CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

A Methodology for Environmentally Informed Decision-Making: Towards Sustainable Projects

By

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CIFE Working Paper #WP 083
September 2003

STANFORD UNIVERSITY

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Abstract

Recent years have brought increased concern for sustainable development. However, despite efforts by policy, scientific, and engineering communities, sustainability remains largely undefined and unachievable. The need for a precise definition of sustainability and a systematic method of making decisions respecting it is apparent. Thus, the primary objective of this paper is demonstrating how, once sustainability is defined, current CIFE VDC tools can be used to help decision makers approach it and its consequences for their research/project/policy choices.

To facilitate this demonstration, we examine a test case: the maintenance of a system of underground tunnels owned by the Nippon Telephone and Telegraph Corporation (NTT). We use a sustainability-based analysis of NTT's options to develop a methodology that can be generalized for decisions in any engineering project. In essence, analyzing the NTT case serves to demonstrate the value of applying VDC tools to sustainability-motivated decisions.

Keywords: Construction, Cost Estimation, Decision-Making, Organization Models, Planning, Process Models, Project Management, Sustainability, Virtual Design and Construction

Introduction

As awareness of environmental issues grows, decision-makers in large projects will encounter increased pressure from outside and inside their organizations to consider environmental impacts and sustainability. New policies and public appeals, together with internal concerns with resource use and corporate citizenship, have already precipitated a number of tools (TEI and LCA, e.g.) to inform project stakeholders of the economic and environmental impacts of their decisions. While these tools do facilitate decision-making with respect to economic, environmental, and social concerns, however, they do so independent of each other. Project stakeholders need a tool that facilitates decision-making by giving them a unified analysis of their decision's environmental and economic impacts. Our work here is an early attempt to answer that need.

Objectives

This paper presents and defines a systematic methodology, the Ung-Berring Method, if you will. It enables project managers to make decisions that take into account economic and environmental considerations as well as the interactions between the two. Using CIFE tools to model decision impact values and costs, our methodology focuses on the comparison of net environmental and net economic values to determine the overall “benefit” of product decisions relative to different stakeholder perspectives.

Points of Departure

Sustainability

Sustainability is notable first for the myriad and wildly different attempts to define it. It originated as a term to describe harvesting of specific natural resources that could be maintained over time (sustainable fishing, for example) (Toman 1992). Since then, however, ecologists, politicians, economists, and engineers have given the word added connotations. Sustainability has been applied with varying success in the economic, environmental, and social realms.

John R. Hicks, 1972 Nobel Prize winner of Economic Sciences, defines economic sustainability as “the amount one can consume during a period and still be as well off at the end of the period.” The general idea of economic sustainability is the maintenance of manmade capital by consuming only the interest on the capital and not the capital itself (Goodland et al 1995).

Environmental sustainability emerged fairly recently as the public became aware of the finitude of natural resources. Robert Paehlke, a professor of the Environmental and Resource Studies Program at Trent University, says environmental sustainability is composed of three elements: “(1) ecology, habitat, biodiversity, and wilderness; (2) air and water quality (pollution); and (3) the conservation, preservation, and management of non-renewable resources [resource sustainability]” (Paehlke 1999). Environmental sustainability is the maintenance of capital in these three areas for human welfare, mainly through the management of sources (harvesting, e.g.) and sinks (emissions, e.g.) (Goodland et al 1995, Paehlke 1999).

Social sustainability concerns itself with the use of resources to preserve and promote socio-cultural equity. It dictates that social well-being, including "community, love, tolerance, compassion, humility, patience, forbearance, [etc.]", be maintained or increased (Goodland 1995).

While these compartmentalized notions of sustainability have merit, current literature tends to combine at least the first two in more useful concepts of weak and strong sustainability (Neumayer 1999). Weak sustainability (WS) is also known as nondeclining capital. Robert Solow, 1987 Nobel Prize winner of Economic Sciences, says WS requires that harvested natural resources be substituted with man-made resources of equivalent value to preserve the total value of the two: "Earlier generations are entitled to draw down the pool so long as they add to the stock of reproducible capital." Essentially, WS makes no distinction between natural and environmental capital (Goodland 1995).

