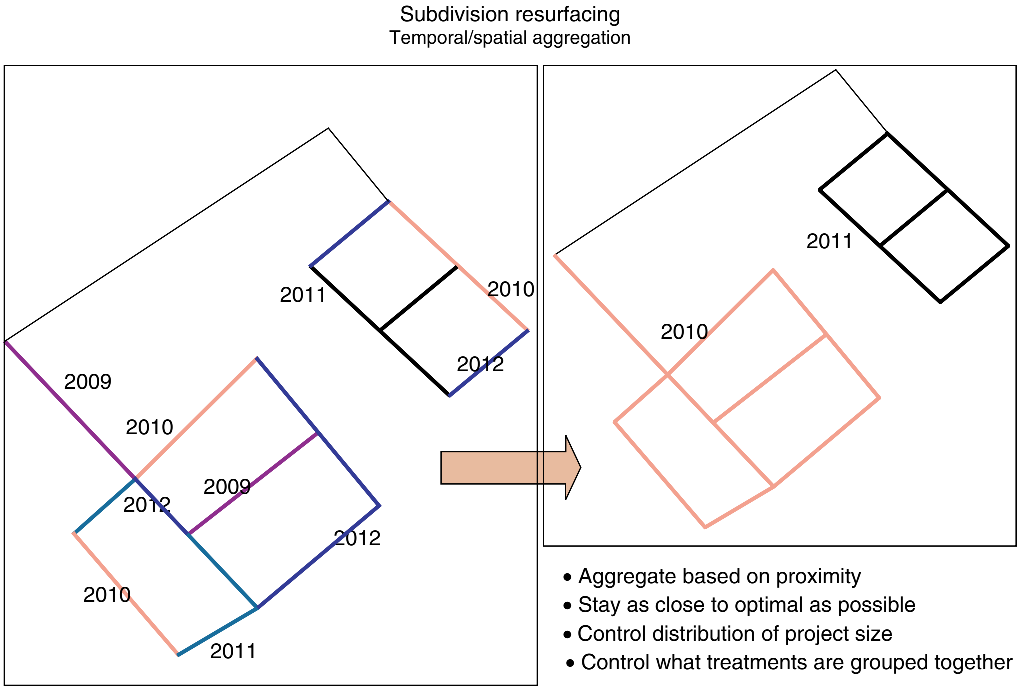
Figure 6: The diagram depicts NBDoT's hierarchical planning process.

In the second stage, a heuristic algorithm (Walters et al. 1999, Remsoft Inc. 1996) uses adjacency and proximity relationships and the LP-generated schedule of activities to create a more reasonable, spatially explicit schedule of activities. The algorithm takes a metaheuristic approach, incorporating Monte Carlo integer programming for initial grouping, bipartite matching and enumeration for initial scheduling, and a greedy algorithm for achieving balanced work-cost flows.

Candidate projects identified in the strategic plan are examined for their spatial proximity to other candidate projects to form larger projects where possible. These grouped projects may include multiple asset types. An example of spatial grouping would be scheduling an entire subdivision for treatment together in one or two consecutive years, as opposed to spreading the work over a longer period (see Figure 7).

In the final stage, candidate projects generated by the models are provided to the program developers, who subsequently select projects and review the available data. They review performance data and view current digital videos of the highway surface and features to make a final, expert judgment on whether the model has suggested a valid candidate.

Adjustments are also made to projects for other reasons, such as functional improvements, operational considerations, and noncondition factors (e.g., safety, project-specific requirements). Directives and operational budgets are monitored to ensure that the



- Aggregate based on proximity
- Stay as close to optimal as possible
- Control distribution of project size
- Control what treatments are grouped together

Figure 7: Grouping all work in a given location (e.g., a subdivision) offers cost and convenience benefits.

overall program development reflects the strategic treatment-category targets established by the global LP model.

