TRANSPORT INFRASTRUCTURE IMPACT EVALUATION

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ABSTRACT

Complex transport infrastructures are supposed to have a profound impact on the people and societies they are planned to serve. These impacts are, more often than not, difficult to estimate, and particularly difficult to quantify. Impact evaluation is, however, critical to the success of the infrastructure. Incorrect prior evaluations may lead to strong negative externalities, and, in the most severe cases, to the disruption of the local economic and social fabrics.

In this article, an impact evaluation scheme is proposed, capable of determining the probabilities associated with each possible external impact, and the effect of project options on these probabilities. Since a cost can be attributed to each available project option, this model can effectively provide the answer to typical analysis questions such as: what is the probability of a given outcome or impact? What is the least cost set of project options capable of achieving a given outcome with a desired probability? For a given maximum cost, what is the project design that leads to minimum negative impacts? An application example is given in the article.

The model is based on a combination of a cost based analysis of the portfolio of internal project options, and a stochastic model (discrete-time Markov chain based) of the external environment, capable of capturing the impact of the internal options in the overall external environment. The fundamental idea behind the proposed method is the notion that isolated systems will tend to converge to their nearest stable point. If the stability point corresponding to a given set of options can be determined, it is, thus, reasonably safe to assume that the external situation will tend to that point. Therefore, when striving for a given outcome, what must be done is to ensure that the external equilibrium point is shifted to the desired outcome. This then defines a set of allowable paths in the internal option plane, from where optimal paths can be obtained.

Keywords: Markov, Impact, Stability, Strategy, Modelling

INTRODUCTION

Claiming that complex transportation infrastructure systems have a deep impact on society is presently regarded as a non-claim: it is considered a well established fact, and a simple matter of common knowledge. The problem with facts that are so well known is that often

one does not take the time to verify them, or to properly consider and analyze the exceptions, which are then typically considered non-interesting anomalies.
Many wrong ideas have been incorrectly propagated or deficiently quantified, just because everybody “knew them” to be facts.

One aspect of the impact on society of these transport infrastructures that should never be taken as granted is its positive or negative sign. It is clear that any major project, or infrastructure, will have both positive and negative externalities. But it is generally considered that these infrastructures have a positive impact on the overall economic growth and, hence, on the development of societies at large.
However, even within this paradigm of positive impact on economy and society, some authors have pointed out that not all sectors of society are affected in the same way, and that some sectors may actually become impoverished. Some recent studies, while confirming this general tendency of transport infrastructure to contribute to aggregate gains in productivity and overall economic growth, also reveal that these infrastructures do not ensure gains for all sectors of the society. At its worst, transport infrastructure may tend to reinforce existing inequalities, and hence make the impoverished classes poorer (Setboonsarng, 2005).
Furthermore, the transfer functions between transport infrastructures, economic growth and social welfare seem to be highly non-linear, and far from direct. For example, in (Kwon, 2005a), the impact on poverty reduction of road development in Indonesia is analyzed; it is found that the poverty reduction impact of roads were different from province to province. In fact, the road infrastructure was determined to be an indirect link between GDP growth and poverty reduction. Every one percent growth in provincial GDP led to a decline in poverty incidence of 0.33 percent in good-road provinces, and a decline of only 0.09 percent in bad-road provinces. Road infrastructures thus seem to have a nonlinear contribution to poverty alleviation.
In societies with high inequalities in the distribution of wealth, it is the non-poor sectors that typically capture the benefits of investments on transport systems. For example, improved roads have immediate benefits to the owners of vehicles, but do not as easily present immediate benefits to impoverished classes (Rayner, 2005).
Another related aspect is the choice of infrastructure, and the compromises it presents. In (Kwon, 2005b), for example, it has been found that high-class roads generate higher returns to GDP than low-class roads. Since, naturally, low-class roads will have a bigger impact on the poor sectors of population, we have that, from a societal point of view, it would be better to invest in low-class roads, but from an economic point of view, high class roads should be preferred.

Many other collateral aspects, such as the premature collapse of the old transportation infrastructures (due to the competition of the new transport systems, both in customer capture and maintenance priorities), the exclusion of regions and people, the destruction of social and urban environments (Graham and Marvin, 2001), and the unintended negative externalities (such as the easier spread of diseases such as HIV/AIDS, increased pollution, emergence of new migration patterns, etc), may help to dictate the success or failure of transport infrastructures as positive contributors to societal development.

