Bridge Life Cycle Assessment
Problem Set 8

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1 Problem

Our company proposes replacing an old, single-lane, rural bridge in Switzerland with a new bridge superstructure. To determine what type of bridge to build, we will use a Life Cycle Analysis (LCA) to compare the environmental impact of a wooden bridge vs. a bridge made of reinforced concrete. Both bridges will span a gap of 8m, yielding a total bridge length of 9m.

Our approach is to determine the materials needed for each bridge type, and then create a process diagram to specify a technology matrix and environmental matrix for the LCA. Then we will solve for the environmental profile using matrix math. The results will reveal the differences in environmental impact due to the concrete and wooden bridges, which will allow us to recommend which type of bridge to build.

The mathematics that will allow us to conduct the LCA is based on matrix operations. Two matrix equations describe the technology (manufactured) and environmental (resource) systems:

$As = f$

$Bs = g$

In these systems, both A and B are matrices describing the relation of the resources and technology to each other, which can be created using data from outside companies. f is the matrix we create to describe how much of each final product we want. g is is the environmental profile vector that we want to solve for in order to ascertain the environmental impact of both bridge options. g will tell us how much of each natural resource we must use in each bridge option. In other words, we know A, B, and f, and we want to calculate g using the vector s as a way to connect the two equations.

First we solve for s:

$s = A^{-1}f$

And then we input s into the second equation to solve for g:

$g = BA^{-1}f$

By comparing g for the concrete and wooden bridges, we will be able to recommend which bridge to build.

2 Reinforced Concrete

Throughout this study, we use cross-sectional designs from a manual from the Transport Research Laboratory [1] to model our bridges. However, for the concrete bridge, we neglect the railings, curbs, paving, and surface crowning. The concrete bridge is reinforced with steel rebar. The bridge is 9m in length, and the supports are 8m apart.

We used data from the Transport Research Laboratory to calculate the mass of rebar and total volume of concrete for the bridge, which we entered into our economic flow matrix, f. The data tables listed six types of rebar, though we ignored "Type D," which is only used in railings. We were given the length of each type of rebar, and a table which listed the cross-sectional area of each type of rebar and how many pieces we would need in each section of the bridge. We used these data to calculate the total volume of steel rebar. Then, using the density of rebar (ρ_{rebar} = 7860 kg/m^3), we calculated the total mass of rebar required for the bridge, 527.3kg. Then we calculated the total volume of concrete required for the bridge by using the dimensions of the bridge to calculate the bridge volume, and subtracting off the volume of the rebar. The calculations were done in an Excel spreadsheet:

REINFORCED CONCRETE BRIDGE
*values in SI

BRIDGE DIMENSIONS	
length	9.000000
width	5.500000
height	0.500000
bridge volume = length*width*height	24.750000

REBAR	Type A	Type B	Type C	Type E	Type F
number of bars	12.000000	12.000000	25.000000	12.000000	12.000000
cross-sectional area	0.000125	0.000200	0.000100	0.000200	0.000200
length	5.500000	1.400000	8.750000	8.500000	5.500000
volume per bar = cross-sectional area*length	0.000688	0.000280	0.000875	0.001700	0.001100
total volume = number of bars*volume per bar	0.008250	0.003360	0.021875	0.020400	0.013200
rebar volume = sum of total volumes					0.067085
rebar mass = 7860*rebar volume					527.288100

CONCRETE	
concrete volume = bridge volume – rebar volume	24.682915

REQUIRED	
concrete	24.682915
rolled section bar	527.288100

After calculating the amounts of rebar and concrete needed, we could perform the matrix analysis. The given technology matrix, A, is:

$A_{concrete} =$

$$\begin{pmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-300 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1890 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -0.052 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -0.903 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -0.9 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -0.022 & -0.15 & 1 & -1.05 & -1.05 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -1.05 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -0.4 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-4.36 & -0.0292 & -0.0042 & -0.0014 & -0.0508 & -0.0219 & 0 & -0.0031 & -0.01 & -0.025 & -0.483 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1.16 & 0 & 0 & 0 & -0.0068 & -0.0375 & 0 & 0 & -0.0363 & -0.069 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
-39.1 & 0 & -0.0264 & -0.0277 & -0.0134 & 0 & 0 & -0.0552 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -0.0002 & -0.34 & 0 & -1.43 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
-10.4 & -0.0049 & 0 & 0 & -0.0049 & -0.0153 & -0.0035 & 0 & -0.002 & -0.004 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
-49.2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
-6.82 & 0 & 0 & 0 & 0 & -0.108 & -0.189 & 0 & -0.309 & -0.0241 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{pmatrix}$$

