Decision Support Model for Assessing Net Public Benefits of Reuse of Waste Materials in Highway Maintenance and Construction Projects

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The state of Minnesota frequently receives requests from an outside source to consider accepting waste materials for reuse in highway maintenance and construction projects. The materials can include glass, roofing shingle tabs, shredded tires, coal ash, railroad ties, and taconite tailings. The Minnesota Department of Transportation (Mn/DOT) recently established a policy requiring that the use of waste material provide both short- and long-term public benefits. Mn/DOT also sought a framework to assess whether such benefits exist. Accordingly, a decision framework and decision support tool in the form of an electronic spreadsheet were developed, tested, and refined through the application of three case studies. The framework and decision support tool spreadsheet are described, and the results of one of the applied case studies are presented to illustrate the types of inputs required by the spreadsheet and the outputs produced. The spreadsheet is a very flexible tool that is able to account for a wide variety of materials and their placement in highways. It compares over a 20-year period the discounted present value of the incremental increase in highway maintenance and construction costs as a result of using taconite tailings in roads to the avoidable costs of disposal through transporting the waste and landfilling it or disposing of the waste material at the source where it is generated (e.g., a taconite mine).

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Frequently the Minnesota Department of Transportation (Mn/DOT) is asked to consider accepting waste products such as coal ash, shredded tires, roofing shingles, or mixed broken glass for use in highway maintenance or construction projects. The department recently established a policy delineating criteria under which it can accept waste materials from outside sources for use in highway maintenance and construction projects. The purpose of the policy is to ensure that Mn/DOT's decisions on waste materials and their recycling and reuse are made in a comprehensive manner respectful of environmental stewardship, public benefit, protection of public health, and limitation of liability.

Under the guidelines set out in the policy, Mn/DOT will accept waste from outside sources under the following criteria:

1. The waste must not be hazardous. Under no circumstances will Mn/DOT accept hazardous waste from others.
2. There must be both a short- and long-term public benefit from the reuse/recycling of waste materials.
3. The long-term effect of the reuse/recycling of waste materials must either improve the environment or, at a minimum, have a neutral effect on the environment.

The policy also states that, at a minimum, Mn/DOT must consider the following factors when assessing benefits and risks:

- Appropriate federal, state, and county agency approvals.

- Engineering performance of the structure incorporating the waste materials. (The performance must be equal to or better than that of the structure without the waste.)
- Constituents of the waste and the waste's toxicity.
- Environmental impacts from incorporating waste materials. (Environmental testing must show an impact equal to or less than that of materials currently used.)
- Recyclability of the new waste-amended construction material. (New material must have fewer or equal environmental impacts compared with nonamended material when recycled.)
- Short-term public benefit from reuse/recycling of waste materials.
- Long-term public benefit from reuse/recycling of waste materials.
- Legal and financial liability.
- Whether there are more cost-effective alternatives to disposing of wastes.
- Impact on Mn/DOT's mission of accepting non-Mn/DOT wastes.
- Potential use of pilot research and development experiments for further information.

Among the steps Mn/DOT recently took to render their policy operational was development of a framework and electronic spreadsheet for assessing two of the criteria listed above—the short-term as well as the long-term public benefit from the reuse/recycling of various types of waste materials—in deciding whether or not to accept waste material from outside sources. For this purpose Mn/DOT contracted with Booz · Allen & Hamilton, Inc. to develop a decision tree and accompanying spreadsheet. The project was carried out under the guidance and close cooperation of Mn/DOT staff.

This study describes the project's decision framework and electronic decision support tool, as well as application of the framework to one of three case studies used in testing and refining both the framework and spreadsheet.

FRAMEWORK

The decision framework focused on estimating the net economic benefit for reusing a particular waste material type. Net economic benefit was defined as the discounted present value of the difference between the future stream of avoidable costs for the normal disposal option and the future stream of costs for disposing of the waste material in highway maintenance or construction projects.

Figure 1 shows the decision framework, which is divided into five sections. The first two sections are used to determine whether the maximum annual quantity of waste can feasibly be used on a proposed portion of highway network. The maximum annual quantity is an analytic parameter for determining whether the roadway network has the capacity to absorb a proposed reuse of waste material. It is also used to explore whether there exist public benefits in the reuse of different quantities of a waste material type.

The remaining three framework sections describe steps for determining whether long- and short-term benefits exist in the use of waste materials in highway maintenance or construction projects.

Feasibility of Using the Maximum Annual Quantity

In the framework's first section, the decision maker first identifies how much of a particular type of waste will be disposed each year for 20 years, as well as the maximum annual quantity. A determination is then made concerning how many lane-miles, shoulder-miles, or embankment-miles will occur, as relevant, based on the following factors:

- Maximum annual quantity,
- An engineering specification for the quantity of waste per mile to be allocated for a particular use (i.e., pavement, base, subbase, shoulders, embankment), and
- Distribution of waste by functional class.

The framework's second section is an assessment of the annual levels of planned work and a determination of whether the maximum annual quantity of reuse will exceed the maximum feasible placement of waste for any functional class. If the maximum annual quantity exceeds the feasible placement for a particular functional class, it will then be necessary to reduce the maximum annual quantity, increase the specified quantity placed per mile, or change the distribution of placement of material across functional classes. If the maximum annual quantity does not exceed the feasible placement for a particular functional class, the decision maker can proceed to the next part of the decision framework.