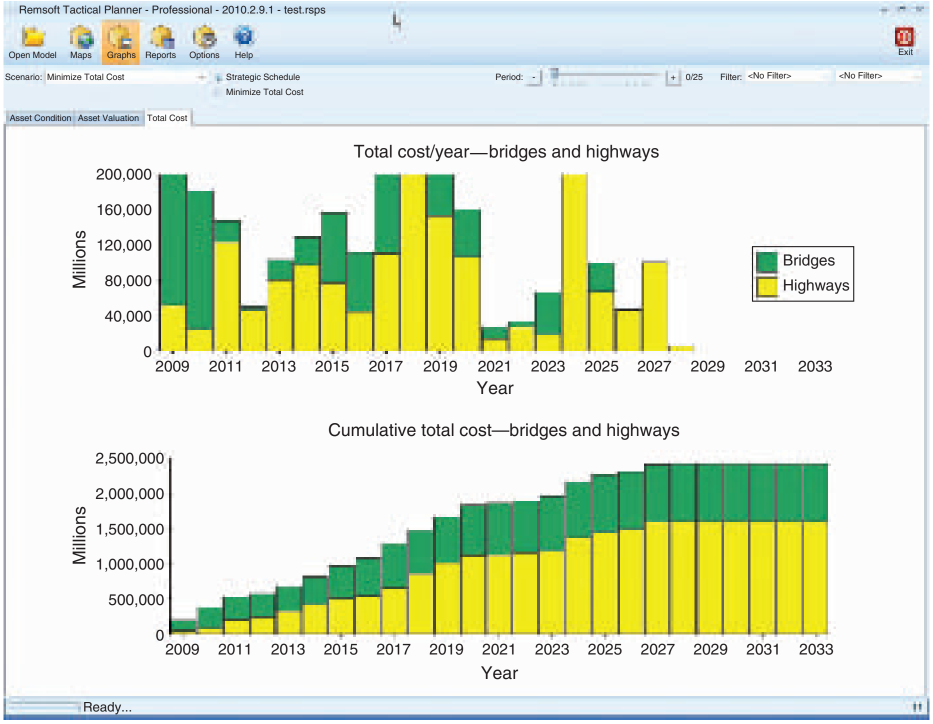
Implementation at NBDoT

Between 2004 and 2009, NBDoT allocated $2 million toward the consulting, software development, and software purchase required to support the project. In 2004–2005, xwave, a Canadian information technology company that served as an external consultant, undertook the framework design, process engineering, project management, and change management. AMS implementation began in April 2005; NBDoT worked with domain experts and consultants (including xwave and software provider Remsoft) to develop the solution, which culminated in the delivery of a functional long-term investment plan in 2007. The system then transitioned from a "project" to an established "program," which became the responsibility of the planning and land management branch of NBDoT.

The NBDoT program was developed using both off-the-shelf and custom software applications. AMS includes the following cornerstone software components.

- Remsoft modeling framework (RMF) and Remsoft modeling engine (RME): Used to build strategic models using asset behavioral information (e.g., the deterioration of roads based on factors such as traffic, climate, or construction class).
- Remsoft spatial scheduler (RSS): Uses heuristic methods to create operational groups of treatments based on their spatial location and suggested treatment timing.
- Program development tool (PDT): A custom application that facilitates the development of annual planning in the tactical (four-year) period.
- Mosek: A commercial LP solver (MOSEK ApS 2010).
- ESRI ArcGIS: Spatial data preparation, data management, and geoprocessing software.
- Transportation network management system (TNMS): An Oracle-based network management system that NBDoT had used for over 20 years.

Figure 8: The graphs show sample reports of six scenarios; they compare the total cost of all repairs over a 25-year planning horizon.



Scenario: Minimize Total Cost
Strategic Schedule
Minimize Total Cost
Period: 0/25
Filter: <No Filter> <No Filter>

Figure 9: Long-term costs for road and bridge work are shown.

Initial Analysis

Three questions related to NBDoT's infrastructure and its current age, location, and condition drove the modeling activity at the project outset.

1. What is the appropriate level of funding to meet the required levels of service?
2. How, when, and where should treatments be applied?
3. What will be the effect on the overall network condition?

To answer these questions and explore alternatives, NBDoT constructed a model using RMF. The appendix shows a detailed description of RMF; Table 1 summarizes its key components.