On the other hand, Strong Sustainability (SS) requires that man-made and natural capital be maintained separately, dismissing the substitutability of resources between the two: "[It] is the paradigm that calls for keeping both the aggregate total value of man-made capital and natural capital and the total value of natural capital itself at least constant" (Neumayer 1999). This concept places more focus on environmental sustainability and places more restrictions on economic sustainability. The related notion of Absurdly Strong Sustainability holds that each natural resource is unique and non-replaceable/non-substitutable even with other natural resources and thus requires the disuse of all natural capital, except for net natural growth (Goodland 1995).

These definitions are variations of the one originally presented in the Brundtland Commission's report "Our Common Future", namely: intergenerational fairness. From an engineering perspective, this notion boils down to a concern for the environmental and social externalities of a given project.

SimVision

SimVision is a software package originally developed at Stanford by CIFE's Virtual Design Team research group (Jin and Levitt 1996) and more recently commercialized by the Vité Corporation. The software enables the symbolic modeling of organizations and complex tasks, and allows the user to put models through tests via simulation. Repeatedly over the last few years, faculty and corporate researchers have demonstrated the validity of SimVision's predictions for work and information flow.

These results are possible because incorporated into SimVision is a symbolic framework that defines organizations and tasks through individual objects associated with connections and dependencies. SimVision outputs not only the expected "direct work" measured by the simple task hierarchy, but also the "hidden work" caused by coordination, rework, and decision-wait, which is a result of the more subtle organizational dependencies.

Total Economic Impact (TEI)

Total Economic Impact analysis is an evaluative tool created by Giga Consulting® to predict the ROIs of potential IT investments. Researchers at CIFE have shown its wider applicability by using it in construction project management as part of their VDC toolkit (Kunz, TEI). We use it here as a central element of our decision-making methodology.

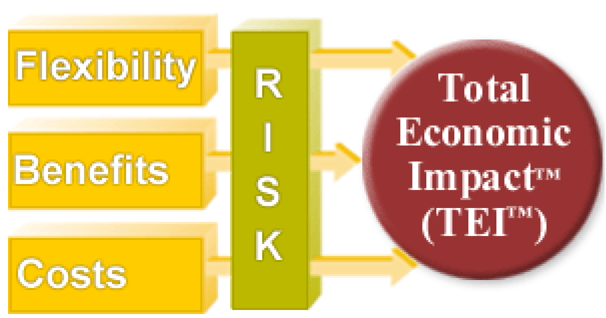

Figure 1: TEI flowchart visualizing the fundamental TEI Process (Giga Information Group)

When used to evaluate investments, TEI quantifies cost and value, requires that they be equal, and finds the specific financial goals necessary to achieve this. In its simplest form (the form we use in this paper), TEI takes the difference of the pro forma capitalized cost and value to find the net benefit of a project proposal.

Expressing Environmental Impacts in Dollar Amounts

Along the lines of Strong Sustainability, we find it useful to assume that the natural environment is a single store of capital—in other words that one form of natural capital is substitutable for another. As a direct consequence of this line of reasoning, we believe it is necessary and appropriate to quantify environmental value. Any number of units would be appropriate to measure this quantity; however, in order to take into consideration environmental effects and economic effects in project decision-making, a standardized metric is necessary. Since we use TEI as the central evaluative tool, it is convenient to quantify natural capital in units of manmade capital (in this instance, the U.S. dollar).

Quantifying environmental value and expressing it in dollars is a task that requires a full body of literature to do it justice. Resource values, extraction costs, associated biodiversity and ecological damages, and risk are only a few of the factors that make this calculation extremely complex. Currently, many assessment methods such as LCA (Life Cycle Assessment) and EIA (Environmental Impact Assessment) analyze the impact of products on the environment, but they fail to measure their results in a way that makes them useful for quantitative cost-benefit analysis. Later in this paper, we will use the idea of an exchange rate between man-made and natural capital (introduced by the artificial devaluation of natural capital by society) in our decision-making protocols. However, for the rough calculations in this paper, a simpler approximation presents itself: the depreciation of natural capital in any given action is about equal to the cost (in dollars) of undoing its damage, and if resources are involved, the value it extracted.