Equally disappointing is to invest considerable resources in transport infrastructures, hoping to foster economic growth, only to find later that these infrastructures have either distorted the social geography of the society and thus created long term economic problems (even though with possible short term economic gains), or to realize that the GDP simply did not respond, on medium/long terms, and that the return of the investment is thus close to zero.

It is thus not clear, a priori, how beneficial (or not) the investment on transport infrastructures will be, nor how considerable their impact will be. It will certainly depend on the context (Dimitriou 2006).

This is not only true when dealing with developing societies. The same is true in the so called developed world. The economic impact of a mega project such as, for example, the Oresund link in Scandinavia or the TENS-T trans-European infrastructure plan is still unclear. The underlying rationale, of opening up national markets to international markets and world trade, may fail to deliver the expected returns.

There is clearly the need to analyze the conditions under which complex transport infrastructures will, indeed, promote economic growth, the positive or negative medium/long term effects they will have on societies and nations, and create conditions for better a priori estimates of the resulting impacts.

Evaluating these impacts is, however, a task which does not always yield easily to quantitative approaches. The fact that many of the concepts involved are qualitative in nature, or, at least, present high degrees of subjectivity when its quantification is attempted, severely hinders the success of numerical estimates of the external impacts. Many of the most common approaches use, therefore, standard qualitative methods to identify the most desirable and viable solutions, and their inherent risks. Such is the case with the frequent use, in this context, of more or less sophisticated derivatives of the standard SWAT or TRIZ analysis. More quantitative and refined approaches have also been proposed, which can, up to a point, provide a certain degree of quantification (ex: AIE-Applied Information Economics (Hubbard, 2007), DETAM-Dynamic Event Tree Analysis Method (Acosta and Siu, 1993), and DYLAM-Dynamic Event Logic Analytical methodology (Siu, 1994)). But the need remains for a tool capable of modelling the external impact of a given transportation project, and providing numerical answers to questions such as: i) what is the probability of each possible impact if a given project option is exercised? ii) what is the least cost set of project options capable of achieving a given minimum probability of a desired positive impact? iii) for a chosen maximum project cost, what is the set of options, and their optimal sequence in time, that maximizes the probability of a given impact (or the aggregate probability of a set of desired impacts?) iv) conversely, for a given overall project cost, what is the set (and sequencing) of project options capable of minimizing the aggregate probability of negative impacts? These questions must, of course, be answered in the preliminary stages of project design and approval, when evaluating the macro features of the project and, ultimately, the approval or rejection of the project as a whole; but they must also be posed and answered during the full project life-cycle, to allow continuous evaluation of more detailed low-level options, whenever needed.

The fundamental problem to be addressed is one of establishing reliable interconnections between an internal plane of project options, and an external plane of resulting impacts. There is, however, a fundamental difference on the nature of the internal (own organization)

and external (impact) planes. While, on the internal plane, one can estimate and assign costs to the portfolio of available options, in the external plane, the best one can hope for is to obtain a probabilistic model which can capture the impact of the internal options in the external environment. Impacts can never be deterministically determined a priori, but their probability can be estimated. There is, therefore, a need for stochastic modelling on the external plane, and a need for deterministic, cost based analysis, on the internal plane.
Both the external plane (the set of impacts, and their individual probability) and the interconnection between this plane and each possible set of project options could be simply obtained by enquiring experts and analysts. This would lead, however, to a huge degree of variability. In fact, the model would become chaotic and non-manageable. The problem lies, of course, in the fact that small differences in the subjective appreciation of the options and its impacts by different experts typically lead to great differences when quantitative evaluations are directly required from these experts. While all the experts may agree with the fact that exercising a given option will have a considerable positive impact, the situation will typically be different, and present an unacceptable degree of variance, if one tries to directly obtain quantitative appreciations, or numerical values of probabilities. The proposed model addresses this problem, by only requiring from the experts very simple and qualitative appreciations.

THE MODEL

In this section, the proposed model will be described. A simple application example will be presented in the next section.
The fundamental idea behind the proposed approach is the notion that isolated systems will always tend to converge to the nearest stable point. If the point of stability corresponding to a given situation can be determined, we can safely assume that the system will tend to that point. It will always be possible to temporarily force the maintenance of unstable equilibrium points, but that effort will be highly energy consuming, and cannot be maintained indefinitely; one cannot beat nature forever.
The practical implication of the concept is clear: when trying to pursue a given objective, one should not commit energy and resources to directly force the desired goal, but, instead, resources should be committed to support the evolution of the situation in such a way that the desired objective becomes a natural point of stability of the system. It we can do that, then the system will naturally evolve to the desired goal. Time and nature will then be working for us, instead of against us. If we cannot achieve this, any effort to attain the desired objective will unavoidably be unsuccessful in the long term (and probably very costly), since we will then be trying to force the system into an unstable state, one which the system naturally tends to abandon.
This rule is a part of every organization’s daily life. For example: the maintenance of high quality levels in human resources, in an organization which does not constitute a pole of attraction for high quality candidates, is not sustainable in the long term. If the organization only attracts candidates of low educational/training levels, it is still possible, through massive internal efforts in education and training, to attain high levels of qualification of its human resources, but that requires a constant, disproportionate effort, non-sustainable in the long-

