Second International Symposium on Engineering Systems
MIT, Cambridge, Massachusetts, June 15-17, 2009

Comparison of Project Evaluation Using Cost-Benefit Analysis and Multi-Attribute Tradespace Exploration in the Transportation Domain

Julia Nickel[1], Adam M. Ross[2] and Donna H. Rhodes[3]
Massachusetts Institute of Technology, Cambridge, MA, 02139

The paper discusses the application of two decision methods, Cost-Benefit Analysis (CBA) and Multi-Attribute Tradespace Exploration (MATE), to the selection of "best" design alternatives across two case studies in the transportation domain. The cases are an airport express for the city of Chicago, and a freight rail line linking Lisbon, Portugal to Madrid, Spain. Through the joint use of MATE and CBA in project selection, shortcomings of CBA can be mitigated. Additional insight is gained with MATE through the ability to explore the distribution of project costs and benefits and related incentives for behavioral shifts, the keeping separate of different types of costs (for example, tangible and intangible), and the systematic exploration of a large number of designs early on in the process of conceptual design.

Key words: *Engineering Systems, Cost-Benefit Analysis, Multi-Attribute Tradespace Exploration, Transportation, Project Evaluation*

Copyright © 2009 by [Julia Nickel, Adam M. Ross and Donna H. Rhodes]. Published and used by MIT ESD and CESUN with permission.

1 Introduction

"Engineering Systems" as understood by MIT's Engineering Systems Division is the study of enabling large-scale complex technical systems, taking into account not only their engineering relationships but also their relationships to public policy, management, and other social sciences. Examples of Engineering Systems are transportation systems, energy generation and distribution systems, or satellite systems. While very different, these systems exhibit a number of common characteristics: long lifecycles, high price tags, and individualized or unique designs. Good and bad choices in the process of conceptual design are locked in and have long-lasting consequences. In this situation, the exploration of a large number of designs in the early design phase increases the odds of selecting a "good" design, where "good" is determined by specific criteria the system stakeholders wish to use.

At the same time, the evaluation of candidate engineering systems is resource-intensive because of the large number of complexities that these systems exhibit. Sussman identifies four kinds of

[1] ESD SM Student, Engineering Systems Division (ESD), 77 Massachusetts Ave, E38-575, Cambridge, MA 02139, juni@mit.edu
[2] Research Scientist, ESD, 77 Massachusetts Ave, E38-575, Cambridge, MA 02139, adamross@mit.edu
[3] Principal Research Scientist, ESD, 77 Massachusetts Ave, E38-575, Cambridge, MA 02139, rhodes@mit.edu

complexity that are of primary concern for Complex Large-scale Interconnected Open Socio-Technical (CLIOS) Systems: structural complexity, evaluative complexity, behavioral complexity and nested complexity (Lloyd 2002; Sussman 2002). He lays out how each of the four characteristics of CLIOS systems is fulfilled for transportation systems (Sussman 2000; Sussman 2002). “Complexity” means that a system is composed of a group of interrelated components and subsystems, for which the degree and nature of the relationships between them is imperfectly known, with varying directionality, magnitude and time-scales of interactions (Sussman 2002). “Structural complexity” refers to a system that consists of a large number of interconnected parts, while “behavioral complexity” means that the exact impact that an internal or external disturbance will have on the system is to hard to model or predict with accuracy. “Nested complexity” is a concept that denotes that a technical system is embedded within an institutional system, which exhibits structural and behavioral complexity in its own right. “Evaluative complexity” suggests that multiple stakeholders exist for a system, who hold different views of what desirable and undesirable aspects of system performance constitute. Even if the behavior of the system could be predicted accurately, which it often cannot, different people will evaluate that behavior differently, making decision-making difficult. The last point is particularly important in the case of transportation systems, in which the interests of economic stimulation and viability, a small environmental footprint, and equitable accessibility for different population groups are often in direct competition. Methods for project appraisal need to account for these complexities of engineering systems. In the context of the examples from the transportation domain in this paper, the term “project appraisal” is used synonymously with the term “system design evaluation”.

This paper discusses the specific insights that two methods provide for project evaluation: Cost-Benefit Analysis and Multi-Attribute Tradespace Exploration. Through the application of both methods to two case studies from the transportation domain, the paper demonstrates the complementary insights provided by both methods, and the potential to thereby improve transportation decision making. A complete application of both methods is demonstrated for Case 1 (Chicago Airport Express), whereas the set-up of MATE and the results of a CBA are discussed for the more complex Case 2 (Portuguese High-Speed Rail). The evaluations in this paper are not intended to provide technical guidance but to illustrate different methods for project appraisal.