Tools and Methods

Modeling

To accurately use TEI analysis, we need to provide it with accurate cost and value estimations. CIFE VDC tools are ideal for modeling and predicting the financial consequences of potential projects. POP (Product Organization Process) models tie together CAD and SimVision models to effectively inform decision-makers about potential risks, construction conflicts, building progress, and financial consequences through visual simulation and graph formulation.

The simplest form of a POP model is a level-1 model. It contains the basic POP elements—a 3D-CAD drawing and SimVision organization and process charts—but using only the dozen or so most significant elements of the project. Of course, beyond level 1 the models can be made arbitrarily complex. For the cost/value estimation in this paper, we made POP models of slightly higher resolution, with an average of around 20 major elements each. This level of detail, while sufficient for our purposes, reflects more the limits of our information than a methodological choice. In practice, more detail is always preferable.

TEEI (Total Economic and Environmental Impact)

TEEI builds upon the existing TEI tool. While TEI was originally intended to make solely monetary calculations, we found the system to be much more versatile. Since we were already converting natural resources and environmental impacts into dollar amounts, we found ourselves able to carry out TEI with environmental figures. TEEI is simply the original TEI coupled with TEI for environmental figures.

Decision-Making Protocols

Even after amassing a data-set on a problem, if the data and problem are complicated, deciding how to use it is highly non-trivial. To aid in this area, we organized our data visually and developed decision-making protocols. These protocols are formulas or simple algorithms for picking the best option for a given situation with given available data.

The visual organization is simple - we organized a spreadsheet as seen in figure 2 with options on the y-axis and parameters (measured data-points) on the x-axis.

	Param W	Param X	Param Y	Param Z
Option 1				
Option 2				
Option 3				
Option 4				
Option 5				

Figure 2: Data Visualization Spreadsheet providing a starting point for applying decision protocols.

The formulas were then easy to express. We found it sensible to have one formula for each possible decision-maker perspective to reflect their different motivations. For example, one stakeholder may be interested in only parameter X, so the protocol would simply be: find the option that maximizes (X), while another stakeholder may weight X and Y equally, and require that Z reach a minimum level, so that protocol would be: find the option that satisfies (Z>Minimum Value) and maximizes (X+Y). The data from these protocols also fits easily on the same spreadsheet, which makes the whole process extremely scalable.

Our Methodology

Now that we have cited existing research and defined necessary tools, we will present a detailed outline of our entire decision-making methodology.

In any difficult situation, the first step must be identifying and clarifying the problem. Only when a clear dilemma exists can any analysis be carried out. Next, while the bulk of our methodology lies in comparing different options, we cannot overemphasize the necessity of identifying all available options. This is unavoidably a mostly-intuitive bit of predictive work, but it must be done with utmost care if the following analysis is to have any validity.

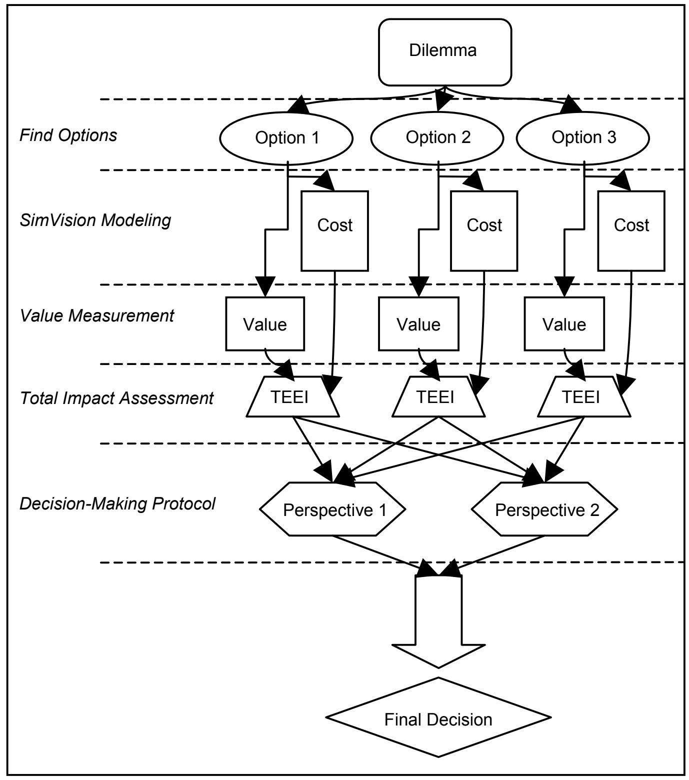

Figure 3: Flowchart of our methodology: Process by which one arrives at a decision from a given dilemma