Our economic flow vector, f, is:

$$f_{concrete} = \begin{pmatrix}
24.6829 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 527.2881 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0
\end{pmatrix}$$

The environmental matrix we are given is:

$$\begin{pmatrix}
15.7 & 0.0105 & 0.015 & 0.01 & 3.62 & 0.117 & 0.49 & 0.0111 & 1.54 & 0.531 & 0 & 0 & 0 & 0 & 0 & 12.2 & 0.012 & 0.245 \\
16.9 & 0 & 0 & 0 & 0.0001 & 0.036 & 0.0207 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.0951 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.0143 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-186 & 0 & -2.12 & 0 & -1.96 & -2.7 & -6 & -0.0249 & -0.5 & -0.09 & 0 & 0 & 0 & 0 & 0 & 0 & -2.02 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.01 & 0.0002 & 0.0001 & 0 & 0.0017 & 0 & 0 & 0.0012 & 0.0004 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.0011 & 0 & 0.0001 & 0 & 0.0005 & 0.0003 & 0.0002 & 0.0025 & 0 & 0.0002 & 0.0002 & 0.0081 & 0.0001 & 0.0001 \\
0 & 0 & 0 & 0 & 0.0005 & 0.0047 & 0.0013 & 0 & 0.0257 & 0.0002 & 0 & 0.0001 & 0 & 0 & 0.0001 & 0.002 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.855 & 0.0756 & 0.0004 & 0 & 0.204 & 0.0237 & 0.14 & 0.979 & 0.0503 & 0.0705 & 0.0894 & 0.838 & 0.0086 & 0.0071 \\
0 & 0 & 0 & 0 & 0.0004 & 0 & 0.0001 & 0 & 0.0013 & 0.0001 & 0.0003 & 0.004 & 0 & 0.0005 & 0.0011 & 0.0002 & 0.0017 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.0001 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.0001 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.0139 & -0.0555 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.0639 & 0 & -0.269 & 0 & -0.0023 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.613 & 0 & 0 & -0.0909 & 0 & -0.0002 & 0
\end{pmatrix}$$

As shown before, we can use these matrices to calculate the scale vector, s:

$$s_{concrete} = \begin{pmatrix} 24.6829 \\ 7404.8745 \\ 46650.7094 \\ 385.0535 \\ 6686.6017 \\ 527.2881 \\ 474.5593 \\ 805.3008 \\ 498.2873 \\ 189.8237 \\ 527.2881 \\ 1137.4906 \\ 125.1269 \\ 2341.3997 \\ 874.0328 \\ 336.7974 \\ 1214.3994 \\ 473.5218 \end{pmatrix}$$

And finally, we can calculate the environmental profile vector, g:

$$g_{concrete} = \begin{pmatrix} 30785.22 \\ 446.4819 \\ 2.847 \\ 0.353 \\ -123606.6655 \\ 11.7457 \\ 14.1077 \\ 20.0933 \\ 7596.2057 \\ 12.0858 \\ 0.0873 \\ 0.041 \\ -22.7557 \\ -241.2841 \\ -777.0106 \end{pmatrix}$$

The rows in this vector correspond to the following environmental variables (all units are kilograms) [2]:

Environmental variables - concrete and wooden bridges:

Waste heat
Waste to inert landfill
Waste to municipal incinerator
Concrete production effluent
Water
Dust to air
Nitrogen oxides
Carbon monoxide
Carbon dioxide
Sulfur dioxide
Hydrocarbons
Methane
Natural gas
Fuel oil
Hard coal

These results are designed to be compared to the results for the timber bridge. However, we can observe some implications of the results immediately. The concrete bridge produces a lot of waste heat, carbon dioxide, and waste to an inert landfill. All these waste products, though undesirable, are fairly inert. Some of the less desirable wastes, such as carbon monoxide, and methane, are output in much lower quantities. This process also consumes a large amount of water, and a fair amount of hard coal and fuel.

On their own, these numbers are interesting but cannot help us make a decision. In order to choose between bridge types, we must repeat our calculations for a timber bridge and compare our results.

3 Timber

Once again, we used the model from the Transport Research Laboratory to design the timber beam bridge [1], though we ignored the railing and extended deck members. Like the concrete bridge, the timber bridge is 9m long, spanning a distance of 8m between supports. The spanning beams are made of glu-lam wood (glued laminated timber). The deck and running boards are made of sawn timber.