2 Cost-Benefit Analysis

Cost-Benefit Analysis (CBA) is one of the most widely accepted and applied methods for project appraisal for large-scale infrastructure investments in the public sector (e.g., by the Federal Aviation Administration, National Highway Safety Administration, Environmental Protection Agency, European Union). CBA is a prescriptive method that provides guidance on the criteria to take into account in decision making, ensuring that the net aggregate benefits to society outweigh net aggregate costs. Typical criteria such as reduction in emissions, delays, crash costs or noise are imposed by the policymaking bodies who designed CBA guidelines that analysts use as references (California Department of Transportation; US Federal Highway Administration 2003); CBA seeks to enumerate all direct costs and benefits *to society* (directly experienced, first-order effects) of a particular design, assigns them monetary equivalents, discounts future values to a Net Present Value (NPV), and adds them to a single number. In line with FHA recommendations (US Federal Highway Administration 2003) only first-order effects are quantified in the CBA analyses cited in this paper. The differences in CBA scores among alternatives allow a ranking of alternatives and a reduction of feasible designs to those that would constitute Kaldor-Hicks improvements. Kaldor-Hicks efficiency is a measure for economic efficiency holding that an outcome is efficient if a Pareto optimal outcome could theoretically be reached by compensating stakeholders who are made worse-off by the outcome without requiring that the compensation be actually carried out. Recognizing suggestions for the improvement of CBA (Wang and Liang 1995; Rivey 2007), classical CBA as referred to in this paper shares the understanding that is defined by the FHA in a primer on Cost-Benefit Analysis (US Federal Highway Administration 2003). Other important studies that are typically performed alongside CBA in project evaluation are a financial feasibility study, Economic Impact Analysis and Environmental Impact Analysis (in the form of an Environmental Impact Analysis (EIA) or Statement). While the National Environmental Policy Act of 1969 (NEPA) requires that external costs be mitigated, the CBA is typically performed before Economic or Environmental Impact Analyses are conducted. CBA can therefore inform the later two analyses and mitigation costs can be included in the EIA, but an analysis of environmental consequences is not performed until after CBA and is typically not therein included.

CBA allows a certain transparency that helps to justify political decisions and makes possible the comparison of different designs on a common scale. The prescription of attributes, such as emissions or reductions in delays, seeks to assure that they are sufficiently prioritized in an evaluation. Two reasons for insufficient prioritization are the overriding of dispersed interests (e.g., emissions) by concentrated interests (e.g., trucking industry), or by agency-focused objectives of the evaluating body that potentially conflict with the public interest.

There are, however, a number of flaws inherent in CBA (Gomez-Ibanez, Tye et al. 1999; Heinzerling and Ackerman 2002). Some of these flaws are the introduction of critical value assumptions through the discounting of non-monetary goods, widely differing practices for the monetizing of non-monetary goods, performance of interpersonal utility comparisons and loss of information about the distribution of costs and benefits, and the aggregation of certain and uncertain costs on a common scale. One methodological source of error when performing a CBA is the comparison of only one, or a limited number of alternatives, to the base case. The FHA therefore recommends that "proper" CBA should consider a "full range of reasonable alternatives" (US Federal Highway Administration 2003). Without a systematic approach to exploring a larger number of feasible alternatives, however, the risk of sub-optimizing always remains.

3 Multi-Attribute Tradespace Exploration

Multi-Attribute Tradespace Exploration (MATE) is a method for system design selection and generation developed and matured at MIT. MATE is a value-based decision and design method for the conceptual design of complex technical systems through tradespace exploration. Developed using aerospace examples, it is ultimately intended to be useful for engineering systems across domains. Ross and Hastings provide an extensive description of the MATE process and give example applications (Ross and Hastings 2006; Ross 2006). Nickel, Ross and Rhodes (2009) demonstrate the first application of MATE to a design problem in the transportation domain (Chicago airport express). This case study is referred to in abbreviated form in this paper as Case 1. The underlying idea of MATE is the use of perceived value by stakeholders as decision metrics. MATE therefore places high importance on the preferences of key decision makers. The method seeks to avoid suboptimal outcomes that are caused by settling on a single point-design early on in the design process, by supporting the systematic development and exploration of a large number of designs early on in the design process. MATE provides a framework for discovering efficient compromise solutions in multi-decision maker tradespaces, such as those that are often encountered in the transportation domain. The information obtained through the MATE process may help multiple decision makers with differing interests achieve an acceptable consensus faster in negotiations.