Next, each option must be scrutinized. Depending on the complexity of a problem and the detail of the analysis, each option may have one to hundreds of costs that need to be modeled and one to hundreds of different elements that need value measurements. Using SimVision we model and sum all economic and environmental costs in each option. At this point, our models also give us the opportunity to familiarize ourselves with each option, seeing how long the project would take and how difficult the process would be to carry out. Using referenced literature and current empirical data, we can find/estimate/project the environmental and economic values of every element in our project options.

These costs and values can then be organized to make up a spreadsheet. We then use TEEI to determine the projected net environmental, economic, and combined benefits of each option, adding our results to the spreadsheet. With this done, we have all the data and visualization necessary for a decision and need only make it.

In the decision-making protocol, it is necessary for the analyst to decide what his/her motivations are. Presumably, a user of this methodology is at least marginally concerned with environmental impacts, so a formula for combining financial and environmental value is required. In our test case analysis, we make some suggestions for doing this. Multiple protocols can be used either to evaluate the views of multiple stakeholders or to help an individual clarify his/her objectives.

Once a decision-making protocol is established, it need only be applied to the values spreadsheet, and the output will be the most desirable option.

NTT – The Test Case

An analysis of a specific test case will better illustrate the use and usefulness of the Ung-Berring methodology. As an organization with large and ongoing AEC expenses, and one requiring a difficult decision regarding its massive infrastructure, the Nippon Telegraph and Telephone Corporation (NTT) is ideal.

Who they are

Established in 1952, NTT is now the world's largest telecommunications company and arguably the most successful, with the highest recurring profit—$12 billion this year. Its current emphasis is adapting to and competing for the increasing demand for broadband service through developing fixed-line and wireless technology (NTT Facts).

While steadily expanding internationally, NTT's existing underground plant facilities are in need of repair. 600 km of tunnels and 600,000 km of pipes, manholes, bridges, etc. built decades ago have aged and deteriorated. While the full extent of cracks, leaks, and concrete corrosion at this point is unknown, it could be significant enough to render these tunnels a net liability. NTT needs to decide what options they have available, what its goals are, and which option best achieves those goals.

Added Considerations

Currently, NTT recognizes its interest in the development of remote-sensing and non-destructive testing of the concrete in its tunnels. In-house development has produced radar and fiber-optic sensing tools, and NTT has partnerships with various academic organizations involved in new detection technology. This position is both helpful to its immediate task by putting a number of powerful tools at their disposal and helpful to the test case by creating a resource-allocation dilemma—which technologies have the greatest potential benefit and therefore deserve further research?

Also important to the test case is a note about NTT's motivations. Of course, as a corporation, NTT must give due respect to the bottom line, but for a variety of reasons NTT has committed itself to "corporate citizenship." In fact, in NTT's 2002 environmental report, President Norio Wada expressed the company's concerns for "sustainable development." He added:

> "It is our challenge to create new businesses while striving arduously to reduce the environmental burden. […] We also take it for granted that our appeal and

leadership of such efforts are our responsibility as a corporate member of society." (NTT Website 2003)

This means that environmental and social impacts must figure somehow in its decision-making process.

Formulating the Problem

For a proper analysis to be made of NTT's case, the problem needs to be defined, bounded, and parameterized. Here, while the specifics are somewhat contrived, we address NTT's problem of what to do with their aging tunnels.

The most important specification in this or any decision analysis is an examination of the options available as solutions. Here we saw five possibilities. NTT can:

Option 1: Repair the Tunnels As Is – arrest the depreciation of the tunnels for a given amount of time

Option 2: Replace the Tunnels with Similar Ones – decommission the current facilities and replace them with equivalent new ones

Option 3: Replace the Tunnels with Micro Tunnels – the proliferation of fiber optic transmission lines makes much smaller tunnels a possibility

Option 4: Upgrade the Current Tunnels – keep the current infrastructure, but install a chosen remote monitoring technology and new concrete protection