The cross-sectional area and number of required beams were given in the design data tables for a variety of bridge lengths. We used the data for an 8m bridge, since 8m is the distance between supports, to calculate the total volumes of glu-lam and sawn wood. The calculations were again done in an Excel spreadsheet, shown below.

TIMBER BRIDGE
*values in SI

TIMBER	Glu-lam	Traverse deck planks	Running Boards
Length	9.000000	3.950000	9.000000
cross-sectional area	0.100000	0.030000	0.060000
number of units	5.000000	30.000000	2.000000
volume = length*cross-sectional area*number of units	4.500000	3.555000	1.080000

REQUIRED	
Glued laminated timber, for outdoor use	4.500000
Sawn timber, planed, air/kiln dried (u = 10%) = sum of volumes of planks and boards	4.635000

Using the timber bridge design, we calculated the amount of each wood product we would need, which we put in the economic flow vector, f. Our economic matrix is:

$A_{timber} =$

$$\begin{pmatrix}
1 & -1.59 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & -1.14 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & -1 & 0 & -1.37 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & -1.15 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -12 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -33.8 & 0 & -11 & -31.1 & -129 & -0.1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -432 & 0 & -266 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
-89.02 & 0 & 0 & 0 & 0 & -56.6 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & -70.3 & 0 & 0 & 0 & -38.2 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & -81.2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{pmatrix}$$

Our economic flow vector is:

$$f_{timber} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 4.635 \\ 4.5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Our environmental matrix is:

$B_{timber} =$

$$\begin{pmatrix}
0 & 122 & 0 & 39.6 & 112 & 46.3 & 0 & 0 & 0 & 0 & 0 & 12.2 & 0.012 & 0.245 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -2.02 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.0017 & 0 & 0 & 0.0012 & 0.0004 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.0004 & 0.0025 & 0 & 0.0002 & 0.0002 & 0.0081 & 0.0001 & 0.0001 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.0002 & 0.0001 & 0 & 0 & 0.0001 & 0.002 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.108 & 0.979 & 0.0503 & 0.0705 & 0.0894 & 0.838 & 0.0086 & 0.0071 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.004 & 0 & 0.0005 & 0.0011 & 0.0002 & 0.0017 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.012 & 0.0002 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.0003 & 0 & 0 & 0 & 0 & 0.0001 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.0139 & -0.0555 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.0639 & 0 & -0.269 & 0 & -0.0023 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.613 & 0 & 0 & -0.0909 & 0 & -0.0002 & 0
\end{pmatrix}$$

The calculated scale vector is:

$$s_{timber} = \begin{pmatrix} 20.8363 \\ 13.1046 \\ 11.4953 \\ 5.3303 \\ 4.635 \\ 4.5 \\ 54 \\ 1231.6162 \\ 3499.668 \\ 2109.5465 \\ 0 \\ 1093.1523 \\ 0 \\ 365.4 \end{pmatrix}$$

And finally, the environmental profile vector for the timber bridge is:

$$g_{timber} = \begin{pmatrix} 15963.2886 \\ 0 \\ 0 \\ 0 \\ 0 \\ 2.7128 \\ 12.5381 \\ 2.4324 \\ 2455.0039 \\ 6.1448 \\ 0.0834 \\ 0.1022 \\ -211.351 \\ -429.6838 \\ -754.9807 \end{pmatrix}$$

Again, the entries in the environmental profile vector correspond to the following environmental variables (all units are kg) [2]:

Environmental variables - concrete and wooden bridges:

Waste heat
Waste to inert landfill
Waste to municipal incinerator
Concrete production effluent
Water
Dust to air
Nitrogen oxides
Carbon monoxide
Carbon dioxide
Sulfur dioxide
Hydrocarbons
Methane
Natural gas
Fuel oil
Hard coal

These results are meant for comparison with the results for the concrete bridge. However, we can notice some things from this vector on its own. Notably, this bridge does not require any water to produce, nor does it produce any waste to inert landfill or to municipal incinerator. However, the bridge creates a lot of waste heat and carbon dioxide. Furthermore, a considerable amount of hard coal, fuel oil, and natural gas are required to create the bridge.

To complete our LCA, we must compare this environmental profile to that of the concrete bridge.