run. We would then be working against nature, in the sense that we would be fighting the natural tendency of the system to evolve to its natural equilibrium point.

More to the point: when designing a complex transportation infrastructure, if we want to avoid or create a given impact in the external environment (be it the social, ecologic or economic environment), we must conceive the project in such a way that the desired impact becomes a natural consequence of the exercised project options, and will therefore necessarily appear, just because nature and time says so. There is no point in artificially trying to take measures to force or promote the desired objective, if it corresponds to a non-stable state of the system. We could do it, as previously discussed, but that would imply a constant waste of resources and, moreover, an effort which cannot be kept forever. We must have time and nature working for us, not against us. Otherwise, we will necessarily lose the battle.

Achieving this goal is, clearly, more difficult than proclaiming it. The model proposed in this article was designed to support these evaluations, and, therefore, contributes to support the overall decision process. In this model, there are three different planes to consider: the *internal plane*, the *external plane*, and the *classification plane*. These planes will be addressed next.

The internal plane

This first plane, the *internal plane*, reflects the internal situation status, and the costs of the possible options. If, for example, the situation under analysis is the expansion of an airport infrastructure, this plane will contain all the possible airport configurations achievable by exercising some (or all) of the considered expansion options.

It consists of an O/D cost matrix C, whose lines and columns are the different possible internal situations. The element c_{ij} of this matrix is the cost of transition from situation i to situation j. This cost will therefore be the aggregate cost of exercising the options that enable this transition. Negative costs (profits) can be assigned to some of the transitions. These negative costs can arise, for example, from selling assets, renting previously required space, diminishing costs due to downwsizing, etc. Note that the cost of simultaneously exercising several options is not necessarily the arithmetic sum of exercising each option individually. These costs can be monthly operational costs, set-up non-recurring costs, or any other type of cost elements suited to the situation being modeled.

This plane is, therefore, deterministic in nature. The internal situation can be altered by exercising some of the options, with known estimated costs.

A graphical view of an hypothetic internal plane can be seen in Figure 1, constituted by 12 different possible situations. The elements of the matrix are, as previously stated, the transition costs between situations. In this figure, the cost of moving to Situation 6 directly from Situation 3 is highlighted.

	Sit. 1	Sit. 2	Sit. 3	Sit. 4	Sit. 5	Sit. 6	Sit. 7	Sit. 8	Sit. 9	Sit. 10	Sit. 11	Sit. 12
Sit. 1	0,0	4,0	6,0	17,0	21,0	23,0	20,0	24,0	26,0	41,0	45,0	47,0
Sit. 2	0,0	0,0	4,5	17,0	17,0	21,5	20,0	20,0	24,5	41,0	41,0	45,5
Sit. 3	0,0	0,0	0,0	17,0	17,0	17,0	20,0	20,0	20,0	41,0	41,0	41,0
Sit. 4	-5,0	-1,0	1,0	0,0	4,0	6,0	15,0	19,0	21,0	22,0	26,0	28,0
Sit. 5	-5,0	-5,0	-0,5	0,0	0,0	4,5	15,0	15,0	19,5	22,0	22,0	26,5
Sit. 6	-5,0	-5,0	-5,0	0,0	0,0	0,0	15,0	15,0	15,0	22,0	22,0	22,0
Sit. 7	0,0	4,0	6,0	17,0	21,0	23,0	0,0	4,0	6,0	19,0	23,0	25,0
Sit. 8	0,0	0,0	4,5	17,0	17,0	21,5	0,0	0,0	4,5	19,0	19,0	23,5
Sit. 9	0,0	0,0	0,0	17,0	17,0	17,0	0,0	0,0	0,0	19,0	19,0	19,0
Sit. 10	-5,0	-1,0	1,0	0,0	4,0	6,0	-5,0	-1,0	1,0	0,0	4,0	6,0
Sit. 11	-5,0	-5,0	-0,5	0,0	0,0	4,5	-5,0	-5,0	-0,5	0,0	0,0	4,5
Sit. 12	-5,0	-5,0	-5,0	0,0	0,0	0,0	-5,0	-5,0	-5,0	0,0	0,0	0,0

Figure 1 - Example of the O/D cost matrix of the internal plane

The external plane

This second plane of the model, the so called *external plane*, represents the possible impacts in the external environment. Due to the inherent probabilistic nature of the occurrence of these impacts, the model will try to predict the probability of each impact. It does so by modeling the external situation with a discrete-time Markov chain, where each state corresponds to one of the identified possible impacts, and the transition probabilities mimic the expected evolution of the external environment.