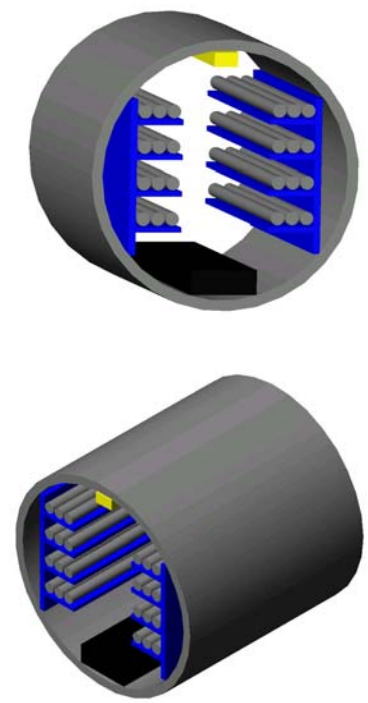

Figure 4: CAD model of an NTT tunnel

Option 5: Do Nothing – leave the tunnels to naturally depreciate for a given amount of time

Finding available options is a crucial task, which in practice should be accomplished by someone with enough knowledge and objectivity to include every possible decision without excluding those he/she considers unlikely to prevail.

Case Analysis

The Current Value of NTT's tunnels

In order to predict the future costs and values of NTT's tunnels with respect to each of the five options, it is first necessary to find their current economic and environmental values. To account for depreciation, material value, productive value, economic liability, and risk we approximated that the economic value of NTT's tunnels is $500 million. We looked at NTT Lifestyle and Environmental Technology Laboratories' environmental reports and LCA analyses and estimated the tunnels' environmental value to be -$80 million. In the following sections, we will look at the changes in these economic and environmental values and the costs associated with each potential option.

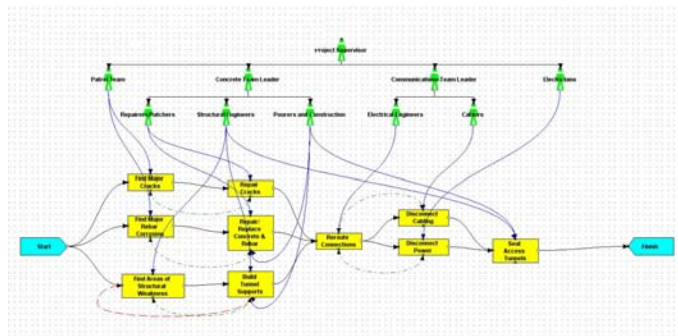

Figure 6: Model of Tunnel Decommissioning

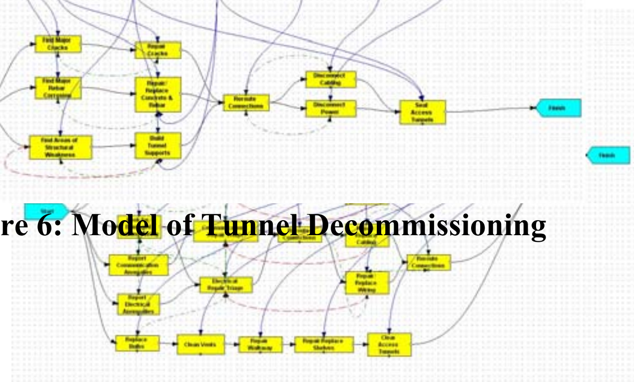

Figure 5: Model of Repairing the Tunnel

Option 1 – Repair the Tunnel As-Is

This option is one simple step – undertake a repair process that will exactly arrest the depreciation of the tunnel, keeping its value constant.[1] We modeled the repair process (figure 5) to determine its associated environmental and economic costs.

The repair process requires a communication team, an electrical team, and a concrete/structural team, each team working in parallel completing a combination of problem detection, problem triage, and problem resolution tasks with communication and rework where necessary. In line with basic SimVision guidelines, the responsible organization had a project manager, a team leader for each major responsibility, and an approximate 1:1 ratio of actors to tasks.

After building the model, all that remained was running a simulation. It predicted a financial cost of $30 million and an environmental cost of $6 million for keeping the tunnel in its ideal condition.

Finding the gross value figures for Option 1 was easy in comparison. Since the repair process was designed to preserve the tunnel in its ideal state, the values should simply remain constant. This puts the financial figure at $500 million and the environmental at -$80 million.