The natural modeling language used in RMF allows NBDoT users who do not have OR expertise to quickly develop sophisticated LP models. For example, a user may specify an objective function that minimizes total expenditures over a 20-year planning period using the following syntax:

```
_MIN TOT$SPENT 1..20.
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RME interprets this statement and other RMF model structures to generate LP matrices in mathematical programming system format and other formats that commercial LP solvers can solve. The appendix shows more complete examples using the modeling language and corresponding notations.

NBDoT explored various scenarios, incorporating alternative objectives and constraints; however, it focused on key metrics, such as total dollars spent and the length of highway in each category class. Results from the LP model include the optimal schedule of actions to be performed and a full range of graphs, maps, and reports to facilitate further analysis. Figure 8 illustrates results from six scenarios.

After the initial analysis, it became apparent to NBDoT that the selection of *what* assets to fix and *when* to fix them was just as critical to improving the overall network conditions as the funding level; simply increasing funding levels under the existing protocols would not improve the overall network condition. The various scenarios provided the optimal funding levels and the optimal schedule of asset treatments necessary to meet NBDoT's objectives for asset condition. Figure 9 illustrates cumulative total cost over the long-term (20–25 years) planning horizon for bridge and highway rehabilitation, and annual expenditures based on an objective of minimizing total cost.

Based on these results, funding for the pavement and bridge rehabilitation capital program was secured at a new level of approximately $180 million annually, with $120 million allocated for pavement rehabilitation. The average annual historic funding level for pavement rehabilitation had been in the range of $50 million.

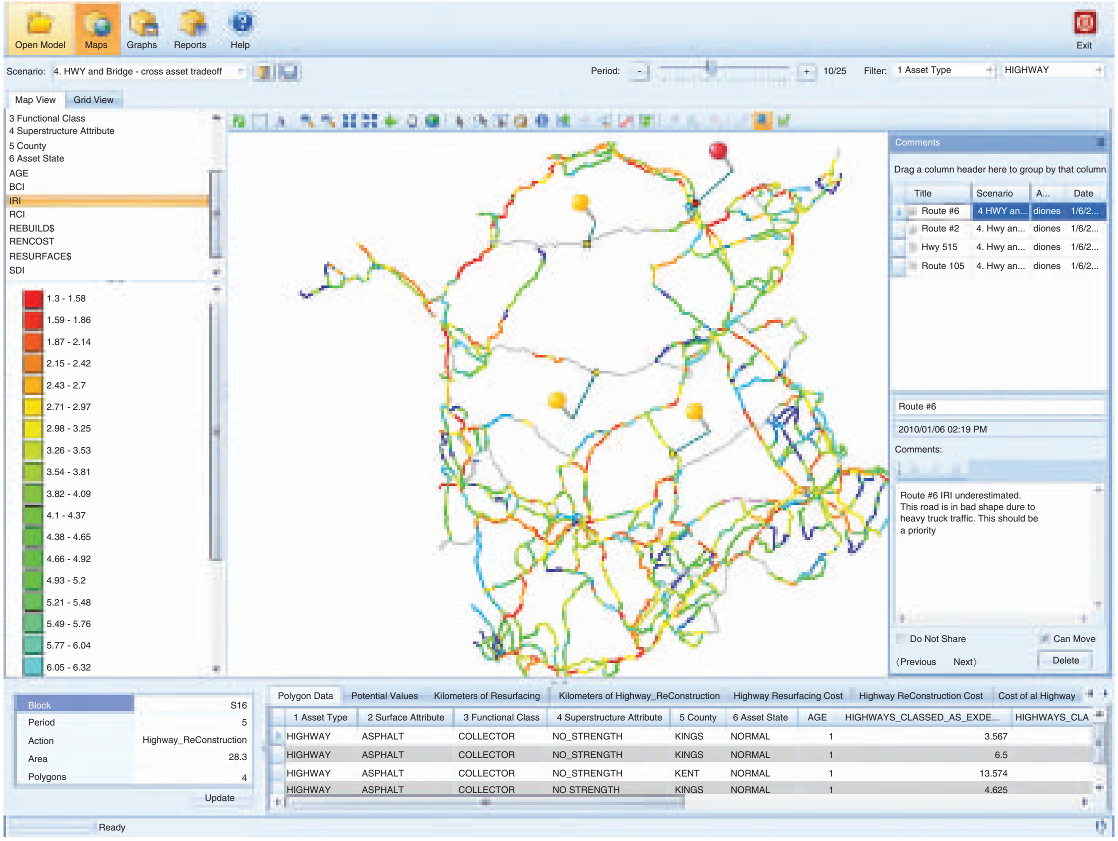
With the baseline approach, plans, and budgets approved, NBDoT moved to spatial scheduling: grouping projects together according to adjacency and proximity to capture project size and related benefits. Figure 10 offers an example of spatial-scheduling outputs available to NBDoT planners.

Value and Impact

As a result of the $2 million development investment in AMS, NBDoT is projected to realize $1.4 billion (discounted) in savings over the 20-year planning horizon—$72 million (discounted) in annual savings for only the road network. The savings are calculated by subtracting the projected cost of the

Component	Description
Asset class	15,271 kilometers of roads, 1,836 bridges, 62 covered bridges, and 773 culverts.
Asset attribute	Up to 10 attributes per asset class, including materials, surface attributes, functional class, superstructure type, deck type, substructure type, county or location, and asset state.
Potential treatments	Highways: nine actions, ranging from crack sealing to minor/major rehabilitation to reconstruction. Bridges: seven actions, ranging from resurfacing of the deck to entire bridge replacement. Culverts: replacement and rehabilitation.
Coefficients	Highways: international roughness index surface distress index, visual inspection rating. Bridges and culverts: a bridge-condition index used for both overall bridge condition and major component condition, including deck, superstructure, and substructure.
Costs	Treatment cost data for each action, asset, or maintenance combination.
Metrics	More than 100 outputs and metrics to track performance.
Time horizon	20 to 40 years, in one-year periods.

Table 1: The table lists the elements of the NBDoT model from late 2007.
***Notes*. Current models are similar but have added certain complexity to accommodate increasing knowledge and change management objectives.**



Scenario: 4. HWY and Bridge - cross asset tradeoff

Period: 10/25

Filter: 1 Asset Type HIGHWAY

3 Functional Class
4 Superstructure Attribute
5 County
6 Asset State
AGE
BCI
IRI
RCI
REBUILD$
RENCOST
RESURFACE$
SDI

1.3 - 1.58
1.59 - 1.86
1.87 - 2.14
2.15 - 2.42
2.43 - 2.7
2.71 - 2.97
2.98 - 3.25
3.26 - 3.53
3.54 - 3.81
3.82 - 4.09
4.1 - 4.37
4.38 - 4.65
4.66 - 4.92
4.93 - 5.2
5.21 - 5.48
5.49 - 5.76
5.77 - 6.04
6.05 - 6.32

Drag a column header here to group by that column

Title	Scenario	A...	Date
Route #6	4 HWY an...	diones	1/6/2...
Route #2	4. Hwy an...	diones	1/6/2...
Hwy 515	4. Hwy an...	diones	1/6/2...
Route 105	4. Hwy an...	diones	1/6/2...

Route #6

2010/01/06 02:19 PM

Comments:

Route #6 IRI underestimated.
This road is in bad shape dure to
heavy truck traffic. This should be
a priority

Block	S16
Period	5
Action	Highway_ReConstruction
Area	28.3
Polygons	4

1 Asset Type	2 Surface Attribute	3 Functional Class	4 Superstructure Attribute	5 County	6 Asset State	AGE	HIGHWAYS_CLASSED_AS_EXDE...	HIGHWAYS_CLA
HIGHWAY	ASPHALT	COLLECTOR	NO_STRENGTH	KINGS	NORMAL	1	3.567	
HIGHWAY	ASPHALT	COLLECTOR	NO_STRENGTH	KINGS	NORMAL	1	6.5	
HIGHWAY	ASPHALT	COLLECTOR	NO_STRENGTH	KENT	NORMAL	1	13.574	
HIGHWAY	ASPHALT	COLLECTOR	NO STRENGTH	KINGS	NORMAL	1	4.625	

Figure 10: Spatial scheduling, indicating the timing and location of treatments, and any location-specific attribute of interest, are displayed on a map. As NBDoT expands AMS, regional planners and others will be able to add notes and suggest changes to the plan. Pushpins on the map are used to identify where local experts have provided additional information.

optimal least life-cycle approach ($2.2 billion, or $110 annually) from the projected cost to attain the desired condition of the road network using the traditional (fix-the-worst-roads-first) approach ($3.6 billion, or $182 million annually).

Because model development for bridges and other assets lagged development for roads, bridges were not considered in the original return on investment (ROI) assessment. Because the bridge, culverts, and other assets are expected to deteriorate over time in a similar fashion, projections are that actual savings will be substantially higher as additional assets are fully implemented in the system.

When the solution was implemented in 2007, NBDoT was able to halt the growth of the number of road kilometers classified as poor (see Figure 11). As of 2009, 1,200 fewer kilometers of roads were designated poor than projected under the traditional funding approach; even greater reductions are expected over the next few years.