However, the probability of each impact clearly depends on the particular options exercised within the project of transportation infrastructure: different project solutions will, in general, dictate different impact probabilities. To represent this dependency, the transition probabilities of the Markov chain are made dependent of the particular situation achieved in the internal plane. This can be interpreted as if each possible internal situation had its own Markov chain. The external plane can, thus, in the limit, be constituted by as many different Markov chains as there are different situations on the internal plane.

A pictorial view of one of these Markov chains can be seen in Figure 2, where only four possible impacts (states) are considered.

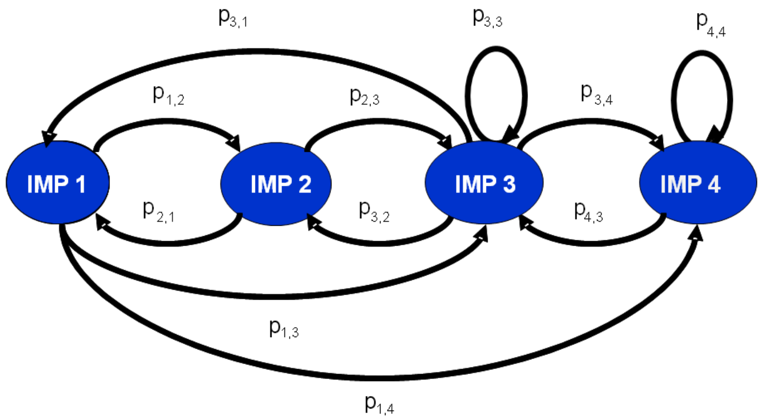

Figure 2 – Four state external plane (Markov chain)

One of the key results of this algorithm is, thus, the estimation of the probabilities of each identified possible impact. These probabilities could, of course, have been directly obtained by enquiring experts and analysts. As was previously discussed, this would imply a huge degree of variability (due to differences in the subjective appreciation of the options and its impacts by different experts), leading to a total lack of reliability of any obtained predictions. Circumventing this variability is the reason for the approach chosen to model the external plane.

Instead of being asked to provide direct numerical values for the probabilities of each impact, the experts are asked only asked to qualitatively compare possible evolutions, two at a time. That is, the type of question posed to the experts area simple questions of the general form: "considering the existing internal and external situations, is it more likely that the systems evolves in this way or in that way?". This type of question allows a high level of agreement between the answers of different experts, even when different subjective evaluations are present. This approach is, therefore, not trying to obtain answers directly concerning the probability of each impact, but, instead, trying to obtain answers concerning the transition probabilities of the Markov chain under analysis.

However, to obtain these transition probabilities, the set of pairwise, purely qualitative answers provided by the experts, must be converted to a numerical scale. To do this, we have successfully used the MACBETH approach (Costa, & Vansnick, 1999).

Once the set of transition probabilities is obtained, the Markov chain can be solved (i.e. the state probabilities determined) and, hence, the stability point of the external situation determined (if the chain has absorbent states), or the steady state probabilities of each impact determined (if the chain does not have absorbent states).

The classification plane

To render the interaction between the internal and external planes more flexible, a third plane is considered, the *classification plane*, whose sole purpose is to be the interface between the two previous planes, grouping different internal situations into classes. Each one of these classes will then correspond to a different Markov chain in the external plane. This classification plane thus allows different internal situations to have the same impact on the probabilities of evolution of the external situation and, therefore, to correspond to the same set of Markov transition probabilities. In the limit, we could have each internal situation mapping to its own class and, therefore, have as many Markov chains in the external plane as there are different situations in the internal plane. A pictorial view of these planes is depicted in Figure 3.