The set-up of a MATE study starts with a definition of mission objective, contexts and constraints on the system. Key decision makers, their attributes, utilities and acceptable ranges for each attribute are identified. *Attributes* are typically performance metrics that the decision maker values. In the next step, *system concepts*, mappings of function to form, and *design variables* are derived. Design variables are designer-controlled, tradable quantitative parameters that in their entirety characterize a specific design. The design variables are derived from the designer's expertise and knowledge as to how an attribute can be displayed by a system, which then leads to the definition of systems concepts. The relationships between attributes and design parameters and attributes and utility, including Multi-Attribute Utility (Keeney and Raiffa 1993), are modeled. The relationships modeled in the last step are sufficient to graphically display several designs in a tradespace. Utility and expense allow the display between two axes of both desirable and undesirable attributes for applications in the transportation domain. *Expense* is akin to the idea of "negative utility" that attributes provide which the designer wants to keep at low levels, like development time or emissions. The idea of Single- Attribute Expense Functions was proposed by Diller in the context of space system development expenses (Diller 2002). The example in (Figure 1) illustrates how a tradespace is read: The Pareto Front consists of designs that are available at the lowest cost for a desired level of utility.

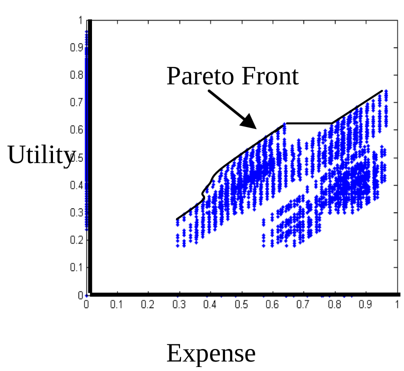

Figure 1: *Tradespace for transportation example (Source: (Nickel, Ross et al. 2009)*

Figure 2: *Airport access via Kennedy Expressway and CTA Blue Line (Source: Google Maps)*

4 Case 1: Chicago airport express

Introduction

Chicago's main airport, O'Hare International, is currently accessible via two main routes: by road via the Kennedy Expressway, and by train via the Blue Line, a rapid transit line operated by the Chicago Transit Authority (CTA) (Figure 2). The Kennedy Expressway is unreliable for airport travelers due to its frequent and highly variable congestion (RoadStats 2008). The CTA Blue Line takes 60 minutes for the 16 mile trip to the airport from downtown and is highly uncomfortable with luggage. The technical details of this case study and the modeling for the MATE and CBA analysis are discussed in (Nickel, Ross et al. 2009).

Stakeholder identification

The main decision making stakeholders of this project are those that are expected to contribute to the funding of the airport express: the City of Chicago, the CTA, and a Private Operator. In addition, the affected public and travelers to the airport have a stake but no formal decision making power. Although application for federal grants is an option once a decision for a design has been made, a preference for a design that could be self-financed is assumed in case no additional funding becomes available. To leverage business experience from the private sector and to secure a contribution to construction expenses, a private sector concessionaire (the Private Operator) was suggested to be charged with the management of the airport express (Parsons Brinckerhoff Consult Inc. 2006). O'Hare and airlines have been excluded as stakeholders from the City's technical studies with no reason given. It appears that the planners at the Mayor's office and the CTA do not count on funding from these parties and therefore do not pay them much attention. An agreement with O'Hare is mentioned stating that permission is given to the CTA to modify its O'Hare terminal to accommodate an airport express (WilburSmith Associates 2004).

Attributes

In MATE, an attribute denotes any cost or benefit, tangible or intangible, that a stakeholder cares about. The lists of attributes are abbreviated versions of those that were elicited in interviews with proxy representatives for MATE, and using guidelines provided by the (US Federal Highway Administration 2003), and the (California Department of Transportation) for CBA, respectively.

Rank	City of Chicago	CTA	Private Operator
1	Estimated tax base change	Up front investment required from CTA	Return on investment, pre-tax
2	Generation of Employment (tied with 1)	Impact on current operations - overall capacity	Little competition from CTA Blue Line and road investments
3	Availability of outside project funding (tied with 1)	- probability of recurring delays to existing trains (tied with 2)	Autonomy in operation (e.g. fare increases, operaiton) (tied with 2)
4	Attraction of visitors to downtown Chicago	Maintainability	Concession payment
5	Equity (spending on other projects) (tied with 4)		

Figure 3: *List of most important attributes elicited from stakeholder interviews*

The lists in Figures 3 and 4 highlight the importance of the selection method for the criteria that are prioritized. Stakeholders in the MATE interviews expressed a more agency-focused point of view pertaining to their respective organizations. The first order costs and benefits mandated by

Benefits	Costs
First order effects	
Travel time savings (speed and reliability)	Capital cost
- To Airport travelers	Operating cost
- To Blue Line riders	Delays to Blue Line passengers
- To drivers (congestion relief on Kennedy)	Delays to drivers on Kennedy Expressway
Emission reduction	Noise to residents
	Adverse neighborhood impacts from construction
Second order effects	
Long-term and short-term job generation	Job losses (from changes in operation at CTA, cab drivers)
Attraction of new business development	Loss of property value in neighborhoods impacted by noise
Increase in property value	

Figure 4: *Relevant costs and benefits of Airport Express options*

the CBA guidelines were not prioritized at all by the interviewed stakeholders. The interests of the City of Chicago are more aligned with the second order effects of CBA, whereas the other two stakeholders are completely detached from the CBA attributes.