Determination of Long- and Short-Term Public Benefits for Reusing a Waste Material

The remainder of the framework provides guidance on determining any long- and short-term benefits for reusing a waste material in highway maintenance or construction.

The third section is used to determine the discounted present value for each year during 20 years of the incremental change in the cost of the roadwork due to the proposed use of waste materials. Inputs for this calculation include the incremental change in delivered price of the material that would normally be used for incorporating the waste material, and other incremental changes in cost such as design, installation, inspection, and life-cycle costs such as maintenance and user costs.

The framework's fourth section is used to determine the avoidable cost of reusing waste materials in highways. The decision tree logic assumes that waste not reused or recycled in highways will either be disposed of at its source of origin or taken to a landfill. Depending on the disposal site and facility, avoidable cost will normally consist of several of the following items: tipping or cover fee, transport costs and facility capital, and maintenance and operating costs. These avoidable costs must be identified for each year during a 20-year period. The discounted present value is then calculated.

The decision tree's fifth section simply asks whether the discounted present value of the avoidable cost of disposing of waste materials in the disposal facility is greater than the discounted present value of the incremental costs of the proposed reuse of the waste for any short- and long-term periods over the next 20 years. If the answer is yes, there are net short- and long-term public benefits; if the answer is no, such benefits are nonexistent.

Electronic Spreadsheet Decision Support Tool

An electronic spreadsheet was developed in Microsoft Excel 97 to render the decision framework operational and to permit Mn/DOT to make calculations for determining whether short- and long-term benefits exist for reusing a waste material obtained from an outside source. The spreadsheet comprises a workbook of five sheets:

Sheet 1: Highway Inputs

This sheet is used to enter inputs for calculating the incremental costs of using a candidate waste material in the pavement, base, subbase, shoulder, or embankment of

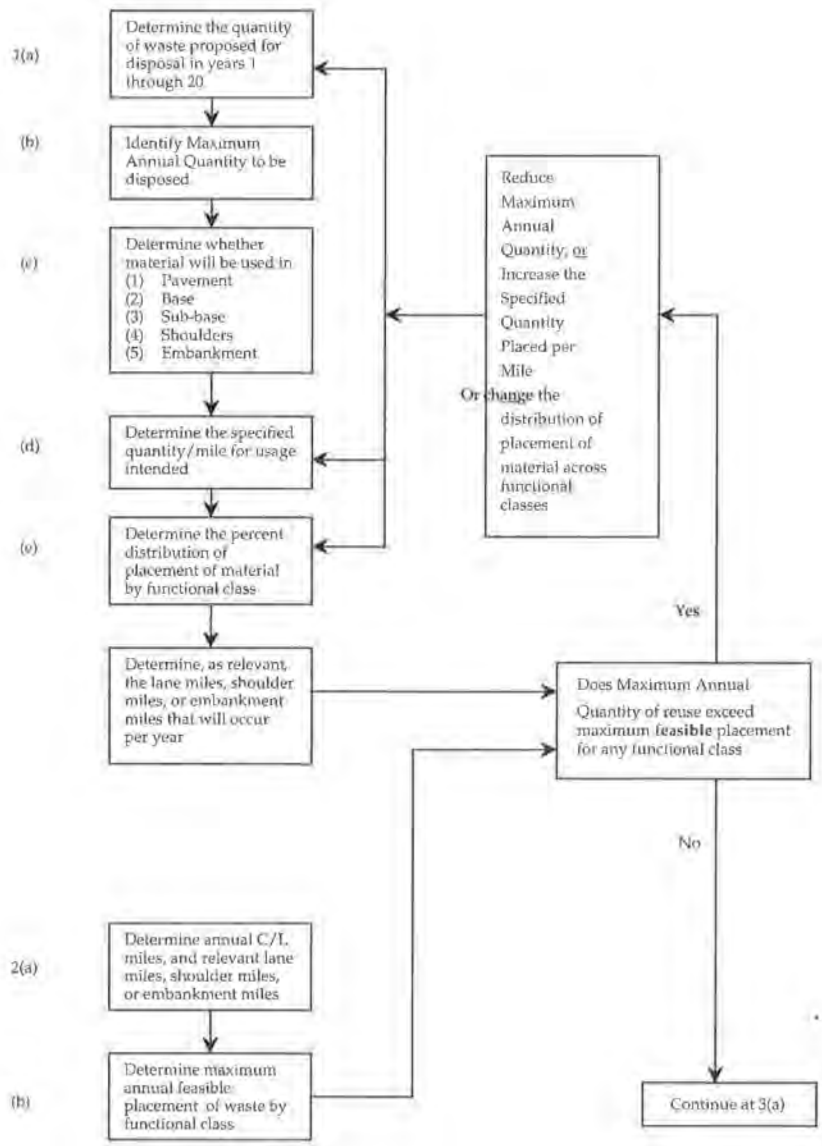

FIGURE 1 Decision tree for determining public benefits of reuse of waste materials in highway maintenance and construction. (*continued on next page*)