Option 2 – Replace with a Similar Tunnel

[1] Our methodology is only intended to evaluate present options – the value calculus we use is somewhat shortsighted for full lifecycle analysis. However, options that end with the project in the exact same scenario at a given future time, like this one, represent possible cycles. In short, if Option 1 is the best option right now, it is likely to be the best option when the repairs it entails are finished, and so realistically it represents an ongoing maintenance cycle.

In this option, the current tunnel is decommissioned, and replaced with a comparable tunnel. This option has two major components – the decommissioning of the existing tunnel and the construction of the similar tunnel.

The decommissioning of the tunnel, as seen in figure 6, requires a general problem detection and problem resolution process to prevent structural failure that would harmfully affect its surroundings (i.e cave-ins under a city street). The construction of the tunnel (figure 7) is linear, having a series of digging, concrete pouring and construction, fixture installation, electrical, and communications tasks that teams complete one after another.

When we ran simulations of each model, they showed that the economic cost of replacing the current tunnel with a new similar one would be $200 million and the environmental costs would be $54 million.

The economic and environmental values of the tunnel reflect this investment. Because we constructed a similar yet slightly newer tunnel the value is also similar. NTT's new tunnel is a $525 million dollar asset. However, since this also means another 600 km of new concrete tunnels put underground, its environmental value would almost double to -$140 million.

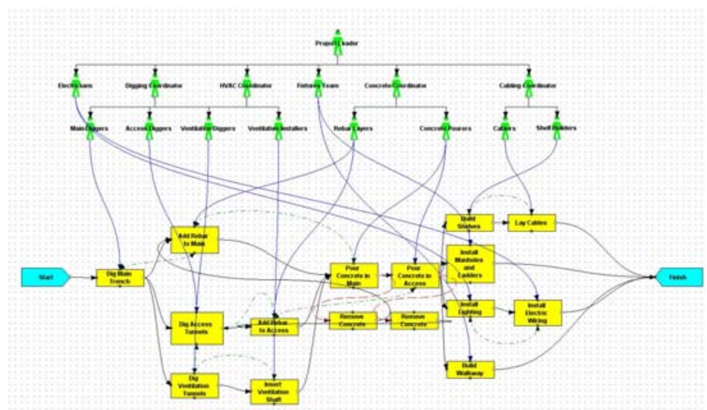

Figure 7: Model of Building a Similar Tunnel

Option 3 – Replace the Tunnels with Micro-Tunnels

Option 3 is a modification of Option 2: the current tunnel is decommissioned, but instead of being replaced with a similar tunnel, the tunnels are substituted with smaller machine-bored micro-tunnels.

Building a micro-tunnel gives NTT an opportunity to use new technology to improve the efficiency and capacity of their communications systems. Holistically, this is a straightforward, linear process that requires the maintenance of the machine digging, the installation of the tunnels, and the installation of the fiber optic cables and repeaters as seen in figure 8.

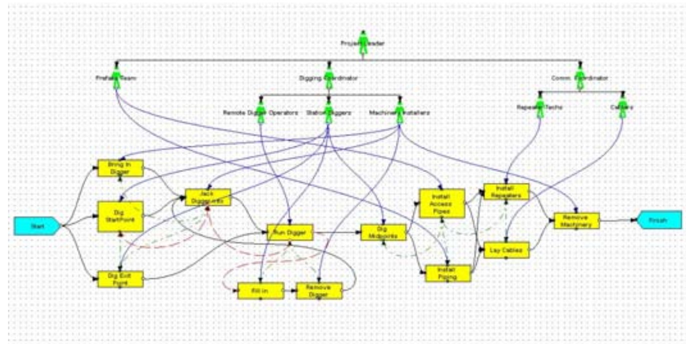

Figure 8: Model of Building a Micro-Tunnel

A combined analysis of simulation results from figure 6 (Tunnel Decommissioning) and figure 8 (Building of Micro-Tunnel) shows that replacing NTT's existing tunnels with a micro-tunnel will economically cost $140 million and environmentally cost $27 million.

After taking into consideration the value of added technology, we found that NTT's new tunnel is valued at $510 million. The micro-tunnel's increase efficiency increased its environmental value, but was largely outweighed by the fact that we installed an additional tunnel. While smaller, the micro-tunnel still has a environmental value of -$100 million.