Generation of system concepts

Three alternative system concepts were evaluated in detail: Route 2, in which a separate right-of-way for the airline express would be built; Bus Rapid Transit (BRT) along the Kennedy Expressway, and an option in which local service would be provided by BRTs, and airport passengers carried along the freed-up tracks of the current Blue Line (Blue Line Switch option, BLS).

Calculate aggregate Cost-Benefit

The focus in the CBA is on changes in travel time, emissions, capital cost and operating cost. Five models were used to simulate cash flows over an assumed useful life of 50 years: an emissions model from the CalTrans website (California Department of Transportation), a self-developed model for maintenance and operating costs, respectively, and a self-developed model for reductions in delays and overall running time to different groups of travelers. Construction costs were taken from look-up tables in technical reports (WilburSmith Associates 2004; Parsons Brinckerhoff Consult Inc. 2006).

In mn 2008 $	Base	Route 2	BRT	Blue Line Switch
DR=7%	0	-97	-70	718
DR=10%	0	170	-37	447

Figure 5: *Aggregate NPVs of airport express options*

Figure 5 shows the outcome of the CBA for the airport express options. All benefits and costs are calculated relative to the base case (current access modes to airport), which therefore by definition is 0. Negative numbers constitute savings to society whereas positive numbers constitute increased costs to society. BRT is beneficial independent of a discount rate between 7% and 10%. Route 2 has high initial costs and provides benefits later on. Savings to society are therefore favored by a lower discount rate. The Blue Line Switch Option (BLS) does not provide any net benefits to society according to this analysis. The CBA analysis shows the crucial impact that the choice of discount rate has on the desirability of a project under the criterion of maximally positive NPV.

Calculate aggregate Utility-Expense, plot tradespace (MATE)

After the steps of attribute and utiliy elicitation, identification of design variables and modeling of underlying relationships, tradespaces were plotted for the three decision-making stakeholders (Figures 6-9). As in reality, the influence of non-decision-making stakeholders is indirect and is only represented insofar as the decision making stakeholders care about representing them.

The attributes elicited in the stakeholder interviews (Figure 3) give a sense of the interests of different stakeholders. Many of the attributes that were expressed in response to the question “What would you value about the airport express?” are higher level political or strategic attributes such as employment generation or return on investment. To operationalize these attributes, they were decomposed into such attributes that can be influenced by the designer and constitute a “fairer” metric for success for the system.