Table 2 provides comparative profiles of the kilometers of highways rehabilitated prior to and following the AMS implementation. At the outset, there was a dramatic shift to intervention strategies associated with the surfaces less than 20 years old. Although the segments 25 years and older were still being addressed, NBDoT focused on the less-expensive treatment categories consistent with the recommendations prescribed by the LP model.

AMS represents a fundamental shift in thinking and practice for NBDoT; the organizational challenges it created were much more difficult to address than were the technological challenges. Similar to most large public service organizations, NBDoT prior to its AMS

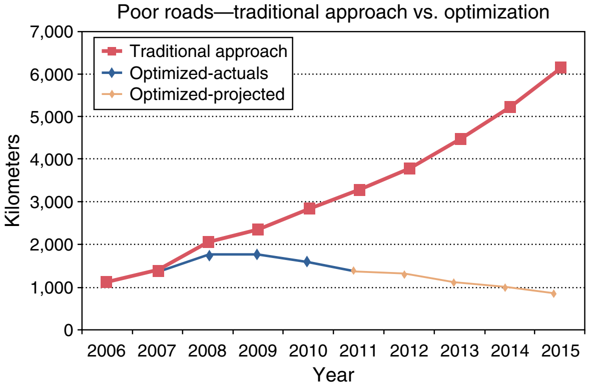


Figure 11: The graph illustrates projected kilometers of poor-quality roads over a long-term time horizon under the "worst-first" protocols approach vs. the new optimized methodology. The actual results experienced since 2007 are very close to the original projections.

implementation had a number of information repositories operating in isolation or independently; consequently, it had to discard many plans. However, when its subject matter experts collaborated in developing the solution, they were able to effectively accomplish true cross-asset optimization.

Shifting from a bottom-up to the top-down approach exemplified by AMS required all employees to surrender their familiar way of working and embrace this new model and decision-making process. To help its staff make this shift, NBDoT identified a number of key risk factors and corresponding approaches to risk mitigation and developed a change management plan to address them. Table 3 summarizes this shift in the planning approach.

	PreAMS 2006/07 + 2007/08	AMS 2008/09 + 2009/10	Net	% change
Years since last rehabilitation treatment	Kilometers of asphalt			
9 to 16	80	420	+340	+525
17 to 24	85	160	+75	+188
25+	60	55	−5	−8
Total	225	635	+410	+282
	Kilometers of chipseal			
	815	1,330	415	+163

Table 2: The table shows the number of kilometers of rehabilitated roads (pavement and chipseal) before and after the AMS implementation.

Planning approach before optimization	Planning approach after optimization
Worst first	Least life-cycle cost
Program focus (silos)	Network focus
Event and consumption focus	Asset focus
Short-term budget management	Long-term asset management planning
Budget-cycle planning	Ongoing planning
Network-level data collection	Sampling inspections
Budget measurement	Performance measurement
Financial evaluation	Managerial valuation
	Continuous improvement process

Table 3: NBDoT change management initiatives resulted in planning changes and improved overall management oversight.

The AMS implementation also transformed how NBDoT manages the public infrastructure, thus improving its overall management oversight. As a result of the mathematical optimization techniques and clearly defined goals and objectives, strategies and plans are now more transparent and easily defensible. AMS provides managers with the capability to make long-term decisions with more confidence and commitment. Because the consequences of deviating from the optimized plan can be easily quantified and communicated to stakeholders, politics has largely been removed from the decision-making process.

The new approach has broken down communication barriers and has provided the touchstone for all NBDoT managers; they are increasingly reliant on it for information and analysis. It has created new levels of collaboration across the organization, allowing department managers and executives to pose what-if questions and explore multiple scenarios in a timely manner to ensure that they have explored all relevant decision-making avenues.

Additional Benefits

In addition to considerable savings, improved transportation infrastructure, and better management oversight, AMS offers other benefits. Using the natural modeling language, which is the basis for RME, transportation-knowledgeable staff without OR expertise can conduct sophisticated analyses (i.e., build, refine, and analyze models). Moreover, NBDoT can achieve quick turnaround on changes to allow for multiple what-if scenarios—an approach that fosters collaboration and helps to dismantle barriers across departmental silos.

NBDoT has also realized a newfound ability to

- effectively plan over long planning horizons, while considering a full range of alternatives;
- provide a more efficient means of allocating funds among the competing needs of NBDoT's transportation network;
- make better-informed decisions by identifying the appropriate timing for applying the most effective and economical treatment to assets, thus minimizing the life-cycle cost of New Brunswick's roads and bridges; and,
- address other important issues associated with the provincial highway system, such as safety, environmental impacts, and carbon-based indices.

Through this work, NBDoT has become a global leader in asset management; its success has attracted the attention of transportation officials around the world. Proof of the change is evident by the support and focus the government has given the AMS initiatives. AMS has been one of the key points in the Premier's speeches in the legislature, and it has garnered comprehensive media coverage—even editorial cartoons. In addition, other government departments have requested NBDoT assistance and guidance with respect to managing their assets.

Lessons Learned

NBDoT learned many lessons as it developed and refined the model. Some notable recommendations include the following.

Pilot, develop, improve. Develop a pilot to test the concept; extend the pilot as a project; when the project has been deemed successful, implement it as a program. Continually improve the program to reflect the organization's current and long-term mandate and vision.

Secure senior management commitment. The success of any endeavor must be driven from the top down. Senior executives must express their confidence and commitment to the project; they must also provide guidance and the necessary resources, including technology resources, to allow the technical staff to find practical solutions. Executive support allowed NBDoT's staff and industry resources working with the staff to deliver a solution ahead of schedule, during a period in which the government is under challenging financial restraint directives.