Option 4 – Upgrade the Tunnel

Upgrading the tunnel is similar to repairing the tunnel in Option 1. It is a single step process designed to update the communications systems, repair and replace sections of the tunnel, improve tunnel maintenance, and add tunnel redundancy.

The process includes the tunnel repair process of Option 1 (problem detection, problem triage, problem resolution), remote sensor installation, and redundant tunnel construction. Project teams work on these three tasks in parallel as seen in figure 9.

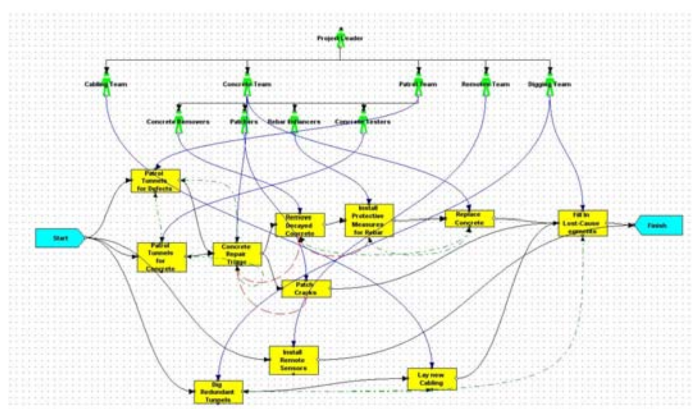

Figure 9: Model of Upgrading the Tunnel

The most complex and valuable of these steps is the remote sensor installation. It has the potential to streamline future repair processes by facilitating problem detection and decreasing repair latency. However, with such a wide spectrum of sensing technology available, each option with non-obvious benefits and faults, we felt that another model was necessary to pick the right one. We adapted the repair cycle model from option 1 to use each sensing option (ultrasonic, laser, fiber-optic, electric potential) to calculate costs and benefits. We ultimately settled on a combination of distributed electric potential measurements and laser scanning as the most useful and economic solution and added it to the upgrade model.

Simulations of this model show an economic cost of $60 million, twice that of Option 1, and an environmental cost of $6.3 million, slightly higher than Option 1.

Added technology and upgraded systems, like Option 3, raise the economic value of NTT's tunnels to $600 million. Also, by upgrading rather than adding a new tunnel, its increased efficiency increases its environmental value without doing affecting the environment. Its environmental value improves slightly to $75 million.

Option 5 – Do Nothing

This option gives NTT the option of doing nothing for the moment and waiting to reevaluate the situation at a later time. Doing nothing eliminates all environmental and economic costs. However, the tunnel depreciates over time, and thus has a capitalized value of $425 million. Its environmental value remains constant at -$80 million.

Decision Analysis

We carried out the above analyses with the express purpose of assembling a general array of data. Essentially, there are 10 important pieces of information, though, two for each option: total environmental value and total financial value. Using these two parameters, we can build decision-making protocols for whatever perspective is necessary.

One other factor may influence a decision here – the notion of an exchange rate between environmental and financial capital. Consider: capitalist society tends to severely devalue natural assets like biodiversity and atmosphere, therefore they can be acquired for less than their worth. This is an empirical claim that at this point we cannot validate, but because it could heavily impact certain perspectives on environmentally significant decisions, we have included flexibility for it in our decision-making model by introducing the variable P ($ Natural Capital / $ Cash). To ignore it, simply set P=1.

In NTT's case, we've developed 5 possible perspectives (some admittedly more likely than others). They are:

A: Maximize X (Only money matters)

B: Maximize Y (Only the environment matters)

C: Maximize X while X+Y > 0 (Minimum Requirement of Weak Sustainability)

D: Maximize X+Y (Only total capital matters) (WS)

E: Maximize XP+Y (Total possible natural capital matters)

F: Find Max X = M, then Maximize XP+Y while X > MV (Total possible natural capital matters as long as money is at least V percent of max total)

Perspective A is the simple mercenary point of view, and perspective B is the corresponding simple Environmentalist point of view. Perspective C is the Mercenary view, with the caveat that the option selected must be at least weakly sustainable. Perspective D takes this to its extreme and maximizes weak sustainability. Perspective E is the intelligent environmentalist view and uses the exchange rate to maximize *potential* environmental value, i.e. the value that would be created if all financial gain was invested in natural capital. Perspective F is the responsible corporation view—it dedicates a percentage of net value from the most profitable option to environmental investment, then sees if it can beat that figure with a different option.