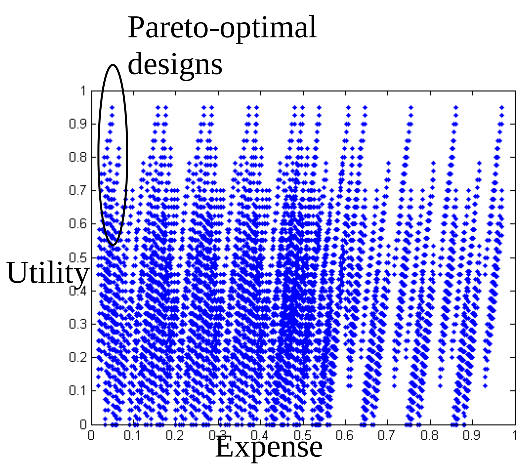

Figure 6: *City of Chicago Tradespace. Expense vs. Utility*

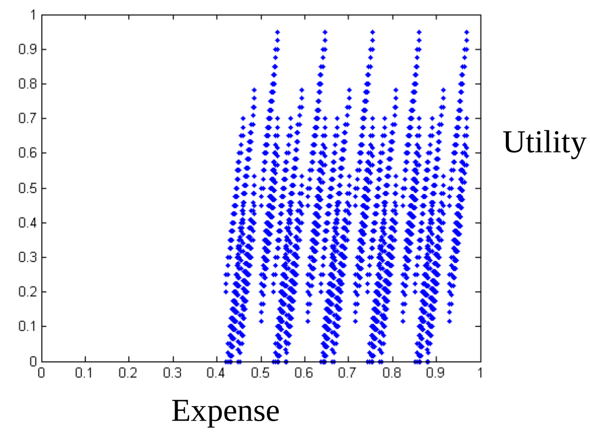

Figure 3: *City of Chicago Tradespace for Route 2. Expense vs. Utility*

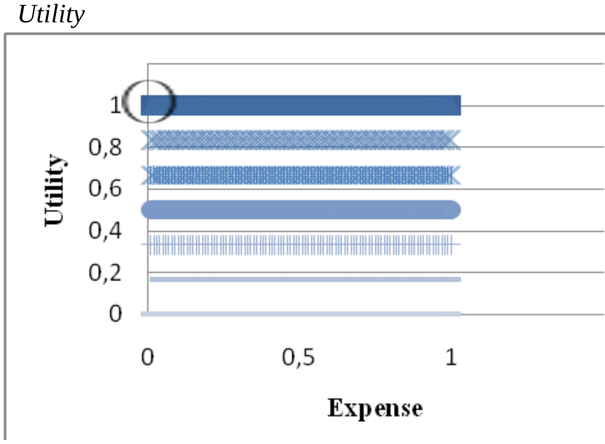

Figure 8: *CTA Tradespace. Expense vs. Utility*

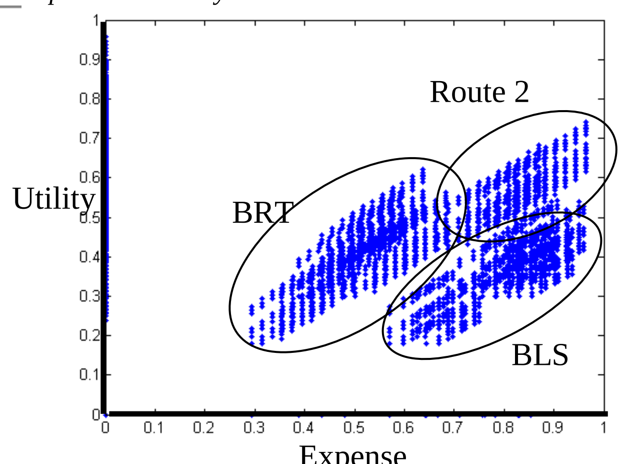

Figure 9: *Private Operator Tradespace. Expense vs. Utility*

The designs that provide high utility at low or no cost in the upper left corner of Figure 6 (indicated by the circle) are possible because the City of Chicago only participates in the initial investment, but not in operating expenditures. This fact means that designs that improve the Quality of Service through for example higher frequency or longer span of service are “free” utility improvements for the City. All Pareto-optimal designs for the City therefore maximize those free service attributes that only impact operating costs. Route 2 (Figure 7) is the most expensive design for the City, since it comes at the highest initial expense. The other two options are much cheaper in relation. The optimal choice of concept for the City of Chicago is BRT. It is important to keep in mind that the City tradespace is one tradespace within a multi-stakeholder problem space. A stakeholder can only choose a design in coordination with other stakeholders. A design that is very beneficial for one stakeholder because it requires only a small financial contribution will require a larger contribution from other stakeholders. Figure 8, the CTA tradespace, is very simple due to only two considered variables which turn out to be independent. The optimal design minimizes the contribution that the CTA needs to make and minimizes span of services to allow enough time for maintenance works. The Private Operator prefers either BRT or Route 2 as concept choice, depending on the desired level of utility.

Determine "best" alternatives
The results of the CBA indicate that BRT is the only solution that provides net benefits to society independent of the discount rate. If a low government discount rate is used, both BRT and Route 2 can be justified. In the tradespace analysis, BRT emerges as the best option for the Private Operator until a utility of approximately 0.6. The tradespace of the CTA is not particularly helpful in selecting a design concept, since the value delivery to the CTA is not affected by the choice of concept. The City of Chicago has the clearest preference for BRT as a concept and maximization of service variables that would only impact operating cost. Overall, there is no clear dominant design that emerges from both analyses. From a combined perspective, BRT seems most likely to achieve the approval of the majority of stakeholders since it provides savings to society independent of discount rate, minimizes initial investment costs for all parties and is the preferred design for the Private Investor (up until a utility of 0.6) and the City of Chicago.

5 Case 2: High-Speed Rail in Portugal

Introduction
Currently no High-Speed Rail (HSR) network exists in Portugal and the existing conventional rail network has several shortcomings, including one-track and indirect connections between important areas of Portugal and Spain. Among the several benefits that the construction of an HSR network is expected to deliver to Portugal are capacity expansion of the current congested transportation infrastructure; reducing the geographical isolation of the country from the rest of Europe; improving cohesion and quality of life in Portugal; stimulating the economy; and reducing the external costs of transportation in the country. The case study concentrates on the axis between Lisbon and Madrid as one of the two main transportation axes in the country, with a possible extension of HSR to the important seaport of Sines.

Stakeholders
This major project will affect a broad number of stakeholders across the entire nation of Portugal and beyond Portuguese borders. The most important decision-making stakeholders are Portugal, Spain, the EU, and a Private Investor. Those four stakeholders will contribute to the funding of the project.

Attributes

The following list (Figure 10) summarizes the attributes that the stakeholders care about (caring about being symbolized by an ‘x’).