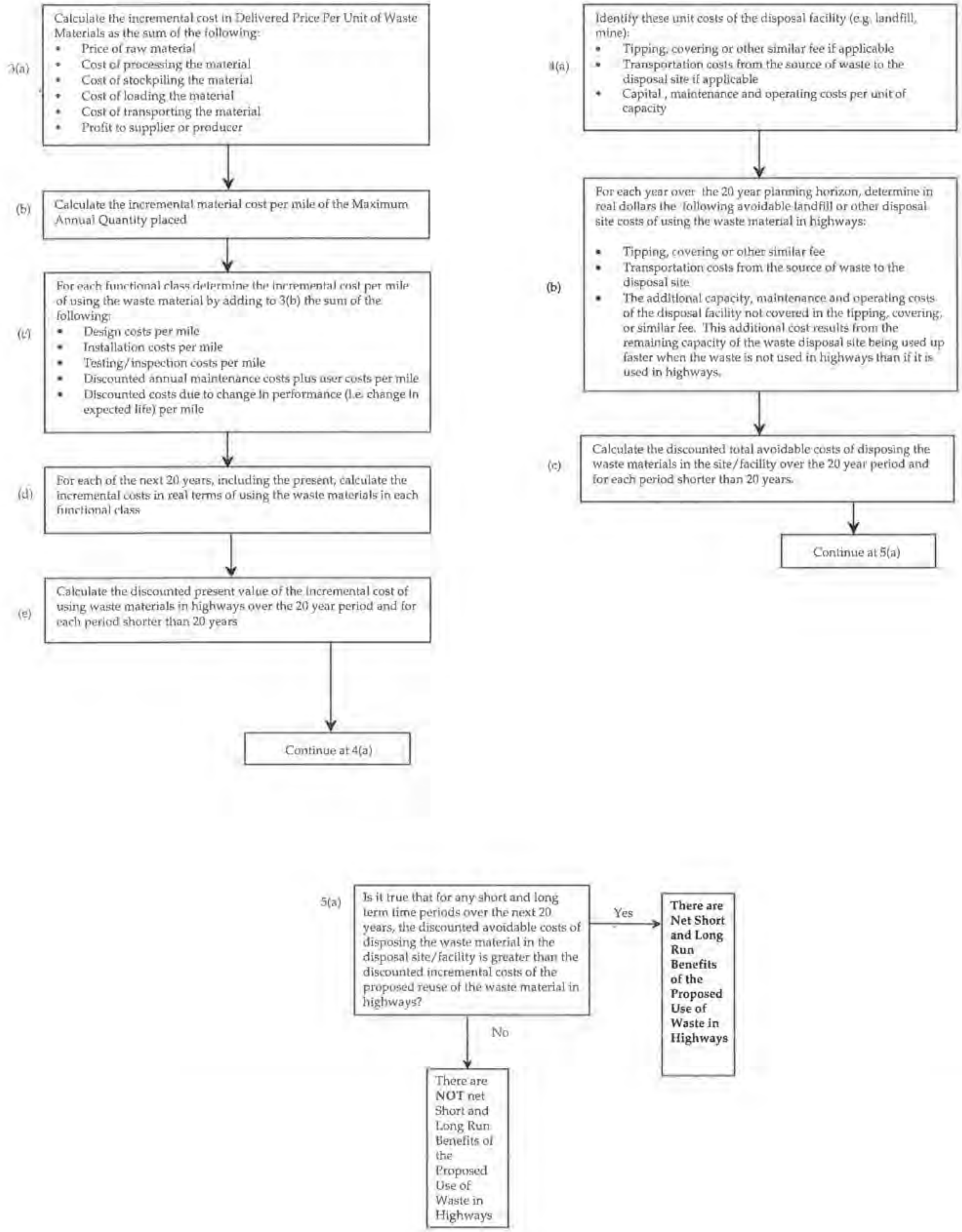

FIGURE 1 (*continued*) **Decision tree for determining public benefits of reuse of waste materials in highway maintenance and construction.**

highways and roads (Figure 2). The sheet performs calculations for determining the feasibility of placing the maximum annual quantity of proposed waste for use in roads given the planned annual centerline miles of relevant roadwork.

Required data inputs include the following:

- Maximum annual quantity of waste proposed for disposal;
- Fraction of maximum quantity to be disposed of each year for 20 years;
- Specified quantity of waste to be placed per mile in the proper units (i.e., lane-mile, shoulder-mile, embankment-mile);
- Location where waste is to be placed (e.g., pavement, base, subbase, shoulder, embankment);
- Distribution of waste by functional class;
- Ratio of various inventory features to centerline miles (e.g., ratio of lane-miles to centerline miles);
- Incremental cost of delivered price of waste material; and

SCENARIO FOR REUSE OF WASTE MATERIALS:		Normal Taconite Tailings Used in Highway Base -- Scenario B, Ship from Virginia MN to Taconite Harbor by Rail, Water & Hwy (04/13/99)			
Type of Material:	Norm. Taconite Tailings	DISCOUNT	0.07	**(ENTER DISCOUNT RATE X 0.01**	
Use of Material:	Base				
MAXIMUM ANNUAL QUANTITY	126720	UNITS:	tons		
	MULTIPLIER	QUANTITY/YR			
Year 0	1.00	126720			
Year 1	1.00	126720			
Year 2	1.00	126720			
Year 3	1.00	126720			
Year 4	1.00	126720			
Year 5	1.00	126720			
Year 6	1.00	126720			
Year 7	1.00	126720			
Year 8	1.00	126720			
Year 9	1.00	126720			
Year 10	1.00	126720			
Year 11	1.00	126720			
Year 12	1.00	126720			
Year 13	1.00	126720			
Year 14	1.00	126720			
Year 15	1.00	126720			
Year 16	1.00	126720			
Year 17	1.00	126720			
Year 18	1.00	126720			
Year 19	1.00	126720			
TOTAL		2534400			
		Placement of Material (Enter 1 if placed there; 0 if not)			
Relevant coverage	Pavement	Base	Sub-base	Shoulders	Embankment
Units of coverage	Lane miles	Lane Miles	Lane miles	Shoulder miles	Embankment-miles
	01		0	0	0
SPECIFIED QUANTITIES PER MILE		Number of miles	Units		
Units placed per lane-mile	[illegible]	16.59942363	lane-miles		
Units placed per shoulder mile		#DIV/0!	shoulder-miles		
Units placed per embankment-mile		#	embank.-miles		
	Freeways	Princ. Arterials	Min.Arterials	Collectors	Local
Lane-mi/centerline mile	0	2	2	2	2
Shoulder mi/centerline mile	0	2	2	2	2
Embankment miles/centerline mile	0	0.1	0.1	0.1	0.1
	Freeways	Princ. Arterials	Min.Arterials	Collectors	Local
Distribution of Placement (Total=1.00)	0	0.4	0.4	0.2	0