Communicate, communicate, communicate. A clear understanding and commitment to the new approach are essential because the front-line workers must ultimately respond and justify the rehabilitation activities to the general public. OR is not a natural fit for many public sector organizations. Its concepts, terminology, and applicability must be communicated well and with a high degree of patience and perseverance.

Be flexible and adaptable. The NBDoT experience showed that many, if not most, infrastructure assets have a predictable rate of depreciation based on age and use, and that the response to treatment can also be predicted. Keeping these factors in mind, NBDoT can add assets to its models over time. In addition, other government departments might find it feasible to apply OR techniques to managing their assets.

Concluding Remarks

The new OR-based AMS supplements NBDoT's expertise with tools to allow the organization to develop and implement an optimized rehabilitation plan to ensure a sustainable provincial transportation network. The modeling framework incorporates long-term objectives and constraints from an operations perspective—it weighs all options, considers costs, timings, and asset life cycles, and produces optimal treatment plans and schedules of activities.

AMS continues to enhance NBDoT's business functions through a process of continuous improvements. The system has been effectively used to develop its annual multimillion-dollar rehabilitation plan for the last three years. In future program development budgets, highway fixtures and ferries will be added to the models.

In a relatively short period, the province of New Brunswick has realized savings of over $70 million annually on pavements. Over the coming years, as AMS is expanded to include the remaining transportation-related infrastructure, this figure is projected to increase significantly. Beyond improving the overall infrastructure quality, AMS will lower annual maintenance demands, provide a higher level of service to the public, and benefit the environment through fewer energy-demanding and intrusive rehabilitation activities.

The cultural shift underway at NBDoT is ongoing, reflecting the positive attitude of leaders and team members who have increased confidence and evidence that their decisions and plans are supported by facts and are delivering the desired results. It is not uncommon to hear staff members ask, "What does asset management (the solution) say?" and "Is this consistent with asset management?" Since its implementation in 2007, AMS has provided the following benefits.

- Quantitative demonstration that the "fix-the-worst-first" approach to highway maintenance is a clearly inferior management protocol;
- significant capital program savings over a 20-year period;
- proof that strategic scheduling of road rehabilitation can prevent roads from deteriorating to a poor condition; thus, it can save money in the long run;
- reversal of the trend toward increasing the number of road kilometers with conditions rated as poor, and basis for actual decreases in the percentage of such roads within the next two to three years;
- support of the local road-building industry by forecasting budget allocations over several years, thus allowing the industry in turn to better plan its staffing and equipment needs over the medium and longer term.

NBDoT's success is generating substantial interest. Other departments within the provincial government are considering adopting its approach to better manage their resources. In addition, highway agencies in other Canadian provinces and in many countries around the world, including the United States, Australia, Costa Rica, and New Zealand, have expressed interest in the solution.

In a largely rural province in which the roads, highways, and bridges are the lifeblood of communities, NBDoT can fulfill its mandate of providing a quality, safe, and effective transportation system, thus keeping New Brunswick's economy and communities vibrant.

While in office, Shawn Graham, Premier of the province of New Brunswick, stated that "the Department of Transportation's operations research-based Asset Management System identifies the right choices to improve infrastructure at the lowest cost to taxpayers. It means our province will enhance the safety and efficiencies of the New Brunswick highway system to the benefit of our economy and all those who depend upon our road system for their education, business, family, recreation and social needs" (Graham 2010).

Appendix

In this appendix, we offer a brief overview of RMF and its natural modeling language. A key feature of RMF is that the entity attributes, coefficients, activities, and metrics are separate from the control structures that determine the model formulation. Changing a generalized model II LP model (Johnson and Scheurman 1977) formulation into a deterministic simulation model can be accomplished by changing a few lines of code; incorporating stochastic elements into that simulation model requires similarly little effort. Because the underlying conceptual model remains intact, RMF allows a user to employ a wide range of solution methodologies and sensitivity analyses and be confident that the various results are comparable.

Figure A.1 illustrates the conceptual model of a simple transportation asset management problem. Attributes and life spans define assets; actions and transitions describe activities to carry out their effects; outputs are the metrics for imposing management control; and coefficients describe the dynamic changes that assets undergo as they age (deterioration). To exert management control in this model, the user can use either optimization (LP/MILP) or simulation by selecting the appropriate keyword (`*OPTIMIZE ON|OFF` or `*QUEUE ON|OFF`).

Assume that the user wishes to formulate this model as an LP with a three-year planning horizon, minimize total expenditures over the planning horizon, ensure that the number of kilometers (two-lane) of highways in poor condition does not increase, and reduce the kilometers of roads in poor condition by at least half by the end of the third year. The appropriate syntax to accomplish this follows.