Stakeholders (left) Attributes (below)	Units	Portugal	European Union	Private Investor	Spain
Total Project Cost	b€	**x**	**x**		
Cost Portuguese Share	%	**x**			
Cost EU Share	%	**x**	**x**		
Cost Spain Share (Border Connection)	%	**x**			**x**
Private Invester Contribution	mn€	**x**		**x**	
Cost Maintenance	€/yr	**x**			
Cost Operation	€/run	**x**			
Portuguese Cost Share Operations	%	**x**			
Spanish Cost Share Operations	%				**x**
Net Travel Time Sines-Madrid	min	**x**			**x**
# Stops	#	**x**			
Overall Travel Time (Pax)	min	**x**	**x**		**x**
Overall Travel Time (Freight)	min	**x**	**x**		**x**
Quality of Coordination at border connection	[1-5]	**x**	**x**		**x**
Max Troughput (Freight)	ton/day	**x**			
Max Capacity (Pax)	pax/day	**x**			
Ease of Transfer to HSR in Evora	[1-5]	**x**			**x**
Risk (for private investor)	[1-9]			**x**	
Security	[1-5]	**x**			
Prestige	[1-5]	**x**			

Figure 10: *Attributes and stakeholders for HSR in Portugal*

In addition, 6 variables were identified that will impact the stakeholder attributes if they change over time (Figure 11). In MATE terminology, these variables are referred to as “Epoch variables”. In a scenario analysis these epoch variables need to be varied and the impact of their changing on stakeholder attributes needs to be explored.

Epoch Variables	**units**
Demand level	ton/year
Demand level	pax/year
Economic situation of EU/world	[1-5]
Portuguese Economy	[1-5]
Economic situation of Spain	[1-5]
Threat level	[1-5]

Figure 11: *Epoch variables for HSR in Portugal*

Benefits	**Costs**
Travel time savings	Initial construction costs
Savings from reduced externalities (crash costs, emissions)	Maintenance costs Operating costs

Figure 12*: Benefits and costs for HSR in Portugal*

A study prepared by a Portuguese transportation consultancy for the Lisbon- Madrid corridor is referred to for the CBA part (Transportes Inovação e Sistemas 2007). The CBA in the cited document assumes that construction, maintenance and operation will be conducted by the same agency. The attributes elicited for MATE under a stakeholder perspective show that the distribution of costs for various design elements are a major concern for this project. This fact suggests that additional insights about why certain stakeholders prefer certain designs over others can be gained through the use of MATE.

System concept generation

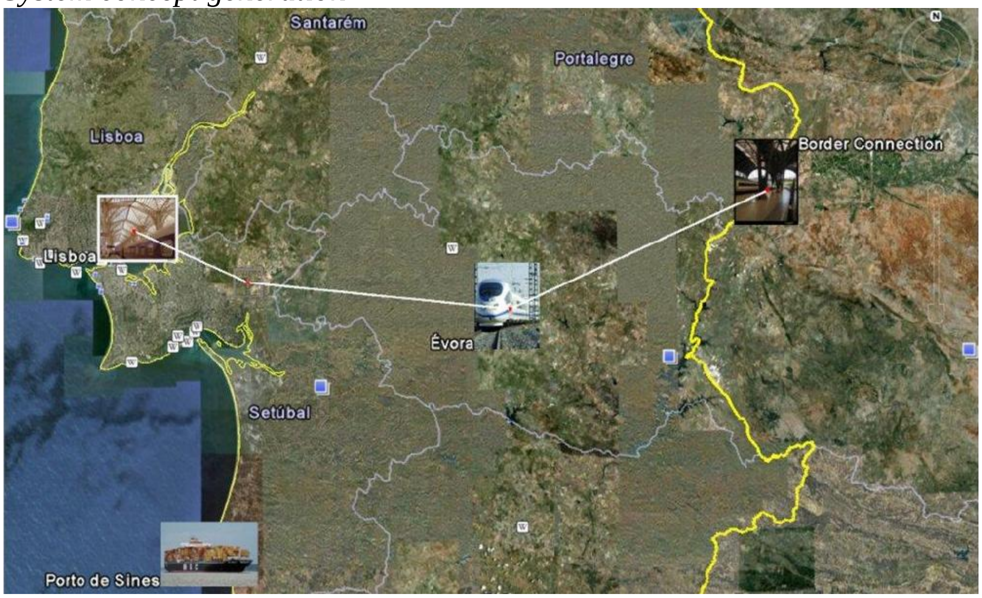

Figure 13: *Possible network routing for the Lisbon-Madrid HSR corridor (Source: Global Images)*

Design Variables	units
Network Routing	discrete corridor choices
Rail type	HSR, Conventional
Loads cov	ton/axle
Loads hsr	ton/axle
Train brand	Alston; Bombardier; Siemens
Land port location	2 choices
Border land port location	south/north on border
Num connections/stops	[1…5]

Design Variables	units
HSR link Sines	[0-1]
Cost share Portugal	%
Cost share EU	%
Cost share Private Investor	%
Cost share border port Spain	%
Cost share operations Portugal	%
Investment in good border interactions	[1…5]

Figure 14: *Design variables*

Figure 14 summarizes design variables, including those that will generate different concepts (network routing, mixed freight and passenger operations).