We can add significant values for each perspective to the spreadsheet, and then the options chosen by each to give a complete view of the analysis.

A		B	C	D	E	F	G
		Total Economic Value (X)	Total Environmental Value (Y)	Total Change in Capital (Weak Sustainability) (X+Y)	Total Potential Environmental Benefit (XP+Y)	Cash Above/Below Profit Requirement (X - MV)	Perspectives Making Choice
Option 1	Repair As Is	470	-86	384	619	11	
Option 2	Replace with Similar Tunnel	325	-194	131	293.5	-134	
Option 3	Replace with MicroTunnel	410	-87	323	528	-49	
Option 4	Upgrade Tunnel	540	-81.3	458.7	728.7	81	A,C,D,E,F
Option 5	Do Nothing	425	-80	345	557.5	-34	B

Figure 10: Data Visualization Spreadsheet: Using simple assumptions it is possible to describe consequences of different actions (column A) from the perspectives of economic cost (column B), environmental cost (column C), and various combinations of these costs (columns D,E,F). The optimal choice depends on the perspective being considered (column

Shown here are the results for all five perspectives using P = 1.5 and V = .85. Option 4 is the clear winner by popularity, and since Perspective B is an unlikely one for any corporation to follow, the most likely option to see implementation. In fact, Option 4 proves to be the best by a high enough margin that it is not sensitive any changes in P or V. So, by the Ung-Berring analysis, upgrading the tunnel proves to be far-and-away NTT's best bet from the standpoints of both sustainability and profit.

Conclusions

Our methodology proved to be an effective way to meaningfully integrate financial and environmental data. We do not necessarily propose that NTT should upgrade its tunnels, as our results show, but rather that NTT could use our methodology together with proper data and care to produce a meaningful decision. The data used in our analysis was almost certainly highly flawed, but the process appears to be valid.

So, in the final analysis, NTT (or any decision-maker with a complex task and concern for sustainability) should be able to adapt our methodology to reach decisions that best achieve its objectives. To the extent that the NTT test case demonstrated this, we consider the test successful.

Given the scalable and generalizable nature of each step of our analysis, it is our hope that future research will find similar methodologies versatile enough to be useful in a broad range of decision-making scenarios. With different levels of detail and cost/value estimation tools, this methodology should be applicable to scenarios as varied as evaluating the significance of potential research, AEC process design, and policy analysis. Also the methodology could be useful simply as a visualization of sustainability and environmental impact.

Recommendations

In light of our findings, we feel that the relationship between CIFE and sustainability requires further inquiry. So, in the short term, we recommend increased research on integrating VDC tools with sustainability issues. CIFE is involved with several project-planning tools (from 4D modeling to supply chain visibility) and would be the perfect candidate for developing a software package to automate this or a similar methodology.

While the potential for this relationship is great, the literature to support it is extremely young. So, while we foresee a VDC/Sustainability curriculum at some future date, creating a class connecting the two now would be premature. It would certainly be valuable, however, to teach some sustainability analysis in the existing VDC curriculum (at Stanford, CEE 143/243).

Sustainability itself, on the other hand, currently has a large and rich literature. Most of it has very little to do with VDC or even Civil Engineering, and lies more in the realm of economic theory. If sustainable development is truly a societal goal, educational institutions need to take more initiative to address it. At the very least an Economics class or seminar dedicated to sustainability would be an excellent opportunity for interested students and would pave the way for sustainability education in other arenas like engineering.

For Stanford students especially interested in our research, we would recommend classes on environmental engineering and decision analysis. In particular MS&E 152 and CEE 176A should be explored along with the mandatory CEE 143/243.

Acknowledgements

To our knowledge, we are among the first to explore the intersection of sustainability and VDC tools. This meant that helpful colleagues rather than literature had to be our main source of inspiration. We therefore owe special thanks to the Center for Integrated Facilities Engineering and Professor John Kunz for their guidance and expertise. We would also like to thank Stanford University and the departments of Symbolic Systems and Civil and Environmental Engineering.

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