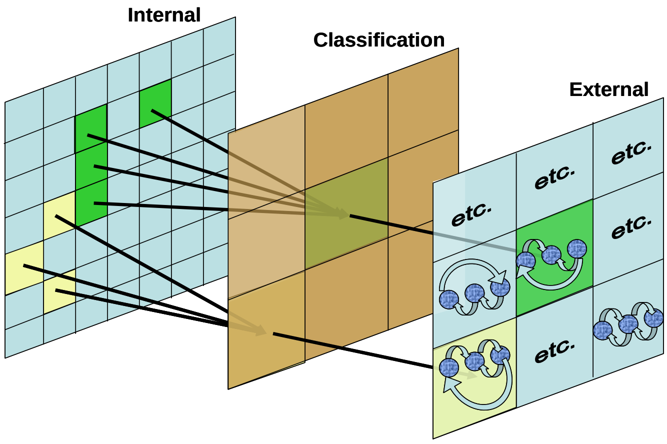

Figure 3 - The three different planes of the model

The algorithm

The overall objective of using the model may be the determination of the set of project options that lead to an internal situation such that the natural equilibrium state in the external plane corresponds to the desired impact (this would correspond to the existence of an absorbent state in the Markov chain); most often, however, there are no absorbent states in the particular set of possible external impacts. In these cases, the steady-state external equilibrium will be a mixture of states, weighted by their individual probability, and the objective may become one of creating a situation where the desired impacts have the highest aggregate probability.
The particular sequence of actions related to the workings of the model depends on the particular question whose answer one is trying to obtain. But the overall scheme is basically the same:

i) List the available internal options, and build the cost matrix corresponding to the internal plane, with each row and column corresponding to a different situation (a different set of exercised options);

ii) List the possible external impacts;

iii) For each situation in the internal plane (or each class of situations, if one decides to use a non-trivial classification plane), estimate the transition probabilities of the corresponding Markov chain (via the MACBETH approach);

iv) Compute the equilibrium point of each Markov chain (e.g. Meyn et al., 1993), and choose the chain with the most useful equilibrium state (or the highest probability in the useful states, if there are no absorbing states), thus determining the desired objective class in the classification plane;

v) On the internal plane, determine the least cost path to one of the positions belonging to the desired class, by using a shortest path algorithm.

Steps iv) and v) correspond to the use of the model with the objective of determining the least cost set (and sequence) of project options to achieve a chosen external impact. If, for example, the objective was to choose the project options that, within a given budget, could maximize the probability of a given impact, then steps iv) and v) would be replaced by:

iv) In the internal plane, determine all the possible situations achievable within the established budget, and thus decide which are the possibly attainable classes in the classification plane;

v) Compute the equilibrium point of each of the Markov chains corresponding to the attainable classes, and choose the chain with the most useful equilibrium state (or the highest probability in the useful states, if there are no absorbing states);

vi) In the internal plane, determine the least cost path to one of the positions belonging to the desired class, by using a shortest path algorithm.

An application example will be given below.

APPLICATION EXAMPLE

In this section, a short example of the use of the proposed model will be provided. Even though necessarily artificial and much simplified, it will, hopefully, capture the nature of this analysis tool.

The project

Consider the case of the national airport of an archipelagic touristic country, currently operating very close to maximum capacity. Ground services are under extreme stress, leading to high delays and latencies in all areas of customer services and, particularly, in luggage handling services. Customer satisfaction levels are at a minimum, which implies a serious risk of losses in touristic summer flows. There is also a growing need of a second runway, capable of increasing the airport landing/take-off rate, thus allowing the expansion of the overall air traffic, both foreign and inter-island. The major identified weaknesses are the following:

i) Single runway limits landing/take-off rate, a problem which becomes seasonally aggravated in summer, due to the then prevailing wind conditions;

ii) Inefficient IT (information technology) support to runway operations, contributing to landing/take-off rate limitations;

iii) Low levels of IT support to customer services, leading to high operation costs, and high queuing delays;

iv) Obsolescent luggage handling system and procedures, leading to very high queuing delays;

v) General lack of terminal space, contributing to the extremely low levels of customer satisfaction.

The options

The need for intervention is, therefore, clear. To address the identified vulnerabilities, several options have been identified:

i) (RUN1): Build a new runway, adequate to summer wind conditions;

ii) (RUN2): Replace and renew the IT infrastructure supporting runway operations. This includes a new control tower, installing a category III MLS (microwave landing system), two new ground control radars, and a new C^2 (command and control) centre;

iii) (CTMR1): Re-engineer all customer related internal processes, in order to speed operations, and decrease system latency and queuing delays;

iv) (CTMR2): Replace the luggage handling system by a modern one, with adequate capacity; implement also CTMR1;

v) (CTMR3): Build a new terminal building from scratch, with modern luggage handling system and customer facilities; implement also CTMR1.