Calculate aggregate Cost-Benefit

The CBA performed by (Transportes Inovação e Sistemas 2007) calculates the number of passengers on the Lisbon-Madrid axis that are needed to return a positive NPV to society. The

	Scenario 1	Scenario 2	Scenario 3
Discount rate	5.5%	4.0%	5.5%
Savings from reduced externalities ($\sum 5\ years$)	770mn	770 mn	0 mn
Required passengers	6.8mn	5.8mn	8.9mn

Figure 14: *Required number of passengers to achieve a positive NPV for society for different scenarios*

calculation only refers to the needed passenger number to offset construction costs from the Portuguese side, which are projected at 2.4bn for the tracks from Lisbon to the Spanish-Portuguese border. In order to generate a positive return to society for the *two* affected countries, the required number of passengers will need to be higher. The authors of the study do not comment on the likelihood that the required numbers of passengers will be achieved by the system.

Outlook on determination of best alternatives in Portuguese HSR case
The set-up of the MATE analysis shows the kinds of questions that it is able to address that CBA does not answer: How much does the distribution of costs between different stakeholders matter, and what if anything are they willing to trade in for a higher share? What preferences do stakeholders have over different cost types such as construction costs, operating and maintenance costs? It is important to be aware of the effects that are created by the fact that government subsidies (EU, Portugal) are typically only granted for initial construction costs, but not for operating costs. Finally, what intangible benefits exist that do not occur to society as a whole, but which individual stakeholders value? Examples for this kind of attribute are gain in prestige or managerial control over the transportation operations. In contrast, CBA assumes a broad view over all affected stakeholders, whether decision making or not. It conveys a sense of the major public benefits of the project, which consist of travel time savings to passengers and, to a lesser degree, in reduction of emissions and crash costs, and makes sure they are accounted for whether the decision makers care about them or not.

6. Discussion of complementary insights from both methods

Inner dynamics of interests between different decision-making stakeholders remain hidden in CBA. Even though Economic Impact Analysis as an additional method tends to shed more light on the distribution of costs and benefits through revelation of such effects as travel time savings or land value increases, the analysis does not apply to the personal interests of involved decision-making stakeholders. The analysis of the Chicago airport express for demonstrative purposes has already revealed several patterns of interests that will be most interesting for all stakeholders in actual negotiations. The CTA has not much to gain and tries to cut their losses. The City is in a situation in which it is only responsible for contributing to the initial investment, but not to operating expenses (this prediction assumes operating self-sufficiency, as is the result from several studies under conservative estimates). The same situation applies to the EU in the case of Portuguese HSR. A trade-off exists between the goals of ridership maximization (City of Chicago) and profit maximization (Private Investor), which also plays an important role for the Portuguese case. The set-up of the MATE analysis for Portuguese HSR suggests that different stakeholders are similarly driven by personal interests that they care strongly about. Interestingly, those attributes do not always need to come at monetary cost or expenses that could be expressed in monetary terms, such as prestige or managerial control. They are simply attributes that stakeholders care strongly about. It is questionable if and to what extent these details would have been revealed in a traditional project evaluation process.

However, in both example cases MATE cannot be relied upon to bring up all important considerations that need to be weighed in a decision. The mandate to capture aggregate small benefits to dispersed stakeholders in CBA proved important in both cases. Both CBAs demonstrated that substantial savings in travel time was the major benefit to the public of the respective projects. If decision makers do not prioritize this attribute in the MATE analysis, a substantial benefit of the project would be overlooked.

While the two CBAs showed that travel time savings are substantial, the evaluation is skewed through the practice of discounting these non-monetary benefits. The desirability of a concept within the same project and the required number of passengers for social viability were influenced heavily by the discount rate, leaving aside problems with the quantification (e.g., impact of low wage levels in Portugal compared with other European countries). A long-term assessment of attributes can for example be made more specific in MATE, through separation into different types of tangible and intangibles costs and benefits and the choice of appropriate discount rates for each. The flexibility to separate out attributes and keep them separate also mitigates the risk of skewing the analysis through the aggregation of more or less certain projections for different attributes.

CBA and the studies that typically follow it (Economic Impact Analysis, Environmental Impact Analysis) are very resource-intensive. Through the use of MATE a broader filtering at a low-fidelity level can be conducted early on in the design process which increases the odds that scarce resources for detailed studies are invested in those that are most worthwhile.

7. Conclusion

Through the joint use of MATE and CBA in project selection, shortcomings of CBA can be mitigated through additional insight into “blind spot” areas. The focus of both methods is different, however, which is why they should be used in a complementary way to improve decision making. MATE seeks to best meet stakeholders’ expectations of what a project should deliver, whereas CBA ensures that dispersed interests of society are taken into account.