```
*OBJECTIVE
_MIN HIGHWAYS_CLASSED_AS_POOR 3
*CONSTRAINTS
TOTAL_DOLLARS_SPENT <= 1,000,000 1..3
HIGHWAYS_CLASSED_AS_POOR <= HIGHWAYS_CLASSED_AS_POOR[-1] 1..3
*FORMAT LINDO
```

RME will interpret the conceptual model framework and control sections to generate an LP in LINDO algebraic format (LINDO Systems 2002), as Figure A.2 shows.

```
CONTROL
*OPTIMIZE  ON   ; matrix generation
*SCHEDULE  ON   ; LP solution playback
*QUEUE     OFF  ; Simulation mode

ATTRIBUTES
*THEME 1 ASSET TYPE
 HW HIGHWAY SECTION
 BR BRIDGE
*THEME 2 ATTRIBUTE - SURFACE
 AR ASPHALT
 WD WOOD
*THEME 3 FUNCTIONAL CLASS
 NONE
 ARTOTH OTHER ARTERIAL
*THEME 4 ATTRIBUTE - SUPERSTRUCTURE
 WS WOOD STRUCTURE
 NS NO STRENGTH
*THEME 5 ATTRIBUTE - COUNTY
YORK
*THEME 6 STATE
 NORMAL
 MS   ROAD HAS BEEN MILLED AND SEALED
 LMS  LATE MILL & SEAL DAMAGE TO SUBSTR LIKELY
 MBS  ROAD HAS BEEN MILL/BASE/SEALED
 LMBS LATE MILL/BASE/SEAL DAMAGE LIKELY
 EOUL END OF USEFULL LIFE