FIGURE 2 Inputs for determining feasibility of using waste materials and for assessing incremental highway costs. (*continued on next page*)

INCREMENTAL COST IN DELIVERED PRICE PER UNIT OF WASTE MATERIAL							
Price of Raw Material	-$0.27						
Cost of Processing the Material	-$0.46						
Cost of Stockpiling the Material	$0.00						
Cost of Loading the Material	$0.00						
Cost of Transporting the Material	$10.85	Note: Transport cost is calculated over the distance the waste is transported					
Profit to Supplier or Producer	$0.00						
TOT. DELIVERED PRICE/UNIT OF MTL.	$10.12	1282406.4 =MAX ANNUAL QUANTITY * TOT DEL PRICE					
MILES IN PROPER UNITS (Rows 34-36)	16.6						
MTL.COST/MI. OF MAX WASTE PLACED (miles expressed in proper units)	$77,253	Note: This is in material cost per mile per year in the proper units (e.g. lane miles, shldr-miles, or emb.-mi) given the Maximum Annual Quantity.					
	COMPONENT INCREMENTAL COSTS PER MILE IN PROPER UNITS BY FUNCTIONAL CLASS						
	Freeways	Prin.Arterials	Min. Arterials	Collectors	Locals		
Material Cost/Mi of Waste Placed	$77,253	$77,253	$77,253	$77,253	$77,253		
Design	$0	$0	$0	$0	$0		
Installation	$0	$0	$0	$0	$0		
Testing/Inspection	$0	$0	$0	$0	$0		
Discounted Annual Maintenance	$0	$0	$0	$0	$0		
Discounted Costs due to Chng in Perform.	$0	$0	$0	$0	$0		
TOTAL INC.COSTS.	$77,253	$77,253	$77,253	$77,253	$77,253		
	INCREMENTAL COST PER MILE MEASURED IN PROPER UNITS OF USING WASTE						
	In Pavements	In Base	In Sub-base	In Shoulders	In Embankments		
Freeways	$0.00	$77,253.40	$0.00	$0.00	$0.00		
Principal Arterials	$0.00	$77,253.40	$0.00	$0.00	$0.00		
Minor Arterials	$0.00	$77,253.40	$0.00	$0.00	$0.00		
Collectors	$0.00	$77,253.40	$0.00	$0.00	$0.00		
Local	$0.00	$77,253.40	$0.00	$0.00	$0.00		
	DISTRIBUTION OF WASTE GIVEN PROPOSED MAXIMUM ANNUAL QUANTITY TO BE DISPOSED						
	Planned Avg. C/L miles/yr		Planned lane miles	Lane-mi of waste	Planned shldr-miles	Shldr-miles of waste	Planned emb-miles
Freeways	0		0	0	0	#DIV/0!	0
Principal Arterials	4		8	6.639769452	8	#DIV/0!	0.4
Minor Arterials	4		8	6.639769452	8	#DIV/0!	0.4
Collectors	2		4	3.319884726	4	#DIV/0!	0.2
Local	0		0	0	0	#DIV/0!	0
Total	10		20	16.59942363	20	#DIV/0!	1

FIGURE 2 (*continued*) Inputs for determining feasibility of using waste materials and for assessing incremental highway costs.

• Incremental cost per mile of design, installation, inspection, and future maintenance costs.

Sheet 2: Highway Costs

This sheet shows the real and discounted incremental costs of using the waste material for each year over a 20-year planning horizon (Figure 3). Costs that are negative represent savings. No data inputs are required for this sheet.

Sheet 3: Take to Site (Landfill)

This sheet is used for entering data inputs to determine the avoidable costs for taking a candidate waste material from its source to a disposal facility, such as a landfill. Avoidable costs are calculated including (*a*) tipping, covering, or other such fee; (*b*) transportation costs; and (*c*) capital, maintenance, and operating costs not included (i.e., capitalized) in the tipping, covering, or other such fee. For capital, maintenance, and operating costs the sheet calculates the difference in costs for when waste is used in roads versus when waste is not used in roads.

Required data inputs include the following:

• Tipping or covering fee;
• Transportation costs;
• Capital, maintenance, and operating costs of the landfill per unit of capacity; and
• Additional capacity requirements.

For the key input of additional capacity requirements, the spreadsheet signals if the cumulative quantity of waste disposed of exceeds the remaining capacity for a particular year.