Future research should address the best way to use both methods, or how to potentially merge them into a joint process. As a high-level method for the conceptual design of systems, MATE is intended to provide high-level architectural guidance. MATE is intended for both concept generation and concept evaluation, while CBA is only intended for concept evaluation. Even though MATE feeds into more detailed planning steps of construction, operation and contract design, CBA will help in eliciting attributes that may have remained unarticulated or unconsidered by the stakeholders at the time of the utility interview. Bearing in mind the public mandate of most design decisions in the infrastructure domain, this information can be fed back into the MATE analysis where it will potentially change attributes or weightings.

The identification of attributes in the Portuguese HSR case suggests that inner dynamics of stakeholder preferences play an extremely important role and need to be understood if a successful project shall be delivered. The MATE analysis of this project is therefore an important area of ongoing research. By revealing and visualizing information about stakeholder preference patterns, MATE contributes to better accounting for the hard-to-come by "evaluative complexity" in project appraisal, which ultimately has to be resolved in negotiations.

Acknowledgements

The authors gratefully acknowledge the funding for this research provided by the Systems Engineering Advancement Research Initiative (SEAri), a research initiative within the Engineering Systems Division at MIT. SEAri (http://seari.mit.edu) brings together a set of sponsored research projects and a consortium of systems engineering leaders from industry, government, and academia. SEAri gratefully acknowledges the support of the MIT-Portugal Program in this research. The authors thank Ms. Diana Rita da Silva Leal of the University of Coimbra, Portugal and visiting student at MIT for her contribution to the case study on Portuguese High-Speed Rail. The paper does not represent any official views or positions by the agencies that are named herein.

References

California Department of Transportation. "Benefit-Cost-Analysis." Retrieved 12/11/2008, from http://www.dot.ca.gov/hq/tpp/offices/ote/benefit_cost/.

Diller, N. P. (2002). Utilizing Multiple Attribute Tradespace Exploration with Concurrent Design for Creating Aerospace Systems Requirements. Aeronautics and Astronautics. Cambridge, MA, Massachusetts Institute of Technology. **S.M.**

Gomez-Ibanez, J., W. B. Tye, et al. (1999). Essays in Transportation Economics and Policy. Washington D.C., Brookings Institution Press.

Heinzerling, L. and F. Ackerman (2002). Pricing the Priceless: Cost-Benefit Analysis of Environmental Protection. Washington D.C. , Georgetown University Law Center.

Keeney, R. L. and H. Raiffa (1993). Decisions with Multiple Objectives- Preferences and Value Tradeoffs. Cambridge, England, UK, Cambridge University Press.

Lloyd, S. (2002). Complex Systems: A Review. Proceedings of the ESD Internal Symposium, Cambridge, MA.

Nickel, J., A. M. Ross, and D. H. Rhodes. (2009). Trading Project Costs and Benefits using Multi-Attribute Tradespace Exploration. 7th Conference on Systems Engineering Research. Loughborough, UK.

Parsons Brinckerhoff Consult Inc. (2006). Express Airport Train Service Business Plan. Final Report.

Rivey, D. (2007). A Practical Method for Incorporating Real Options Analysis into US Federal Benefit-Cost Procedures. Engineering and Management. Cambridge, MA, Massachusetts Institute of Technology. **S.M.** .

RoadStats, L. (2008). "Gary- Chicago- Milwaukee Corridor Travel Statistics Kennedy to O'Hare 2008." Retrieved 12/07/2008, from http://www.gcmtravelstats.com/Default.aspx?selLinks1=24.

Ross, A. M. (2006). Managing Unarticulated Value: Changeability in Multi-Attribute Tradespace Exploration. Engineering Systems Division. Cambridge, MA, Massachusetts Institute of Technology. **PhD**.

Ross, A. M. and D. E. Hastings (2006). Assessing Changeability in Aerospace Systems Architecting and Design Using Dynamic Multi-Attribute Tradespace Exploration. AIAA Space 2006 San Jose, CA.

Sussman, J. (2000). Introduction to Transportation Systems. Norwood, MA, Artech House Publishers.

Sussman, J. (2002). Collected Views on Complexity in Systems. Proceedings of the ESD Internal Symposium. Cambridge, MA

Transportes Inovação e Sistemas (2007). Análise custo-benefício das linhas de alta velocidade Lisboa-Porto e Lisboa-Madrid.

US Federal Highway Administration. (2003). "Economic Analysis Primer: Benefit-Cost Analysis." Retrieved 2/19/2009, from http://www.fhwa.dot.gov/infrastructure/asstmgmt/primer05.cfm.

Wang, M.-J. and G. S. Liang (1995). "Benefit-Cost Analysis using Fuzzy Concept." The Engineering Economist **40**(4): 359- 376.

WilburSmith Associates (2004). Ridership and Revenue Forecast Final Report. Prepared for the Chicago Department of Transportation and the Chicago Transit Authority.