The problem

Local authorities have, however, raised several difficulties to the project of the main island airport expansion. Their main driver is the fear of the impact that the airport expansion may have on the inter-island boat service. This mode of transportation has traditionally been one of the substantive supports of local economies, using the considerable touristic flows between the main island (where the national airport is located) and the smaller islands; any considerable negative impact on this line of business (even if replaced by a corresponding increase in air flows) may create severe difficulties to the island local (already precarious) economies, due to the loss of the positive externalities that the existence of regular boat services have in the local social and economic fabrics.
It is consensually recognized that the increase in the main airport's capacity will probably have an overall positive impact, due to the possibility of increasing the incoming foreign touristic flows (and, therefore, the overall need for inter-island transportation). There is, however, an underlying fear that the resulting shift in the modal distribution of inter-island flows may have severe negative impacts in the local economies and wealth distribution of the smaller, more vulnerable islands.
The problem to be solved is, thus, how to quantify the probabilities of the different possible impacts, relate them to the available project options, and choose the least cost path leading to a solution with high probability of having the adequate impact.

The internal plane

Each one of the identified options will have an associated cost, but these individual costs are not independent. Simultaneity and precedence may affect the costs of each particular option. The applicable cost matrix C can be seen in Figure 4 (the costs in this example are not real). As previously discussed, the lines and columns of this matrix are the attainable internal situations, with element c_{ij} being the cost of transition from situation *i* to situation *j*, and, therefore, the aggregate cost of exercising the options that enable this transition. This matrix shows, for example, that exercising simultaneously options RUN1 and RUN2 has a higher cost than the added costs of the individual options (since the IT system should then be capable of supporting the operation of both runways); also, one can conclude that the cost of directly moving from CTMR1 to CTMR3 is lower than the cost of successive moves from CTMR1 to CTMR2, and then to CTMR3. Note that, in this example, CTMR 1 will always be exercised.

			NOT RUN1						RUN1					
			NOT RUN2			RUN2			NOT RUN2			RUN2		
			CTMR1	CTMR2	CTMR3	CTMR1	CTMR2	CTMR3	CTMR1	CTMR2	CTMR3	CTMR1	CTMR2	CTMR3
NOT RUN1	NOT RUN2	CTMR1	0,0	4,0	6,0	17,0	21,0	23,0	20,0	24,0	26,0	41,0	45,0	47,0
		CTMR2	0,0	0,0	4,5	17,0	17,0	21,5	20,0	20,0	24,5	41,0	41,0	45,5
		CTMR3	0,0	0,0	0,0	17,0	17,0	17,0	20,0	20,0	20,0	41,0	41,0	41,0
	RUN2	CTMR1	-5,0	-1,0	1,0	0,0	4,0	6,0	15,0	19,0	21,0	22,0	26,0	28,0
		CTMR2	-5,0	-5,0	-0,5	0,0	0,0	4,5	15,0	15,0	19,5	22,0	22,0	26,5
		CTMR3	-5,0	-5,0	-5,0	0,0	0,0	0,0	15,0	15,0	15,0	22,0	22,0	22,0
RUN1	NOT RUN2	CTMR1	0,0	4,0	6,0	17,0	21,0	23,0	0,0	4,0	6,0	19,0	23,0	25,0
		CTMR2	0,0	0,0	4,5	17,0	17,0	21,5	0,0	0,0	4,5	19,0	19,0	23,5
		CTMR3	0,0	0,0	0,0	17,0	17,0	17,0	0,0	0,0	0,0	19,0	19,0	19,0
	RUN2	CTMR1	-5,0	-1,0	1,0	0,0	4,0	6,0	-5,0	-1,0	1,0	0,0	4,0	6,0
		CTMR2	-5,0	-5,0	-0,5	0,0	0,0	4,5	-5,0	-5,0	-0,5	0,0	0,0	4,5
		CTMR3	-5,0	-5,0	-5,0	0,0	0,0	0,0	-5,0	-5,0	-5,0	0,0	0,0	0,0

Figure 4 - The internal plane

The external plane

As previously discussed, the behavior of the external environmental is modeled with discrete-time Markov chains, whose nodes are the possible external situations, in terms of the impact that must be analyzed. In this case, and to keep the example simple and manageable, the considered possible situations for the inter-island boat service are:

STATE1 (obl): Oblivion:
STATE2 (dec): Residual and highly vulnerable;
STATE3 (sol): Solid, but non-dominant mode;
STATE4 (dom): Dominant mode of inter-island transportation.