LIFESPAN
HW AR ?  ? ? ? 139
BR ?  ? WS ? ? 121

ASSETS
*A BR WD NONE WS YORK NORMAL    90 193
*A HW AR ARTOTH NS YORK NORMAL  13 10.343
*A HW AR ARTOTH NS YORK NORMAL  18 28.629

ACTIONS
*ACTION ARESURFACE Y RESURFACE ACTIVITY
 *OPERABLE ARESURFACE
  HW AR ARTOTH ? ? NORMAL _AGE >= 10 AND _AGE <= 25
*ACTION ARECONSTRUCTION Y REBUILD THE HIGHWAY
 *OPERABLE ARECONSTRUCTION
  HW AR ? ? ? ? _AGE >= 25
*ACTION ABRMAINT N MAINTAIN BRIDGE
 *OPERABLE ABRMAINT
  BR ? ? ? ? NORMAL _AGE >= 30
*ACTION ABRRENEW Y REBUILD BRIDGE
 *OPERABLE ABRRENEW
  BR ? ? ? ? ? _AGE >= 60

TRANSITIONS
*CASE _DEATH
 *SOURCE HW ? ? ? ? ?
  *TARGET ? ? ? ? ? EOUL 100 _AGE 40
 *SOURCE BR ? ? ? ? ?
  *TARGET ? ? ? ? ? EOUL 100 _AGE 120
*CASE ARESURFACE
 *SOURCE HW AR ? ? ? NORMAL @AGE (10..15)
  *TARGET HW AR ? ? ? MS 50
  *TARGET HW AR ? ? ? MBS 50
 *SOURCE HW AR ? ? ? NORMAL @AGE (16..25)
  *TARGET HW AR ? ? ? LMS 50
  *TARGET HW AR ? ? ? LMBS 50
 *SOURCE HW AR ? ? ? MS @AGE (8..12)
  *TARGET HW AR ? ? ? MS 50
  *TARGET HW AR ? ? ? MBS 50
 *SOURCE HW AR ? ? ? MS @AGE (13..20)
  *TARGET HW AR ? ? ? LMS 50
  *TARGET HW AR ? ? ? LMBS 50
 *SOURCE HW AR ? ? ? MBS @AGE (18..12)
  *TARGET HW AR ? ? ? MS 50
  *TARGET HW AR ? ? ? MBS 50
 *SOURCE HW AR ? ? ? MBS @AGE (13..20)
  *TARGET HW AR ? ? ? LMS 50
  *TARGET HW AR ? ? ? LMBS 50
```

```
*CASE ARECONSTRUCTION
 *SOURCE HW AR ? ? ? ?
  *TARGET HW AR ? ? ? ? 100
*CASE ABRMAINT
 *SOURCE ? ? ? ? ? ?
  *TARGET ? ? ? ? ? ? 100
*CASE ABRRENEW
 *SOURCE BR ? ? ? ? ?
  *TARGET BR ? ? ? ? NORMAL 100

OUTPUTS
*OUTPUT oTot$Resurfacing  Cost of Resurfacing
 *SOURCE aResurface yResurface$
*OUTPUT Otot$Reconstruction Cost of Reconstructing
 *SOURCE aReconstruction yRebuild$
*OUTPUT Ohw$pent Cost of all highway construction
 *SOURCE OTOT$RESURFACING + OTOT$RECONSTRUCTION
*OUTPUT oBridgerenew$pent Bridge Renewal cost
 *SOURCE abrrenew yrencost
*OUTPUT oBridgemaint$pent Bridge Maintenance Cost
 *SOURCE abrmaint yrencost
*OUTPUT oBr$pent Total Bridge Cost
 *SOURCE oBridgerenew$pent + oBridgemaint$pent
*OUTPUT Total_Dollars_Spent Total expenditure
 *SOURCE ohw$pent + ototbridge$pent
*OUTPUT Highways_Classed_As_Poor (_TH3) Roads in
Poor Condition
 *SOURCE hv ar artoth ? ? ? @YLD (yiri, 2.7..50)
_INVENT _AREA