Sheet 4: Take from Site (Mine)

In some cases the source of a candidate waste material is the disposal site. For example taconite tailings proposed for use in highways would otherwise be disposed of at the source of the material—the settling basin of a taconite mine. Typically in such cases there is no tipping fee and also minimal or no transport costs. The main issue is the avoidable cost of capacity expansion. Using the waste material in highways delays the time for when expansion of the disposal facility is required, which results in avoidable costs (Figures 4*a* and 4*b*).

If the spreadsheet signals that the cumulative quantity of waste to be disposed of in a particular year exceeds the remaining capacity, the primary data input for this sheet is additional capacity required. The sheet also requires input data for capital, maintenance, and operating costs per unit of capacity.

Sheet 5: Net Benefits

This sheet adds the incremental costs of using the candidate waste in highways to the avoidable cost of not placing the waste in the disposal facility (Figure 5). Costs are calculated in real and discounted dollars for every year over a 20-year period. If the discounted costs of the sum of the incremental highway costs and the avoidable waste disposal costs are positive in the short and long term, then there are net public benefits over the short and long term.

Case Studies and Sample Spreadsheet Calculations

Three case studies were conducted during the course of this project to test the decision framework and spreadsheet and to refine them in an iterative manner. Each case study was realistic, based primarily on actual disposal facilities, but they included some hypothetical elements and inputs to simplify data collection. The three case studies were as follows:

• Case Study 1: Reuse of Taconite Tailings
• Case Study 2: Reuse of Mixed Broken Glass as Aggregate in Granular Base of Roads
• Case Study 3: Reuse of Roofing Shingle Tabs in Bituminous Pavement Mix

To illustrate the spreadsheet and its calculations, the remainder of this study describes in further detail Case Study 1.

Case Study 1: Taconite Tailing Reuse in West Iron Range, Minnesota

Problem Statement

Water quality in the Lake Superior watershed must be protected and preserved as directed by state and federal regulation as well as international agreements. The protection level assigned to the area is generally higher than for most other surface waters in Minnesota.

Acquiring aggregate along Lake Superior north of Duluth is becoming more difficult: the resource appears to be in adequate supply, but increasing complications are encountered when acquiring permissions to open new aggregate pits. The lack of aggregate sources appears most severe in Cook County (approximately 70 mi northeast of Duluth). However, from an engineering standpoint,

TOTAL COSTS OF USING WASTE											
*****IN PAVEMENTS*****	Freeways		Principal Arterials		Minor Arterials		Collectors		Local		YEAR TOTAL
YEAR	REAL	DISCOUNTED	REAL	DISCOUNTED	REAL	DISCOUNTED	REAL	DISCOUNTED	REAL	DISCOUNTED	REAL
0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
1	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
4	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
5	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
6	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
7	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
8	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
9	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
10	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
11	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
12	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
13	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
14	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
15	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
16	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
17	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
18	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
19	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
20 YEAR TOTALS	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
*****IN BASE*****	Freeways		Principal Arterials		Minor Arterials		Collectors		Local		YEAR TOTAL
YEAR	REAL	DISCOUNTED	REAL	DISCOUNTED	REAL	DISCOUNTED	REAL	DISCOUNTED	REAL	DISCOUNTED	REAL
0	$0	$0	$512,963	$512,963	$512,963	$512,963	$256,481	$256,481	$0	$0	$1,282,406
1	$0	$0	$512,963	$479,404	$512,963	$479,404	$256,481	$239,702	$0	$0	$1,282,406
2	$0	$0	$512,963	$448,041	$512,963	$448,041	$256,481	$224,021	$0	$0	$1,282,406
3	$0	$0	$512,963	$418,730	$512,963	$418,730	$256,481	$209,365	$0	$0	$1,282,406
4	$0	$0	$512,963	$391,337	$512,963	$391,337	$256,481	$195,668	$0	$0	$1,282,406
5	$0	$0	$512,963	$365,735	$512,963	$365,735	$256,481	$182,868	$0	$0	$1,282,406
6	$0	$0	$512,963	$341,809	$512,963	$341,809	$256,481	$170,904	$0	$0	$1,282,406
7	$0	$0	$512,963	$319,447	$512,963	$319,447	$256,481	$159,724	$0	$0	$1,282,406
8	$0	$0	$512,963	$298,549	$512,963	$298,549	$256,481	$149,274	$0	$0	$1,282,406
9	$0	$0	$512,963	$279,018	$512,963	$279,018	$256,481	$139,509	$0	$0	$1,282,406
10	$0	$0	$512,963	$260,764	$512,963	$260,764	$256,481	$130,382	$0	$0	$1,282,406
11	$0	$0	$512,963	$243,705	$512,963	$243,705	$256,481	$121,852	$0	$0	$1,282,406
12	$0	$0	$512,963	$227,762	$512,963	$227,762	$256,481	$113,881	$0	$0	$1,282,406
13	$0	$0	$512,963	$212,861	$512,963	$212,861	$256,481	$106,431	$0	$0	$1,282,406
14	$0	$0	$512,963	$198,936	$512,963	$198,936	$256,481	$99,468	$0	$0	$1,282,406
15	$0	$0	$512,963	$185,921	$512,963	$185,921	$256,481	$92,961	$0	$0	$1,282,406
16	$0	$0	$512,963	$173,758	$512,963	$173,758	$256,481	$86,879	$0	$0	$1,282,406
17	$0	$0	$512,963	$162,391	$512,963	$162,391	$256,481	$81,195	$0	$0	$1,282,406
18	$0	$0	$512,963	$151,767	$512,963	$151,767	$256,481	$75,884	$0	$0	$1,282,406
19	$0	$0	$512,963	$141,838	$512,963	$141,838	$256,481	$70,919	$0	$0	$1,282,406
20 YEAR TOTALS	$0	$0	$10,259,251	$5,814,736	$10,259,251	$5,814,736	$5,129,626	$2,907,368	$0	$0	$25,648,128

FIGURE 3 Real and discounted incremental highway costs over 20 years.