4 Comparisons

One of the major considerations we must take into account is the lifetime of each bridge. The concrete bridge lasts approximately twice as long as the timber bridge. Thus, in order to compare the two bridges, we will multiply the numbers in the environmental profile vector for timber by two. This results in the following environmental profiles for the bridges:

$$g_{concrete} = \begin{pmatrix} 30785.22 \\ 446.4819 \\ 2.847 \\ 0.353 \\ -123606.6655 \\ 11.7457 \\ 14.1077 \\ 20.0933 \\ 7596.2057 \\ 12.0858 \\ 0.0873 \\ 0.041 \\ -22.7557 \\ -241.2841 \\ -777.0106 \end{pmatrix} \qquad 2(g_{timber}) = \begin{pmatrix} 31926.5772 \\ 0 \\ 0 \\ 0 \\ 0 \\ 5.4256 \\ 25.0762 \\ 4.8648 \\ 4910.0078 \\ 12.2896 \\ 0.1668 \\ 0.2044 \\ -422.702 \\ -859.3676 \\ -1509.9614 \end{pmatrix}$$

For convenience, the environmental variables (in kg) that correspond to the rows in the environmental profiles are included again below [2]:

Environmental variables - concrete and wooden bridges:

Waste heat
Waste to inert landfill
Waste to municipal incinerator
Concrete production effluent
Water
Dust to air
Nitrogen oxides
Carbon monoxide
Carbon dioxide
Sulfur dioxide
Hydrocarbons
Methane
Natural gas
Fuel oil
Hard coal

Comparing the environmental profiles, we notice that the waste heat for the two bridges is very similar, as is the production of sulfur dioxide. However, the concrete bridge is much more wasteful in terms of waste to inert landfill and to municipal incinerator, concrete production effluent, and used water. The concrete bridge also creates much more carbon dioxide than the wooden bridge. Furthermore, the concrete bridge produces more dust and carbon monoxide than the timber bridge.

Production of the timber bridge, however, uses significantly more natural gas, fuel oil, and hard coil than production of the concrete bridge. The timber bridge also produces more nitrogen oxides, hydrocarbons, and methane.

Which of these environmental profiles is more advantageous depends on what resources are available as well as the effects of the low-mass products (dust, methane, hydrocarbons, etc.) of the bridge construction. Comparing the low-mass emissions from the two bridges, the concrete bridge produces more of four types of low-mass waste (waste to municipal incinerator, concrete production effluent, dust, and carbon monoxide). The timber bridge produces more of 3 types of low-mass waste (nitrogen oxides, hydrocarbons, and methane). By the numbers, these results sound similar. However, the low-mass wastes created by timber bridge production are more toxic (methane and hydocarbons are greenhouse gases) than those created by cement bridge production. So, based on low-mass emissions alone, the concrete bridge would be a better choice.

The other factors to consider are large-mass waste and consumption variables. The values of waste heat and sulfur dioxide emissions for each bridge are comparable, so we only need to consider waste to inert landfill, water consumption, carbon dioxide waste, and consumption of natural gas, fuel oil, and hard coal. In terms of these resources and wastes, the main advantage of the concrete bridge is that it uses less natural gas, fuel oil, and hard oil, while the made advantage of the timber bridge is that it uses no water and produces no inert landfill waste.

In terms of natural resources, mining and forest clear cutting are both harmful for the environment. Water in Switzerland is likely not too scarce, given the amount of glacier runoff from the Alps. The availability of these resources therefore slightly favors the concrete bridge. However, all of these factors must be taken into account for the final decision.

5 Conclusion

In conclusion, our company recommends construction of a cement bridge. Cement bridges produce lower levels of hazardous emissions such as hydrocarbons, nitrogen oxides, and methane. Furthermore, cement bridges use significantly less natural gas, fuel oil, and hard coil than timber bridges. Given the increasingly high price of energy, it is important to minimize the amount of energy resources used. While timber bridges produce less carbon dioxide and require no water for construction, we believe the increased amount of natural gas, fuel oil, and hard coal, as well as the toxic emissions associated with the production of the timber bridge, are large enough concerns that the cement bridge remains the best option. The water required for cement production should not be difficult to acquire in Switzerland, where glacier melt from the Alps is plentiful. In addition, the lifetime of cement bridges is twice that of timber bridges, requiring less labor overall to maintain the bridge.

References

[1] Transport Research Laboratory (2000). Overseas Road Note 9: A design manual for small bridges. Department for International Development, London, UK.

[2] Class handout, "Problem Set 8 – Life Cycle Assessment," April 29, 2009.