Each one of the Markov chains in the external plane will thus have these four states.

In the example, it will be assumed that RUN1 and RUN2 are equivalent options in terms of the external impact on the inter-island boat service. Thus, we only need to consider nine different classes in the Classification plane and, therefore, nine different sets of transition probabilities in the external plane. Two of the transition matrices (for the two extreme cases in the number of options exercised) are shown in Figure 5 and Figure 6.

CTMR1 ONLY		DESTINATION			
		STATE1	STATE2	STATE3	STATE4
ORIGIN	STATE1	85%	15%	0%	0%
	STATE2	70%	30%	0%	0%
	STATE3	10%	40%	50%	0%
	STATE4	10%	40%	45%	5%

Figure 5 - Transition matrix. CTMR1 only.

ALL OPTIONS EXERCISED		DESTINATION			
		STATE1	STATE2	STATE3	STATE4
ORIGIN	STATE1	15%	5%	60%	20%
	STATE2	10%	0%	65%	25%
	STATE3	0%	5%	15%	80%
	STATE4	0%	5%	5%	90%

Figure 6 - Transition matrix. All options exercised.

Note that, as previously discussed, these transition probabilities are obtained with the MACBETH method (Costa, & Vansnick, 1999): experts are asked to qualitatively compare (pairwise) the possible transitions; afterwards, all these qualitative appreciations are converted to a numerical scale via linear programming. In the case of this example, a license free (demo) version of the M-MACBETH® software package was used (available at *www.m-macbeth.com*).

Each of the Markov chains corresponding to these transition matrices will have a different solution, in terms of state probabilities. Solving the Markov chains is easily done by computing the left eigenvector of the transition matrices (e.g. Meyn et al., 1993). For this example, the MATLAB® software package was used. The results can be seen in Figure 7.

	Exercised options	Pobl	Pdec	Psol	Pdom
Class 1	CTMR1	82%	18%	0%	0%
Class 2	CTMR2	82%	18%	0%	0%
Class3	CTMR3	82%	18%	0%	0%
Class 4	(RUN1 or RUN2), CTMR1	3%	15%	70%	45%
Class 5	(RUN1 or RUN2), CTMR2	2%	17%	67%	48%
Class 6	(RUN1 or RUN2), CTMR3	1%	17%	60%	55%
Class 7	RUN1, RUN2, CTMR1	2%	15%	25%	79%
Class 8	RUN1, RUN2, CTMR2	1%	5%	15%	83%
Class 9	RUN1, RUN2, CTMR3	1%	5%	9%	84%

Figure 7 - State probabilities for all nine classes

Let us now suppose that the objective is to find the least costly way to achieve a probability $p \geq 0.75$ of maintaining the boat service as the dominant mode of inter-island transportation. As can be seen in Figure 7, there are only three classes (Classes 7, 8 and 9) that serve the purpose. The problem, thus, becomes one of determining the least cost path to a situation in the internal plane that maps to one of those classes. These situations are highlighted in Figure 8. In this figure, the least cost path to any cell mapping to one of the desired classes, obtained with the Dijsktra algorithm (e.g. Carter & Price, 2001), is also represented.

			NOT RUN1						RUN1					
			NOT RUN2			RUN2			NOT RUN2			RUN2		
			CTMR1	CTMR2	CTMR3	CTMR1	CTMR2	CTMR3	CTMR1	CTMR2	CTMR3	CTMR1	CTMR2	CTMR3
NOT RUN1	NOT RUN2	CTMR1	0,0	4,0	6,0	17,0	21,0	23,0	20,0	24,0	26,0	41,0	45,0	47,0
		CTMR2	0,0	0,0	4,5	17,0	17,0	21,5	20,0	20,0	24,5	41,0	41,0	45,5
		CTMR3	0,0	0,0	0,0	17,0	17,0	17,0	20,0	20,0	20,0	41,0	41,0	41,0
	RUN2	CTMR1	-5,0	-1,0	1,0	0,0	4,0	6,0	15,0	19,0	21,0	22,0	26,0	28,0
		CTMR2	-5,0	-5,0	-0,5	0,0	0,0	4,5	15,0	15,0	19,5	22,0	22,0	26,5
		CTMR3	-5,0	-5,0	-5,0	0,0	0,0	0,0	15,0	15,0	15,0	22,0	22,0	22,0
RUN1	NOT RUN2	CTMR1	0,0	4,0	6,0	17,0	21,0	23,0	0,0	4,0	6,0	19,0	23,0	25,0
		CTMR2	0,0	0,0	4,5	17,0	17,0	21,5	0,0	0,0	4,5	19,0	19,0	23,5
		CTMR3	0,0	0,0	0,0	17,0	17,0	17,0	0,0	0,0	0,0	19,0	19,0	19,0
	RUN2	CTMR1	-5,0	-1,0	1,0	0,0	4,0	6,0	-5,0	-1,0	1,0	0,0	4,0	6,0
		CTMR2	-5,0	-5,0	-0,5	0,0	0,0	4,5	-5,0	-5,0	-0,5	0,0	0,0	4,5
		CTMR3	-5,0	-5,0	-5,0	0,0	0,0	0,0	-5,0	-5,0	-5,0	0,0	0,0	0,0