Year	Annual Qty Waste Disposed at Facility Less Qty Used in Hwys	Cumulative Amount Disposed	Begin Period Cumulative Capacity	Capacity Test: CUM.DISP>CUM.CAP?	CAPACITY ADDED	End Period Cumulative Capacity	Facility Costs with Reuse of Waste Materials in Highways			
							Capital Cost	Maint. Cost	Operating Cost	Total Cost
0	99873280	99873280	500000000	Capacity OK		500000000	$0	$1,000,000	$1,000,000	$2,000,000
1	99873280	199746560	500000000	Capacity OK		500000000	$0	$1,000,000	$1,000,000	$2,000,000
2	99873280	299619840	500000000	Capacity OK		500000000	$0	$1,000,000	$1,000,000	$2,000,000
3	99873280	399493120	500000000	Capacity OK		500000000	$0	$1,000,000	$1,000,000	$2,000,000
4	99873280	49936640	500000000	Capacity OK		500000000	$0	$1,000,000	$1,000,000	$2,000,000
5	99873280	0599239680	500000000	ADD CAPACITY	200000000	700000000	$8,000,000	$1,000,000	$1,000,000	$10,000,000
6	99873280	699112960	700000000	Capacity OK		700000000	$0	$1,400,000	$1,400,000	$2,800,000
7	99873280	798986240	700000000	ADD CAPACITY	1000000000	1700000000	$40,000,000	$1,400,000	$1,400,000	$42,800,000
8	99873280	898859520	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
9	99873280	998732800	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
10	99873280	1098606080	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
11	99873280	1198479360	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
12	99873280	1298352640	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
13	99873280	1398225920	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
14	99873280	1498099200	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
15	99873280	1597972480	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
16	99873280	1697845760	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
17	99873280	1797719040	1700000000	ADD CAPACITY	400000000	2100000000	$16,000,000	$3,400,000	$3,400,000	$22,800,000
18	99873280	1897592320	2100000000	Capacity OK		2100000000	$0	$4,200,000	$4,200,000	$8,400,000
19	99873280	1997465600	2100000000	Capacity OK		2100000000	$0	$4,200,000	$4,200,000	$8,400,000
TOTALS							$64,000,000	$51,200,000	$51,200,000	$166,400,000

(a)

FIGURE 4 Waste material in highways: (*a*) avoidable costs with disposal. (*continued on next page*)

Year	Annual Quantity of Waste Processed At Disposal Facility	Cumulative Amount Disposed	Begin Period Cumulative Capacity	Capacity Test: CUM.DISP>CUM.CAP?	CAPACITY ADDED	End Period Cumulative Capacity	Facility Costs Without Reuse of Waste			
							Capital Cost	Maint. Cost	Operating Cost	Total Cost
0	100000000	100000000	500000000	Capacity OK		500000000	$0	$1,000,000	$1,000,000	$2,000,000
1	100000000	200000000	500000000	Capacity OK		500000000	$0	$1,000,000	$1,000,000	$2,000,000
2	100000000	300000000	500000000	Capacity OK		500000000	$0	$1,000,000	$1,000,000	$2,000,000
3	100000000	400000000	500000000	Capacity OK		500000000	$0	$1,000,000	$1,000,000	$2,000,000
4	100000000	500000000	500000000	Capacity OK		500000000	$0	$1,000,000	$1,000,000	$2,000,000
5	100000000	600000000	500000000	ADD CAPACITY	200000000	700000000	$8,000,000	$1,000,000	$1,000,000	$10,000,000
6	100000000	700000000	700000000	Capacity OK		700000000	$0	$1,400,000	$1,400,000	$2,800,000
7	100000000	800000000	700000000	ADD CAPACITY	1000000000	1700000000	$40,000,000	$1,400,000	$1,400,000	$42,800,000
8	100000000	900000000	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
9	100000000	1000000000	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
10	100000000	1100000000	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
11	100000000	1200000000	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
12	100000000	1300000000	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
13	100000000	1400000000	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
14	100000000	1500000000	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
15	100000000	1600000000	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
16	100000000	1700000000	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
17	100000000	1800000000	1700000000	ADD CAPACITY	400000000	2100000000	$16,000,000	$3,400,000	$3,400,000	$22,800,000
18	100000000	1900000000	2100000000	Capacity OK		2100000000	$0	$4,200,000	$4,200,000	$8,400,000
19	100000000	2000000000	2100000000	Capacity OK		2100000000	$0	$4,200,000	$4,200,000	$8,400,000
TOTALS							$64,000,000	$51,200,000	$51,200,000	$166,400,000

(b)

FIGURE 4 (*continued*) Waste material in highways: (*b*) mining site costs without disposal.