COEFFS
*Y ? ? ? ? ? ?
 _AGE YAGE
   1   1
 100 100
*Y HW ? ? ? ? ?
 _AGE YDEPRE
  1 1.0
  5 0.95
 10 0.80
 20 0.5
 25 0.0
*YC HW AR ARTOTH ? ? ?
 YVALUE YDEPRE * 400
*Y HW AR ARTOTH ? ? ?
 _AGE YRCI YIRI YSDI
  1 7.5 0.57 10
 15 5.5 2.29  7.9
 30 2.5 6.19  6.5
*Y HE AR ? ? ? ?
 _AGE YRESURFACE$ YREBUILD$
  1             50   0
 15            160   0
 18            180   0
 25            300 350
*Y BR ? ? WS ? ?
 _AGE YPCENT YRENCOST
 1 100 0
 20 99 0.322
 32 90 1
 40 79 1.4
 48 63 2
 60 01 3

*YT ? ? ? ? ? ?
YDIS4% _DISCOUNTFACTOR (4%,1,HALF)
```

Figure A.1: A simple transportation asset conceptual model is rendered in RMF using natural modeling language.

```
!Objective
MIN
OBIMIN) TOTALDO1+TOTALDO2+TOTALDO3
ST
C1R1) OUT00001 <= 28.62899971
C1R2) OUT00002 -OUT00001 <= 0
C1R3) OUT00003 -OUT00002 <= 0
C2R1) OUT00003 <= 14.31449986
! Initialize Existing Assets
x3)   A3+A4+A7+A9+A13+A16+AU19 = 193
x4)   A2+A6+A12+AU20 = 10.34300041
X5)   A1+A5+A11+AU21 = 28.62899971
! Future Asset Transfer Rows
! Period 1 C8)
-A4 + RU22 = 0
! Period 1 C9)
-A3+R8+R10+R14+R17 + RU23 = 0
! Period 1 C10)
 -0.5A2 + RU24 = 0
! Period 1 C11)
 -0.5A2 + RU25 = 0
! Period 1 C12)
 -0.5A1 + RU26 = 0
! Period 1 C13)
 -0.5A1 + RU27 = 0
! Period 2 C14)
-A9-R10 + RU28 = 0
! Period 2 C15)
-A7-R8+R15+R18 + RU29 = 0
! Period 2 C16)
 -0.5A6 + RU30 = 0
! Period 2 C17)
 -0.5A6 + RU31 = 0
! Period 2 C18)
 -0.5A5 + RU32 = 0
! Period 2 C19)
 -0.5A5 + RU33 = 0
! Period 3 C20)
-A16-R17-R18 + RU34 = 0
! Period 3 C21)
-A13-R14-R15 + RU35 = 0
! Period 3 C22)
 -0.5A12 + RU36 = 0
! Period 3 C23)
 -0.5A12 + RU37 = 0
! Period 3 C24)
 -0.5A11 + RU38 = 0
! Period 3 C25)
 -0.5A11 + RU39 = 0
! Accounting variables
+180A1 +144.28572083A2 +3A3 +3A4 -TOTALDO1 = 0
+197.14285278A5 +152.14285278A6 +3A7 +3R8 +3A9 +3R10 -TOTALDO2 = 0
+214.28572083A11 +160A12 +3A13 +3R14 +3R15 +3A16 +3R17 +3R18
-TOTALDO3 = 0
+A5 +A11 +AU21 -OUT00005 = 0 !HIGHWAYS_CLASSED_AS_POOR(ARTOTH) [1]
+OUT00005 -OUT00001 = 0 !HIGHWAYS_CLASSED_AS_POOR[1]
+A11 +AU21 -OUT00006 = 0 !HIGHWAYS_CLASSED_AS_POOR(ARTOTH) [2]
+OUT00006 -OUT00002 = 0 !HIGHWAYS_CLASSED_AS_POOR[2]
+AU21 -OUT00007 = 0 !HIGHWAYS_CLASSED_AS_POOR(ARTOTH)[3]
+OUT00007 -OUT00003 = 0 !HIGHWAYS_CLASSED_AS_POOR[3]
```

Figure A.2: This example illustrates a simple transportation asset model formulated as an LP (LINDO algebraic format).

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