Figure 8 - Least cost path to desired classes.

As can be seen, this optimal path implies that the best (least cost) strategy to expand the airport, and still leave the boat service as the dominant inter-island mode of transportation is:

i) Firstly, replace and renew the IT systems supporting runway operations (option RUN2)
ii) As a second phase, build a new runway (option RUN1);
iii) To achieve the desired level of modal dominance of the boat service, the options CTMR2 and CTMR3 should not be exercised.

The cost of this path is 39 (units of cost), and it corresponds to the sequence of project options that, at minimum cost, provides the desired probability of boat service dominance on the inter-island flows (79%).

Trying to interpret the obtained result in this artificial and overly simplified example must be done with extreme care, but the results seem to correspond to the following line of reasoning:

- We must allow the expansion of incoming touristic traffic, by expanding the airport runway capacity;
- The limitations in customer service quality will play a vital role in the avoidance a modal shift in inter-island flows, and the unwanted negative impact on the boat service.

CONCLUSIONS

A method to evaluate the external impacts of complex transport infrastructures was presented. It allows modelling of both the deterministic cost of internal options, and the stochastic nature of the external impact of these options. It thus provides the solution to several optimisation problems, such as the determination of the least cost option for a desired impact, or set of impacts. An example was given, illustrating its application in answering the question: "What is the least cost path that leads to the desired impact"? This is a typical question, in the sense that it directly supports the choice (and optimal sequence) of project options to be exercised. Nevertheless, there are many other questions that may be made to the model, such as: "For a given maximum cost, what is the project path that leads to the most favorable impacts?"; or "What is the path that minimizes a given function of cost and negative impact?". All these questions can easily be answered within the model's framework, providing quantitative, robust support to the decision process.

REFERENCES

Acosta, C., and Siu, N., (1993). Dynamic event trees in accident sequence analysis: application to steam generator tube rupture. Reliability Engineering and System Safety, Vol 41, pg 135-154, 1993.

Carter, M. W. and Price, C. C., (2001). Operations Research: A Practical Introduction, Boca Raton, Florida, USA, CRC Press.

Costa, C. Bana and Vansnick, J.C., (1999). The MACBETH approach: basic ideas, software and an application. IN MESKENS, N., ROUBENS, M., (Ed.) Advances in Decision Analysis, Dordrecht, Kluwer Academic Publishers.

Dimitriou, H. T., (2006). Urban Mobility and Sustainability in Asia and the Power of Context, China Planning Network 3rd Annual Conference, Beijing, 2006.

Graham, S. and Marvin, S. (2001). Splintering Urbanism: Networked Infrastructures, Technological Mobilities, and the Urban Condition. New York: Routledge, 2001.

Hubbard, D. (2007). How to Measure Anything: Finding the Value of Intangibles in Business, John Wiley & Sons.

Kwon, E. (2005a). Infrastructure, Growth and Poverty Reduction in Indonesia: A Cross-Sectional Analysis. ADBI Workshop on Transport Infrastructure and Poverty Reduction, Manila, July 2005.

Kwon, E. (2005b). Road Development and Poverty in the People's Republic of China. ADBI Workshop on Transport Infrastructure and Poverty Reduction, Manila, July 2005.

Meyn, S. P. and Tweedie, R. L. (1993). Markov chains and Stochastic Stability, New York, USA, Springer.

Rayner, N. (2005). The Importance of Transport Services for Poverty Reduction. ADBI Workshop on Transport Infrastructure and Poverty Reduction, Manila, July 2005.

Setboonsarng, S. (2005). Impact of Rural Roads in Agrarian Reform Communities. ADBI Workshop on Transport Infrastructure and Poverty Reduction, Manila, July 2005.

Siu, N. (1994), Risk Assessment for dynamic systems: An overview. Reliability Engineering and System Safety, Vol 43, 1994, pg 43-73