Year	Discounted Costs without Reuse of Waste	Discounted Costs with Reuse of Waste	Discounted Avoided Costs
0	$2,000,000	$2,000,000	$0
1	$1,869,159	$1,869,159	$0
2	$1,746,877	$1,746,877	$0
3	$1,632,596	$1,632,596	$0
4	$1,525,790	$1,525,790	$0
5	$7,129,862	$7,129,862	$0
6	$1,865,758	$1,865,758	$0
7	$26,653,689	$26,653,689	$0
8	$3,957,662	$3,957,662	$0
9	$3,698,749	$3,698,749	$0
10	$3,456,775	$3,456,775	$0
11	$3,230,631	$3,230,631	$0
12	$3,019,281	$3,019,281	$0
13	$2,821,758	$2,821,758	$0
14	$2,637,157	$2,637,157	$0
15	$2,464,633	$2,464,633	$0
16	$2,303,395	$2,303,395	$0
17	$7,217,896	$7,217,896	$0
18	$2,485,257	$2,485,257	$0
19	$2,322,670	$2,322,670	$0
TOTALS	$84,039,597	$84,039,597	$0

FIGURE 5 Discounted avoided mining site costs of reusing waste in highways.

taconite tailing, a waste of iron ore mining, appears to be an acceptable replacement aggregate.

Taconite, which is a very hard rock that contains magnetic iron, has been open pit mined in northeast Minnesota since the 1950s. The rock is normally covered with till overburden, which is removed and stockpiled, thereby exposing the taconite. The taconite is drilled and blasted to a manageable size and then transported by truck or rail to a crusher. Water is added to the crushed rock, and the iron is extracted with electromagnets.

The remainder of the water and waste rock material is pumped to a large settling vat called a thickener, whose purpose is to separate water from the tailing. Flocculent chemicals are added to speed the settling process. The decanted thickener water is reused in the process, and the thickened tailing is pumped as a slurry from the bottom of the thickener tank to a type of monofill called a tailing basin.

The majority of tailing basins are enclosed by earthen dikes divided into subsections. Excess water in the basin is recovered for reuse. Tailing basins, which are permitted by the Minnesota Department of Natural Resources and the Minnesota Pollution Control Agency, are also designed to allow seepage water to discharge. Generally as one subsection of the basin fills another is opened for disposal.

The finished product from the mines is taconite pellets. The pellets are transported from each mine by rail to ship docks on Lake Superior. The pellets are then transported by ship to steel mills in Ohio and Illinois.

Some taconite mines import limestone from Michigan to enhance the quality of their pellet. For these mines, limestone is hauled back from the dock to the mine by rail.

Two of the six taconite mines have railroads leading to dock facilities on the northern parts of Lake Superior, in the towns of Silver Bay and Taconite Harbor (Lake and Cook counties, respectively). Unfortunately the tailing from both mines contains asbestos-like particles that are suspected carcinogens, and the U.S. Supreme Court has ordered the tailing be disposed of underwater and covered.

The four other mines lie west of the lake around the cities of Virginia and Hibbing. They all have railroad lines leading to dock facilities on Lake Superior, in Duluth Harbor. Among these mines, the closest tailing source to Cook County is approximately 130 highway miles away.

Assumptions and Calculations

Following is a partial list of assumptions and calculations for Case Study 1:

- Tailing available (all mines western range).
- Course tailing = 30 million tons/year.
- Normal tailing = 100 million tons/year.
- Price (Inland Steel, free on board, mine site—Virginia, Minnesota) = $0.50/ton.

- Truck (country driving) = 0.10/yd^3 to 0.15/yd^3 per mile.
- Truck (city or congested driving) = 0.15/yd^3 to 0.40/yd^3 per mile.
- Option for rail and barge (rail to Duluth estimated at 61 mi, barge/ship from Duluth to Schroder approx. 70 mi).
- Pit run aggregate = \$1.00/yd^3 to \$1.25/yd^3.
- Processed aggregate = \$2.00/yd^3.
- Density of aggregate = 15.5 ft^3/ton.
- Density of normal taconite tailings = 16.6 ft^3/ton.
- Assumed incremental processing cost = \$0.00.
- Normal taconite tailings would be used in base of reconstructed roads.
- Waste material used in base would be placed under the pavement surface only.
- All roads in Cook County in which waste material would be used are 2-lane with 12-ft lanes.
- Planned average reconstruction would be 10 mi per year distributed as 40 percent principal arterials, 40 percent minor arterials, and 20 percent collectors.
- Anticipated annual feasible placement of taconite tailings (126,720 tons of waste) is a tiny fraction of annual production of taconite tailings (100,000,000 tons per year), and this amount would have no noticeable effect on the timing of new taconite settling basin capacity expenditures.
- Reasonable assumed size of taconite settling basin is 12 to 13 mi^2.
- Capacity of some mines will be defined by the perimeter of the entire settling basin, whereas the capacity of other mines will be based on the capacity of the cell.
- Alternative assumptions for the size and timing of capital expenditures for settling basin capacity expansion as a test of whether maximum annual quantity of waste to be used in highways has any effect on the avoidable capital, maintenance, and operating costs of using the taconite tailings as base material in highways. (Under numerous alternative assumptions involving capacity additions of 200 million to 2 billion tons, given the relatively tiny amount of total available taconite tailings to be used in highways, the avoidable cost was zero.)
- Remaining capacity of the mines = 500,000,000 tons of tailings, implying 5 years of remaining life.
- Capital cost per unit of capacity = \$0.04 per ton; maintenance cost = \$0.002 per ton; and operating cost = \$0.002 per ton.

Alternative scenarios for transport and capacity expansion of taconite settling basin:

- Scenario A—Ship waste by highway from Virginia, Minnesota. Assumed a new settling basin with 2 billion

	TAKE WASTES TO DISPOSAL SITE (e.g. Landfill)				TAKE WASTES FROM DISPOSAL SITE (e.g. Mine)			
	DISCOUNTED PRESENT VALUE				DISCOUNTED PRESENT VALUE			
Year	Incremental Highway Costs	Avoided Costs of Not Using Disposal Site	Difference	Cumulative Savings (costs) through Year	Incremental Highway Costs	Avoided Costs of Not Using Disposal Site	Difference (Avoided -Hwy Costs)	Cumulative Savings (costs) through Year
0	\$1,282,406				\$1,282,406	0	-\$1,282,406	-\$1,282,406
1	\$1,198,511				\$1,198,511	0	-\$1,198,511	-\$2,480,917
2	\$1,120,103				\$1,120,103	0	-\$1,120,103	-\$3,601,020
3	\$1,046,826				\$1,046,826	0	-\$1,046,826	\$4,647,846
4	\$978,342				\$978,342	0	-\$978,342	-\$5,626,188
5	\$914,338				\$914,338	0	-\$914,338	-\$6,540,526
6	\$854,522				\$854,522	0	-\$854,522	-\$7,395,047
7	\$798,618				\$798,618	0	-\$798,618	-\$8,193,666
8	\$746,372				\$746,372	0	-\$746,372	-\$8,940,038
9	\$697,544				\$697,544	0	-\$697,544	-\$9,637,582
10	\$651,910				\$651,910	0	-\$651,910	-\$10,289,492
11	\$609,262				\$609,262	0	-\$609,262	-\$10,898,754
12	\$569,404				\$569,404	0	-\$569,404	-\$11,468,158
13	\$532,153				\$532,153	0	-\$532,153	-\$12,000,311
14	\$497,339				\$497,339	0	-\$497,339	-\$12,497,651
15	\$464,803				\$464,803	0	-\$464,803	-\$12,962,454
16	\$434,395				\$434,395	0	-\$434,395	-\$13,396,849
17	\$405,977				\$405,977	0	-\$405,977	-\$13,802,826
18	\$379,418				\$379,418	0	-\$379,418	-\$14,182,244
19	\$354,596				\$354,596	0	-\$354,596	-\$14,536,840
TOTALS	\$14,536,840				\$14,536,840	0	-\$14,536,840	N.A.

FIGURE 6 Discounted net public benefits of reuse of waste.

TABLE 1 Results of Scenarios A and B

Scenario	Change in Highway Cost From Using Waste (Expressed in Discounted Present Dollars)	Avoidable Settling Basin Cost (Expressed in Discounted Present Dollars)	Avoidable Settling Basin Costs Less Change in Highway Cost	NET SHORT AND LONG TERM BENEFITS?
Scenario A. Transport wastes by highway and 2 billion ton expansion of settling basin upon exhaustion of remaining capacity	$12.9 million	$0	-$12.9 million	NO
Scenario B. Transport waste by rail/barge/highway and expansion of settling basin in 200 million, 1 billion, and 400 million ton increments	$14.5 million	$0	-$14.5 million	NO

tons of capacity, sufficient to dispose of 100 million tons for 20 years, would be constructed when remaining capacity was used up.

• Scenario B—Ship waste by rail 68 mi from Virginia, Minnesota, to Duluth, transfer to barge, transport 80 mi by water to Taconite Harbor in Cook County, transfer to truck and transport remaining distance by highway. Assumed transfer costs at \$0.10 tons/yd^3 and that additional settling basin capacity would be provided by settling basin cells with the following incremental capacities: 200,000,000 tons; 1,000,000,000 tons; and 400,000,000 tons.

Application of Decision Tree and Spreadsheet

The decision tree and spreadsheet were used to determine the yearly maximum feasible placement of taconite tailings in the base of highways in Cook County, Minnesota, and to assess whether net short- and long-term benefits existed for using the waste.

The decision tree's first page was used to determine whether the initial quantity proposed to be reused—100,000,000 tons of taconite tailings per year—was feasible given the maximum annual feasible placement of taconite tailings in the highway base by functional class. The answer was no. The proposed quantity of taconite tailings used annually was therefore reduced to 126,720 tons, a feasible level.

The remainder of the decision tree and spreadsheet were then applied under Scenarios A and B to determine whether the avoidable costs of using the taconite tailings exceeded the incremental change in the cost of using the taconite tailings in lieu of regular aggregate in the base. (Note that the example spreadsheets in Figures 2 to 6 refer to Scenario B only.) The results are presented in Table 1.

Conclusions

Reuse of waste materials in highway maintenance and construction projects is a critical area of public policy. Key issues include the effect of waste material on life-cycle costs, the ability to recycle parts of highways that contain waste materials, reduction of the waste stream produced by the economy at large, and the prevention of pollution. States need a framework and analytic tools for making decisions about whether net public benefits exist for using waste materials coming from sources outside a department. The experience of Mn/DOT in developing such a framework and corresponding decision support tool is testimony to the feasibility of quantitatively assessing the long- and short-term net economic benefits of using waste materials in highway maintenance and construction projects. Moreover, such a framework and decision support tool have an important role in practical decision making when states must decide whether or not to accept a waste material from an outside source.